Expansion of cattle ranching in Latin America:

A farm-economic approach for analyzing investment decisions

Promotor: prof.dr. A. Kuyvenhoven
Hoogleraar Ontwikkelingseconomie

Co-promotor: dr. R. Ruben
Universitair Hoofddocent Leerstoelgroep Ontwikkelingseconomie

Promotiecommissie: dr.ir. E.H. Bulte, Universiteit van Tilburg, Nederland
dr. M.D. Faminow, International Development Research Centre (IDRC), Uruguay
prof.dr.ir. R.B.M. Huirne, Wageningen Universiteit, Nederland
prof.dr.ir. A.J. van der Zijpp, Wageningen Universiteit, Nederland

Expansion of cattle ranching in Latin America:

A farm-economic approach for analyzing investment decisions

Peter C. Roebeling

Proefschrift
ter verkrijging van de graad van doctor
op gezag van de rector magnificus
van Wageningen Universiteit,
prof.dr.ir. L. Speelman,
in het openbaar te verdedigen
op dinsdag 16 september 2003
des namiddags te half twee in de Aula

Expansion of cattle ranching in Latin America: A farm economic approach for analyzing investment decisions / Peter C. Roebeling. PhD-thesis, Wageningen University (2003).
With ref. – With summaries in English and Dutch.
ISBN 90-5808-860-X

Subject headings: investment / uncertainty / dynamic optimization / cattle ranching / land speculation / resource degradation / deforestation / Latin America

Abstract

It is generally recognized that cattle ranching in Latin America occupies the major part of the agricultural area, that pasture expansion in favor of cattle ranching is the principal cause of deforestation, and that the conversion of forest into pasture has important environmental consequences. Within the so called 'cattle ranching debate', the expansion of cattle ranching is attributed to the characteristics of cattle ranching, the increased demand for beef products, government policies, land speculation, and resource degradation. Most of the arguments put forward in this debate are, however, qualitative and incomplete in a number of respects. The objective of this study is to obtain an improved understanding of investment and resource use decisions of cattle ranchers in Latin America. To this end, we develop an analytical framework that enables the quantitative appraisal of factors that are considered to have contributed to the expansion of cattle ranching since the 1960's. Illustrative examples are given for cattle ranchers in the Atlantic Zone of Costa Rica.

The increase in Latin American beef production is often explained by the increased demand for beef products, though was accompanied by a considerable decrease in beef prices since the mid 1970's. This study demonstrates that investments in land are deflated due to expected decreases in beef prices, though inflated due to expected fluctuations in beef prices. For a risk-neutral cattle rancher in Costa Rica it is shown that the inflationary effect resulting from fluctuations in beef prices outweighs the deflationary effect resulting from expected decreases in beef prices, with subsequent consequences for deforestation.

The role of land speculation as a contributor to deforestation is highly debated, and largely comes down to whether or not land prices tend to rise over time. In this study it is shown that variability in land prices alone is a sufficient condition for land speculation and inflated levels of investment in land, with subsequent consequences for deforestation. Furthermore, it is shown that increasing land prices only lead to inflated levels of investment in land and deforestation if the land sales price increases relative to the land purchase price. The opposite occurs when the land purchase as well as the land sales price increase.

The role of resource degradation on the expansion of cattle ranching is sparsely and mostly qualitatively dealt with in literature. This study shows that resource degradation provides cattle ranchers the incentive to continuously convert forest into pasture, as forest areas form an important source of fertility for cattle ranchers operating at the agrarian frontier. Fertilizer does not form an economically viable alternative for soil fertility, as current fertilizer prices and application costs per kilogram are far higher than the cost per kilogram of soil fertility obtained through deforestation.

The presented farm-economic approach forms a contribution to current cattle ranching modeling approaches, especially in the Latin American context. Contrary to existing cattle ranching models, that invariably assume a fixed farm size and that do not consider uncertainty or resource degradation, the cattle rancher is considered a profit maximizer who uses land as a productive resource as well as an investment object. It is shown that this approach facilitates the analysis of resource use and investment decisions of cattle ranchers, thereby taking farmer objectives, production possibilities and resource constrains, as well as the relevant economic and policy environment into account.

Acknowledgements

Cattle ranching and deforestation in Latin America is a widely discussed topic amongst scientists and the man on the street alike. The first time I was confronted with this topic professionally was at the *Centro Internacional de Agricultura Tropical* (CIAT, Colombia) in 1995, where I worked (in the sideline) with Joyotee Smith and Vicente Cadavid on a very simple linear programming model for cattle ranchers in the Colombian Savanna. Just before I went back to The Netherlands, Joyotee asked me to consider the possibility to do a Ph.D.-dissertation on cattle ranching and deforestation in Colombia. As I just obtained my M.Sc.-degree at Wageningen University (WU) in that year, I was, however, more interested in actually doing applied research. Yet, the idea remained and resulted, eventually, in this Ph.D.-dissertation. I would like to thank a number of people who supported me in this process.

During my stay in Costa Rica I was always welcome at the *Centro Internacional de Política Económica* (CINPE) in Heredia. At the CINPE I was not only offered a place to work, though also surrounded by professional colleagues and friends who turned the CINPE into an excellent working environment. In particular I would like to thank Edmundo Castro, Fernando Sáenz, Gerrardo Barrantes, Leidy Jiménez and Hannia Corrales, with whom I worked very closely and with great pleasure on the *Políticas Agrarias* research project. You've shown me a lot more of Costa Rica than just volcanoes, rainforests and beaches.

I continued my work in Costa Rica at the Research Program on Sustainability in Agriculture (REPOSA) in Guapiles. I am grateful to Hans Jansen, Bas Bouman, Huib Hengsdijk and André Nieuwenhuyse for showing me that interdisciplinary research can actually be very fruitful and inspiring. I won't forget the beers we enjoyed in the Tucan, Los Lagos and Rio Verde. Furthermore, I would like to express gratitude to Carlos Arragón and Luis Quiros for assisting me in constructing databases and showing me around in Guápiles, and Fernando Cambronero and Olga Carvagal for their secretarial support.

My colleagues at CINPE, REPOSA and the Development Economics Group of WU inspired and supported me to formulate my Ph.D.-proposal. I thank Johan Bouma and Bert Boerrigter of the former *Steunpunt Costa Rica* for arranging the funds that allowed me to realize this Ph.D.-dissertation.

In March 1999 I started my Ph.D.-dissertation at the Development Economics Group of WU. I thank my promoter Arie Kuyvenhoven and my co-promotor Ruerd Ruben as they played an important role in arranging this Ph.D.-position and for critically reviewing earlier versions of this Ph.D.-dissertation. Special thanks go to my (unofficial) supervisor Eligius Hendrix, who was always interested in discussing and developing new ideas and who showed me that mathematics is more than just a tool. This dissertation also greatly benefited from the constructive criticisms provided by Henk Moll, Rob Schipper, Nico Heerink and Gideon Kruseman (Development Economics Group), by Erwin Bulte and Daan van Soest (Tilburg University), as well by my former colleagues of the CINPE and REPOSA. Furthermore, I greatly appreciated the fruitful informal discussions with my fellow Ph.D.-students Marcel Spijkerman, Johan Brons, Marrit van den Berg and Marijke Kuiper. Finally, I would like to express gratitude to Ingrid Lefeber and Henny Hendrikx for their support.

While working on my Ph.D.-dissertation I worked part-time for the Representative Advisory Council of WU and the MGS Ph.D.-council. Luisa Trindade, I think we made a great team during our time at the Representative Advisory Council. Evelien Verbij, Nick den Hollander and Joanna Gusc, I'm glad that you were willing to take over my work at the Representative Advisory Council and the Mansholt Graduate School. It's encouraging to see that the fate of the Ph.D.-students and postdocs of WU is in good hands.

Apart from the professional support provided by my colleagues, I received enormous moral support from my family and friends. Pa, Ma, Ger, Wilma, Heleen and Robby, this dissertation didn't come out of the blue. It is based on the numerous discussions we've had over the years, especially those on Saturday morning while enjoying a cup of coffee. Henk, Gusta, Tonke and Olaf, the interest you showed in my work kept me going through the relatively difficult final phase of this research. In addition, I would like to thank Marrit, Marijke, Huib, Fernando, Luisa, and Evelien for the countless relaxing dinners we shared together, Jan and Monique for the refreshing weekends and holidays we spent together, and Bart for receiving my returns that were sometimes loaded with modeling frustrations. Marijke, thanks for taking (and finding) the picture that is now on the cover of this Ph.D.-dissertation.

Merijn, I'm extremely grateful for the space and liberty you've given me to write my Ph.D.-dissertation, as well as for the patience you've had with me. Especially the final phase of this research must have been hard for you, as I had less time for you and because I was often absent-minded. At whatever time of the day (or night) I scribbled ideas on pieces of paper, and once I even started deriving differential equations on a (paper) place mat while we were having dinner at H41! Your energy, spirit and cheerfulness definitely contributed to the finishing of this Ph.D.-dissertation and is, therefore, also a bit yours.

Table of contents

List of tables

List of figures

Acronyms

f.o.c.	first-order conditions
h.o.t.	higher-order terms
l.h.s.	left-hand side
r.h.s.	right-hand side
AU	Animal Unit
AZ	Atlantic Zone
BCA	Beneift-Cost Analysis
FAO	Food and Agricultural Organization
ha	hectare
kg	kilogram
LD	Labor Days
mm	millimeter
Mt	Metric ton
N	Nitrogen
NPV	Net Present Value
PASTOR	Pasture and Animal System Technical coefficient generatOR
SFP	Soil Fertile Poorly drained
SFW	Soil Fertile Well drained
SIW	Soil Infertile Well drained
SSR	Sum of Squared Residuals
US	United States
US$	US dollar
yr	year

1 Introduction

1.1 Problem statement

Forest clearing and subsequent conversion to pasture for livestock production has been one of the most profound land transformations in Latin America during the past decades (Hecht, 1992; Kaimowitz, 1996). Accordingly, many ecologists have blamed livestock producers for the consequences of deforestation for biodiversity, global and regional climate, and soil resources (see for example Downing *et al*., 1992; Faminow, 1998). Despite numerous discussions in the literature, it is, however, still not fully understood why livestock production in Latin America has grown so quickly.

Different types of producers are involved in livestock production in Latin America. Small farmers, traditional ranchers and investment ranchers are generally recognized as themost important producers (Hecht, 1992; Kaimowitz, 1996; Faminow, 1998). Investment ranchers and, to a minor extent, traditional ranchers are generally described as *cattle ranchers*, who maximize profit and produce beef by grazing one type of animal on large tracts of natural pastures (Squirres and Vera, 1992).

In this study we will focus on cattle ranching in Latin America, for a number of reasons. In the first place, cattle ranchers own most of Latin America's agricultural land and cattle stock, but form a minority in the total number of farmers (Kaimowitz, 1996; Faminow, 1998). Secondly, pasture expansion in favor of cattle ranching is considered the principal cause of deforestation in tropical Latin America (Ledec, 1992; Hecht, 1992; Kaimowitz, 1996). Finally, the conversion of forest into pasture has important environmental consequences, such as loss of biodiversity, emission of trace and greenhouse gases, and resource degradation due to soil erosion and nutrient depletion (Myers and Robbins, 1991; Williams and Chartres, 1991; Haynes and Williams, 1993; Veldkamp, 1994; Plant and Keller, 1999; Veldkamp *et al*., 1999).

Figures from the FAO (2002) confirm that cattle ranching in Latin America plays a dominant role in terms of land use, and that the sector has grown considerably during the past decades. Between 1961 to 1999, permanent pastures accounted for no less than 80% of the agricultural area, while the share of permanent pastures in the total area grew from about 25% in 1961 to almost 30% in 1999 (FAO, 2002). The increase in pasture area was largely facilitated by a decrease in forest and woodland area, which implies a rate of deforestation of up to 2.2 million hectare ha per year or 0.2% of the total forest and woodland area per year. As a result, Latin America accounts for more than 42% of global deforestation. During this same period, Latin American beef production increased by about 2.6% per year.

The expansion of cattle ranching in Latin America is highly debated in the literature. This so- called “cattle ranching debate” generally identifies five factors to explain the expansion of cattle ranching (Hecht, 1992; Seré and Jarvis, 1992; Kaimowitz, 1996; Faminow, 1998). First, cattle as such allows the development of agricultural activities in agrarian frontier areas where markets do not yet exist or are distant, while pasture-based beef production allows the development of distant and large pasture areas. Second, the increased Latin American demand for beef products in general and the increased local demand for beef products in particular led to a considerable increase in beef production. Third, government policies, such as subsidized livestock credit, infrastructure development, land titling, and migration programs, provided cattle ranchers the incentive to expand their cattle ranching activities. Fourth, land speculation generates economic returns over and above the returns obtained from beef production and, consequently, cattle ranchers hold more land for beef production than what would be optimal from a productive point of view. Finally, resource degradation contributes to the expansion of cattle ranching, as more land is required to maintain beef production and because virgin forest areas are converted into pasture to take advantage of their initially high fertility levels.

The causes of expansion mentioned in the Latin American cattle ranching debate are, however, mostly qualitative and incomplete in some respects. It remains unclear why beef production increased despite the considerable decrease and variability in real beef prices since the mid-1970's. Also, the role of land speculation in deforestation is under discussion, and it largely comes down to whether or not land prices tend to rise over time. Finally, the literature deals only sparsely, and mostly qualitatively, with the role of resource degradation in the expansion of cattle ranching in Latin America.

1.2 Objectives

The present study aims to contribute to our understanding of investment and resource use decisions of cattle ranchers in Latin America. It offers an analytical framework that enables the quantitative appraisal of factors that are considered to have encouraged the expansion of cattle ranching since the 1960's. The objectives of this research are the following:

- to recapitulate the economic factors behind the expansion of cattle ranching in Latin America as given in the literature;
- to develop an analytical framework that enables the investigation of investment and resource use decisions of cattle ranchers in Latin America;
- to assess the effect of those economic factors (beef prices, land speculation and resource degradation) that are currently weakly grounded or not mentioned in the literature.

This study intends to contribute to a number of fields in existing literature. First, this study contributes to the Latin American cattle ranching debate. Many of the arguments put forward in the cattle ranching debate are of a qualitative nature. By contrast, this study quantifies the effect of, for example, land speculation and resource degradation on investment and resource use decisions of cattle ranchers. Moreover, some of the arguments used in the cattle ranching debate are counterintuitive from a farm-economic perspective. For example, the increase in Latin American beef production over the last decades is often explained by the increased demand for beef products (Seré and Jarvis, 1992; Kaimowitz, 1996; Faminow, 1997, 1998), even though it was accompanied by a considerable decrease in real beef prices (FAO, 2002). The current study shows that farm level beef production can increase even when beef prices decrease, due to speculative returns from beef production. Another example is the hypothesis that land speculation leads to inflated levels of investment in land, which is considered the case when land prices tend to rise over time (Hecht *et al*., 1988; Van Hijfte, 1989; Hecht, 1992; Kaimowitz, 1996; Smith *et al*, 1997; Faminow, 1998). We show, however, that a general increase in land prices leads to deflated levels of investment in land, as it becomes more expensive to keep land for cattle ranching. Finally, new arguments are added to the cattle ranching debate. It is shown that mere fluctuations in land and beef prices give rise to speculative returns and, subsequently, inflated levels of investment in land.

Second, this study contributes to current cattle ranching modeling approaches, especially in the Latin American context. Existing cattle ranching models are not considered adequate for analyzing resource use and investment decisions of cattle ranchers in Latin America. They invariably assume a fixed farm size (*i.e.* land is not considered an investment option) and do not take uncertainty or resource degradation into account (see for example Standiford and Howitt, 1992; Nicholson *et al*., 1994; Costanza and Neuman, 1997; Bulte *et al*., 2000). These aspects are fundamental to cattle ranching in Latin America (Squirres and Vera, 1992; Downing *et al*., 1992; Kaimowitz, 1996; Faminow, 1998), and we therefore develop a farm-economic model which considers the cattle rancher as a profit maximizer, who uses land as a productive resource and as an investment object. This farm-economic approach facilitates the analysis of resource use and investment decisions and simultaneously takes farmer objectives, production possibilities and resource constrains, as well as the relevant economic and policy environment into account (Varian, 1992; Mas-Colell *et al*., 1995; Sadoulet and De Janvry, 1995). We use farm size and rate of investment as proxies for the pressure on agrarian frontier forest areas: farm size because cattle ranchers mostly operate in agrarian frontier forest areas, and the rate of investment because a larger rate of investment implies a larger farm size and because the rate of investment is indicative for the speed with which cattle ranchers encroach on the forest.

Finally, this study adds to existing Neoclassical investment and soil nutrient stock approaches. The model presented in Chapter 6 forms an extension of the Neoclassical investment theory (*e.g.* Abel and Eberly, 1994, 1997) because explicit investment rules are derived for the case of stochastic capital prices while considering investment costs that are symmetric or asymmetric in the rate of investment. The model presented in Chapter 7 extends the existing models for soil nutrient stocks (*e.g.* McConnell, 1983; Barbier, 1990; Barret, 1991; Bulte and Van Soest, 1999; Bulte *et al*., 2000). It relaxes the assumption of a fixed farm size and recognizes that the purchase of land implies a nutrient inflow.

This study also provides numerical applications of the different versions of the cattle ranching model for the Atlantic Zone (AZ) of Costa Rica. The AZ is located in the eastern part of Costa Rica, and is characterized by a hot and humid climate throughout the year (Nieuwenhuyse *et al*., 2000). The mean annual temperature is about 26° C, and rainfall varies between 3,500 mm and 4,000 mm per year. The AZ encompasses almost 920,000 ha, of which about 37% was used for agriculture in 1995 (Roebeling *et al*., 2000). The most important agricultural land uses included pasture for cattle ranching (72%), banana production (14%) and pasture for milk production (11%). In terms of value added, the situation was quite different. Almost 90% of total value added in the AZ was generated by banana production, 4% by plantain production, and only 3% by beef production. According to the latest agricultural census of 1984, cattle ranchers represented only 9% of all farms in the AZ (DGEC, 1987).

1.3 Organization

Chapter 2 provides a historical overview of the development of cattle ranching in Latin America and the debate surrounding the sources of expansion and the subsequent environmental consequences. It starts with a characterization of the most important livestock producers in Latin America, and continues with an overview of the importance and development of (pasture-based) beef production, consumption and trade in Latin America from 1961 to 1999. Next, we summarize the major arguments put forward in the cattle ranching debate that explain the rapid expansion of cattle ranching over the last decades. Finally, we discuss the most important environmental consequences related to the conversion of tropical forest areas into pastureland for cattle ranching.

Chapter 3 gives an overview of the most important investment theories to date and the mathematical tools that are used in the development of these theories, as both are used extensively in this study. Three major investment theories have been developed in the past decades. Benefit-cost analysis forms the basis for the evaluation of investment projects, in which benefits and costs of an investment project are compared by using a number of procedures. The Neoclassical and Tobin's q-theory of investment go one step further, and state that investments in fixed capital inputs should continue up to the point where the marginal costs of the investment are equal to its marginal returns. The option approach adds that marginal investment costs not only include purchase and installation costs, but also the opportunity cost of keeping the investment option alive. Two mathematical tools are useful in solving investment problems concerned with determining the investment path that maximizes the sum of (uncertain) annual profit streams over time. Dynamic optimization techniques make it possible to determine the optimal investment path that maximizes the discounted sum of annual profit streams over time, while stochastic calculus can characterize the development of uncertain variables over time that affect the decision to invest. This chapter is especially for those readers who are not that familiar with investment theory, dynamic optimization or stochastic calculus.

Chapter 4 presents and develops a farm-economic model for cattle ranchers in Latin America. It enhances existing approaches in that it relaxes the (restrictive) assumption of a fixed farm size and allows the inclusion of stochastic processes. On the basis of the Neoclassical investment theory we develop a deterministic reversible investment model, in which the cattle rancher is considered a profit maximizer who uses land as a productive resource as well as an investment object. The cattle rancher is engaged in pasture-based beef production (beef cattle fattening), thereby using one type of cattle and natural pastures to produce beef according to a constant returns to scale production function that is quadratic in the stocking rate. Land is considered a stock variable as purchase and productive implantation of forested land for grazing is subject to investment costs, while cattle is considered a variable input because it is a nearly liquid source of capital. The model is solved analytically and a numerical example of the model is given for an average cattle rancher in the AZ of Costa Rica on the basis of 1995 data. The corresponding production function for natural-pasture-based beef production as well as the investment cost function are derived and determined empirically.

Chapter 5 examines the effect of decreasing and fluctuating beef prices on investment decisions by cattle ranchers in Latin America. Although the profitability of cattle ranching in Latin America is often doubted, in view of the decrease in real beef prices over the last decades, beef production grew by almost 3% yr^{-1} over the period 1961 to 1999. Besides factors such as speculative returns from land and government subsidies, this expansion is attributed to the increased Latin American demand for beef products in general and the increased local demand for beef products in particular. Nowhere in this demand debate, however, is the importance of speculative returns from beef production emphasized, while the cattle rancher can, in practice, obtain short-term gains by adjusting the level of beef production in response to changing beef prices. Based on the model presented in Chapter 4, a stochastic reversible investment model is developed in which beef prices are modeled as a geometric Brownian motion. The model is solved analytically and, again, applied numerically to the case of Costa Rica. The development of beef production, consumption and trade in Costa Rica between 1961 and 1999 is discussed, and it is shown that real beef export prices in Costa Rica evolve according to a geometric Brownian motion.

Chapter 6 investigates the effect of land speculation and interest rate subsidies on investment decisions by cattle ranchers in Latin America. Cattle ranching is viewed as the easiest vehicle for securing the land while waiting for land prices to rise. At the same time, it provides economic returns in the form of beef production. Proof for the hypothesis that land speculation leads to inflated levels of investment in land is invariably related to the question whether land prices tend to rise over time, but does not consider the short-term speculative gains that can be accomplished through the purchase and sale of land. On the basis of the model developed in Chapter 4, a stochastic reversible investment model is developed in which land prices are modeled as a geometric Brownian motion. The model is solved analytically for the case of quadratic as well as exponential investment costs, and also applied to the case of Costa Rica. The development of real land prices and livestock interest rates over the past decades is discussed, and it is shown that real land prices in Costa Rica evolve according to a geometric Brownian motion.

Chapter 7 looks at the effects of fertilizer price subsidies and land price appreciation on sustainable cattle ranching in Latin America. Soil nutrient availability is one of the most important factors determining present and future pasture productivity in Latin America. Economic farm models concerning the trade-off between current soil degradation and future productivity invariably assume a fixed farm size. However, this assumption does not hold for cattle ranching in Latin America because land is a productive resource as well as an investment object for cattle ranchers. In addition, land is also considered an important source of fertility for cattle ranchers operating at the agrarian frontier. On the basis of the model developed in Chapter 4, a deterministic reversible investment model with adjustment costs is developed in which land dynamics as well as soil nitrogen dynamics are specifically taken into account. Steady-state reduced form equations and conditions for global optimality are derived, and a numerical example of the model is given for an average beef cattle rancher in the AZ of Costa Rica. The corresponding stocking rate and nutrient dependent production function for pasture-based beef production is derived and determined empirically.

Finally, Chapter 8 discusses the most important findings that follow from this study, major policy implications of these findings are presented, and, finally, limitations of the applied approach are discussed and suggestions for future research are provided.

2 Cattle ranching in Latin America: overview and debate

2.1 Introduction

Cattle ranching in Latin America has been widely discussed in the literature (*e.g.* Downing *et al.*, 1992; Kaimowitz, 1996; Faminow, 1998). Over 40% of the global deforestation since the 1960's occurred in the tropics of Latin America. Pasture for beef cattle ranching was the most common replacement for these cleared tropical forest areas, and this has important environmental effects. The ensuing expansion of cattle ranching over the past decades is commonly explained by the increased Latin American and U.S. demand for beef products, despite the general decrease in real Latin American and world market beef prices.

The factors that are considered to have encouraged the expansion of cattle ranching in Latin America are topic of much debate. This chapter summarizes the most important issues put forward in this so-called "cattle ranching debate". Its purpose is threefold: 1) to provide a historical overview of the importance and development of cattle ranching in Latin America, 2) to summarize the major arguments put forward in the cattle ranching debate to explain the rapid the expansion of cattle ranching over the past decades, and 3) to assess the environmental consequences related to the conversion of tropical forest areas into pasture-land for cattle ranching.

The remainder of this chapter is structured as follows. In Section 2.2, the most important types of livestock producers in Latin America are characterized. Section 2.3 provides an overview of the importance and development of (pasture-based) beef production, consumption and trade in Latin America from 1961 to 1999. Section 2.4 discusses the different forces behind this recent expansion of cattle ranching and Section 2.5 covers environmental consequences. Section 2.6 contains conclusions and observations.

2.2 Livestock producers in Latin America

Different types of producers perform livestock production in Latin America. As each type of producer has its own specific objectives, production possibilities and market constraints, each of them responds differently to changes in markets, technology and policy (Kaimowitz, 1996). On the basis of Hecht *et al.* (1992), Kaimowitz (1996) and Faminow (1998), three major types of livestock producers can be identified: 1) traditional ranchers, 2) investment ranchers, and 3) small farmers.

Traditional ranchers hold medium and large farms, have been involved in livestock production for many decades and, consequently, are located in the established cattle ranching regions. They inherited most of their land or obtained it through claims on public lands, although some of it was purchased in recent decades. As a result, Kaimowitz argues, these ranchers are more interested in recurrent returns obtained from beef production than in the long-term profitability of the total livestock production system (*i.e.* taking into account recurrent returns from beef production as well as the opportunity costs of land). Moreover, for these ranchers, land and cattle may have a prestige value that exceeds the direct economic return (Ledec, 1992).

Investment ranchers hold relatively large tracts of pastureland, and are mostly capitalist entrepreneurs who view cattle ranching as an attractive investment (Kaimowitz, 1996). Most investment ranchers are (wealthy) government officials, businessmen and merchants who either went into the business on their own or formed joint ventures with established livestock ranchers (Edelman, 1992). Although they had hardly any or even no experience in beef cattle production, they were attracted by government land grants, rising land values, subsidized credits, limited supervision requirements and, in some cases, tax advantages (Hecht, 1992; Kaimowitz, 1996; Faminow, 1998). Consequently, investment ranchers are not only interested in recurrent returns from beef production, but also in the returns that can be obtained from rising land prices and land speculation (Crotty, 1980; Kaimowitz, 1996).[1] Moreover, Kaimowitz notes that investment ranchers tend to adjust their farm size and/or cattle stock in response to changed market conditions.

Small farmers, without access to prime agricultural land, are characterized by some crop production in combination with dual-purpose livestock production. These farmers are interested in recurrent returns from crop and livestock production. Livestock production is mainly focussed on calf, milk and (to a minor extent) beef production, and provides advantages such as diversification of farm output, income smoothing and relatively low labor requirements (Kaimowitz, 1996; Faminow, 1998). Compared to the much larger traditional and investment ranchers, small farmers portray higher stocking rates and greater use of crop residues as animal feed (Kaimowitz, 1996).

Investment ranchers and, to a minor extent, traditional ranchers are the type of livestock producers that Squirres and Vera (1992) describe as *cattle ranchers*. They define cattle ranching as a specialized form of livestock production that is characterized by: 1) profit maximization, 2) production of beef for the market, 3) cattle grazing extensively on natural pastures, 4) raising one single type of animal, and 5) operating large pasture areas. In Latin America, cattle ranchers own most of the agricultural area and cattle stock while forming a minority relative to the total number of farmers (Downing *et al*., 1992; Kaimowitz, 1996; Faminow, 1998). In general, they can be found where there are large tracts of land with (so far) few alternative agricultural uses (for example the Pampas of Argentina, the Amazon in Brazil, the Llanos in Colombia, and the tropical lowlands in Central America).

2.3 Importance and development of cattle ranching over the period 1961 to 1999

This section discusses the importance and the development of pasture-based beef production in Latin America over the period 1961 to 1999. First, we will look at the development of pasture, crop and forest areas. Next, we discuss the development of beef production, consumption, and trade and then we analyze the development

---

[1] Beef production is mostly oriented towards steer fattening, as it provides the quickest returns at a relatively low risk and at relatively low management and supervision costs (Kaimowitz, 1996).

of productivity and intensity of beef production. In line with, for example, Seré and Jarvis (1992), Kaimowitz (1996) and Faminow (1998), the discussion is divided into the periods before and after the mid-1970's.[2]

2.3.1 Pastures, crops and forest in total land use

Livestock production in Latin America is mostly pasture-based and oriented towards beef and, to a minor extent, milk production (Seré and Jarvis, 1992). As a consequence, the livestock sector dominates land use. Latin American land use data for the period 1961 to 1999 (see Table 2.1) show that permanent pastures accounted for about 80% of the total agricultural area (*i.e.* the sum of arable crops, permanent crops and permanent pastures). During this period, the share of permanent pastures in the total area increased from about 25% in 1961 to almost 30% in 1999, while the share of arable and permanent crops increased from about 5% to 7.5%. Note, however, that the rate of pasture expansion decreased over time from $3.8*10^6$ ha yr^{-1} in the 1960's to $0.8*10^6$ ha yr^{-1} in the 1990's.

Table 2.1 Land use for Latin America over the period 1961 - 1999

	1961		1971		1981		1991		1999	
	10^6 ha	%	10^6 ha	%	10^6 ha	%	10^6 ha	%	10^6 ha	%
Arable and permanent crops	98	4.9	113	5.6	133	6.6	143	7.1	151	7.5
Permanent pastures	500	24.8	540	26.8	565	28.1	591	29.4	594	29.5
Forest and woodland	1019	50.6	980	48.7	952	47.3	936	46.5	933	46.4
Other	396	19.7	378	18.8	362	18.0	342	17.0	333	16.5
Total area	2012	100.0	2012	100.0	2012	100.0	2012	100.0	2012	100.0

Source: FAO statistical database (2002).

The increase in pasture area was largely facilitated by a decrease in forest and woodland area, while the increase in crop area was accomplished through a decrease in pasture area (Hecht, 1992; Kaimowitz, 1996). Over the period 1961 to 1999, the share of forest and woodland in the total area declined from about 50% in 1961 to just over 45% in 1999. Consequently, forest and woodland clearance in Latin America amounted to up to $2.2*10^6$ ha yr^{-1} or 0.2% of the total forest and woodland area per year. This is more than 42% of global deforestation (FAO, 2002). In line with the reduced expansion of the pasture area over the concerned period, the rate of forest and woodland clearance decreased from about $3.8*10^6$ ha yr^{-1} in the 1960's to $0.3*10^6$ ha yr^{-1} in the 1990's.

2.3.2 Beef production, consumption and trade

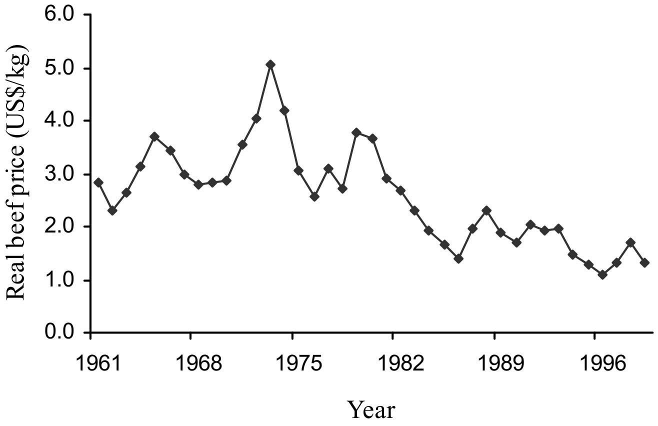
Figures 2.1 and 2.2 give the development of real world market beef prices and the development of Latin American beef production, consumption, export and import over the period 1961 to 1999, respectively. Latin

---

[2] The existence of a break point around the mid-1970's is mainly explained by the reduced export possibilities after the mid-1970's (see Section 2.3.2).

American beef trade is relatively small compared to domestic production.[3] From 1961 to the mid-1970's, about 7.7% of total beef production was destined for the export market while only 0.4% of total beef consumption was met by beef imports. World market demand for beef products was relatively high compared to world market supply. Per capita beef consumption in the United States increased with 20% in the 1960's due to rising real incomes (Williams, 1986), and global demand for pasture-fed beef increased with more than 20% in the first half of the 1970's due to the petroleum crisis (Edelman, 1985).[4] As a result, real world market beef prices were relatively high, the total export value averaged $1.37*10^9$ US\$ yr^{-1}, and the total import value averaged $0.08*10^9$ US\$ yr^{-1}. After the mid-1970's, Latin American beef exports dropped, and only 1.5% of total beef production went to the export market while about 1% of total beef consumption was met by beef imports. World market beef demand diminished, while world market beef supply grew. Per capita beef consumption in the United States declined because consumers became more health-conscious and real incomes stagnated, while the European Economic Community became a net exporter instead of a net importer of beef products (Kaimowitz, 1996). Consequently, real world market beef prices fell, the total export value decreased to $0.36*10^9$ US\$ yr^{-1}, and the total import value increased to $0.21*10^9$ US\$ yr^{-1}. Kaimowitz (1996) notes that the export of Latin American beef was, furthermore, hindered by the enforcement of quality measures and health regulations in the United States as well as by over-valued exchange rates.

Figure 2.1 **Real world market beef prices over the period 1961 - 1999**



Source: FAO statistical database (2002).

Note: Prices in constant 1995 US$.

Latin American beef consumption increased relatively slowly between 1961 and the mid-1970's. Per capita beef consumption in the region declined due to declining real incomes in general and increasing real beef

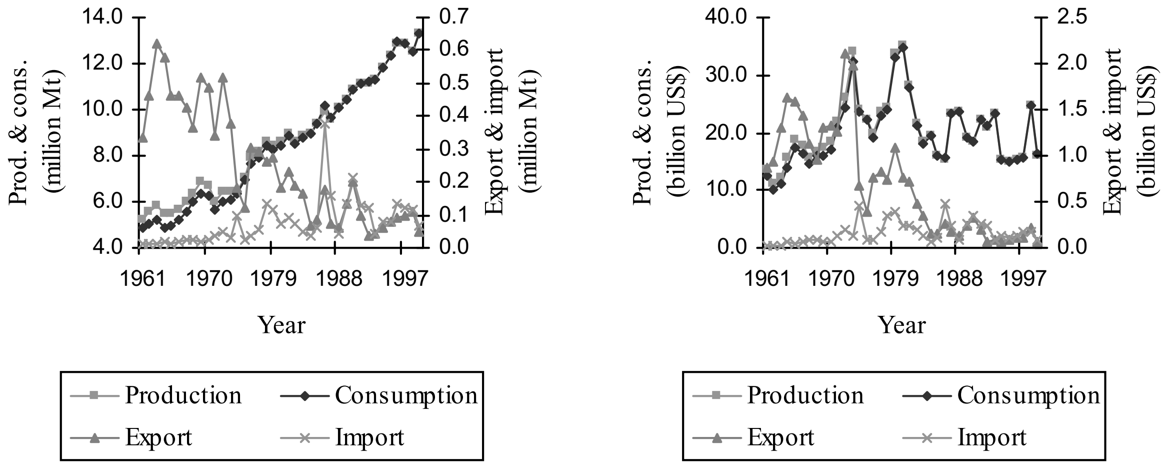
---

[3] Seré and Jarvis (1992) note that the international beef market is a residual market of high volatility because of the existence of cattle cycles and buffer policies of developed countries.

[4] Rising petroleum prices pushed up the price of feed grains and (thus also) the price of grain-fed beef. Consequently, consumers switched to the less expensive pasture-fed beef.

prices in particular, although it was offset by population growth levels of almost 3% yr^{-1} (Kaimowitz, 1996). Consequently, Latin American beef consumption increased with about 2.0% yr^{-1} over the period 1961 to 1973, while the value of beef consumption increased with no less than 9.2% yr^{-1} due to the increase in real world market beef prices. After the mid-1970's, Latin American beef consumption grew more rapidly. Although per capita beef consumption stabilized (till the 1990's) – owing to real income stabilization and a process of substitution in consumption from beef to poultry (Rivas *et al.*, 1988; FAO, 2002) – population growth was still over 2% yr^{-1} and local demand for livestock products increased due to government migration programs as well as spontaneous migration (Faminow, 1998). As a result, Latin American beef consumption increased with about 3.1% yr^{-1} after the mid-1970's, while the value of beef consumption decreased with about 0.2% yr^{-1} as a result of the decline in real world market beef prices.

Figure 2.2 **Beef production, consumption, export and import quantity (a) and value (b) for Latin America over the period 1961 – 1999**


(a) (b)

Source: FAO statistical database (2002).

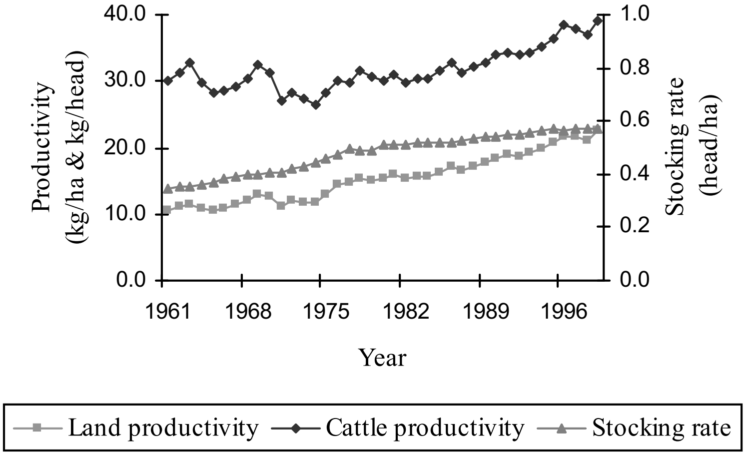
Note: Production, consumption, export and import values are calculated on the basis of real 1995 world market prices.

In line with Latin American beef consumption, beef production increased relatively slowly over the period 1961 to the mid-1970's. Real world market beef prices rose, due to increased Latin American and world market demand for beef products. This provided the incentive for cattle ranchers to increase beef production (Seré and Jarvis, 1992). Consequently, beef production increased with about 2.0% yr^{-1} between 1961 and the mid-1970's, while the value of beef production increased with 9.1% yr^{-1} due to the rise in real world market beef prices. After the mid-1970's, Latin American beef production increased more rapidly. Declining real world market beef prices, over-valued exchange rates and reduced access to export markets favored the domestic sale of beef (Seré and Jarvis, 1992), while Latin American demand for beef products increased (FAO, 2002). As a result, beef production increased with about 2.9% yr^{-1}, whereas the value of beef production decreased with about 0.3% yr^{-1} due to the decline in real world market beef prices.

2.3.3 Productivity and intensity of beef production

Fig. 2.3 depicts productivity and intensity indicators of beef cattle production in Latin America for 1961 to 1999, as determined from the FAO database (2002). In 1961, land productivity amounted to about 10 kg of beef per hectare, cattle productivity was 30 kg of beef per head, and the stocking rate equaled 0.35 head per hectare.[5] Between 1961 and 1999, land productivity more than doubled, which is explained by a one-third increase in cattle productivity in combination with an almost doubled stocking rate. Cattle productivity was improved through the introduction of improved cattle breeds, artificial insemination, and increased use of veterinary inputs, while stocking rates were increased through the introduction of improved pasture varieties, increased use of fertilizers and herbicides, and investments in fences and water supply (Kaimowitz, 1996).

Figure 2.3 **Productivity and intensity of beef production for Latin America over the period 1961 - 1999**



Note: Based on the FAO statistical database (2002).

The increase in beef production over the period from 1961 to the mid-1970's was mainly attained through extensification. Beef production per hectare grew with less than 1.5% yr^{-1}, as a consequence of an increase in the stocking rate in combination with a decrease in cattle productivity (+2.0% yr^{-1} and –0.6% yr^{-1}, respectively). Increasing real world market beef prices induced cattle ranchers to sell their beef cattle at a lower age, while at the same time expanding the pasture area (+0.7% yr^{-1}) and the cattle stock (+2.6% yr^{-1}) to increase beef production (+2.0% yr^{-1}). The expansion of the cattle stock was accomplished through increased use of veterinary services aimed at elevating off-take rates and lowering (calf) mortality rates. The situation changed after the mid-1970's, when the increase in beef production was attained through a combination of extensification and intensification. Beef production per hectare grew with more than 2.5% yr^{-1}, owing to an increase in stocking rate as well as cattle productivity (+1.1% yr^{-1} and +1.4% yr^{-1}, respectively). Decreasing

---

[5] These productivity and intensity figures are underestimated, as the FAO data on cattle numbers are aggregated over beef, multi-purpose and milk cattle, and the FAO data on the permanent pasture area are aggregated over used, unused and abandoned pastures.

real world market beef prices induced cattle ranchers to sell their beef cattle at a higher age, but also encouraged the adoption of more productive cattle breeds. Compared to the period 1961 to the mid-1970's, this led to a relatively small expansion of the pasture area (+0.3% yr^{-1}) and the cattle stock (+1.4% yr^{-1}), and a relatively large increase beef production (+2.9% yr^{-1}).

To gain insight into the factors that determine cattle and land productivity of beef production in Latin America over the period 1961 to 1999, two linear regression models are developed, in which real world market beef prices (in 1995 US$ kg^{-1}), the stocking rate (in head ha^{-1}) and an exogenous trend are explanatory variables (see Table 2.2). The estimation results are corrected for problems of heteroskedasticity, by using White's heteroskedasticity consistent covariance matrix estimator, which provides correct estimates of the coefficient covariances in the presence of heteroskedasticity of unknown form (White, 1980).

Table 2.2 Productivity estimation results of beef production for Latin America over the period 1961 - 1999

	Cattle productivity[1]		Land productivity[1]	
Explanatory variables[2,3]				
Constant	56.314	***	-	
Price beef	-1.580	***	-0.899	***
Stocking rate	-65.546	***	60.709	***
Squared stocking rate	-		-77.356	***
Trend	0.542	***	0.336	***
Performance indicators				
R^2 (adj.)	0.838		0.957	
LM-test (prob.)	0.002		0.000	
Number of observations	39		39	

Notes: [1] Cattle productivity is given in kg beef $head^{-1}$ and land productivity is given in kg beef ha^{-1}.

[2] Price beef in 1995 US$ kg^{-1} and stocking rate in head ha^{-1}.

[3] Significant at the 10% level, the 5% level (**), and the 1% level (***).

Source: FAO statistical database (2002).

The regression model for cattle productivity (in kg beef $head^{-1}$) is based on the frequently suggested linearly decreasing relation between production per animal and stocking rate (see Chapter 4, Section 4.2 for a more elaborate discussion) and includes a constant, the price of beef, the stocking rate, and a trend as explanatory variables. The beef price determines the selling age of beef cattle, and is negatively and significantly related to cattle productivity. When beef prices are higher, and given that cattle weight gain decreases with age, beef cattle is sold at a lower age (and thus lower weight!) in order to increase beef production (Crotty, 1980). The stocking rate determines the feed availability per head, and is negatively and significantly related to cattle productivity. When the stocking rate is larger, competition for feed increases while total feed supply decreases due to trampling and, consequently, weight gain per head is reduced (Jones and Sandland, 1974; Bouman *et al.*, 1998). Finally, the trend indicates the exogenous growth of cattle productivity over time, and is positively and significantly related to cattle productivity. This result implies that cattle productivity has increased over time due to, for example, the adoption of more productive cattle breeds. The parameter coefficients all have the expected sign, and are significantly different from zero at the 1% level according to the *t*-test. The explanatory power of the model is good as reflected in the relatively high adjusted R^2 values, while the LM-test points towards problems with serial correlation.

The regression model for land productivity (in kg beef ha^{-1}) is based on a quadratic relationship between animal production per hectare and stocking rate, which follows from the just mentioned linear relationship between production per animal and stocking rate (see Chapter 4, Section 4.2). Explanatory variables include the price of beef, the stocking rate, the squared stocking rate, and a trend. The beef price is negatively related to land productivity, which is explained by the fact that beef prices and cattle productivity are related negatively (see previous paragraph). The stocking rate and squared stocking rate are, respectively, positively and negatively related to land productivity. An increase in the number of beef cattle per hectare leads to an increase in beef production per hectare, while cattle productivity decreases in the stocking rate. The trend, finally, determines exogenous growth of land productivity over time, and is positively related to land productivity. This result implies that land productivity has increased over time due to, for example, the adoption of improved pasture species. All parameter coefficients have the expected sign, and are significant at the 1% level according to the *t*-test. The high R^2 value indicates that the explanatory power of the model is high, although the LM-test indicates the occurrence of serial correlation.

2.4 Sources of expansion

The previous section showed that cattle ranching in Latin America has grown considerably since the 1960's. This expansion is generally explained by: 1) the characteristics of cattle ranching, 2) the increased demand for beef products, 3) government policies, 4) land speculation, and 5) resource degradation (Hecht, 1992; Seré and Jarvis, 1992; Kaimowitz, 1996; Faminow, 1998). The following subsections will address each of these sources of expansion.

2.4.1 Characteristics of cattle ranching

The characteristics of cattle ranching or pasture-based beef production in Latin America, are part of the explanation of the fast growth of this sector over the past decades. Cattle as such possesses a number of advantages. First, cattle provides manure and traction, which is especially important for farmers and ranchers in remote areas where access to nutrient and traction markets is limited (Faminow, 1998). Second, cattle provides banking services in the form of an investment opportunity, liquid savings or a hedge against inflation, especially where financial markets are limited or absent (Hecht, 1992). Third, cattle is easy to transport at relatively low cost (Hecht, 1992; Faminow, 1998). Finally, cattle provides prestige and access to financial services through its collateral value (Kaimowitz, 1996). Consequently, cattle plays an important role for farmers and cattle ranchers in agrarian frontier areas where markets are distant or failing altogether.

Pasture-based beef production also holds a number of advantages (Hecht, 1992; Faminow, 1998). In the first place, its labor requirements are relatively low. On average, labor requirements in cattle and natural-pasture management amount to approximately 0.9 LD $head^{-1}$ yr^{-1} and 1.6 LD ha^{-1} yr^{-1}, respectively (Bouman *et al*., 1998). Secondly, external input requirements of cattle and natural pastures are relatively low. On average, costs of veterinary services and dietary supplements amount to up to 13 US\$ head^{-1} yr^{-1}, and the costs of herbicides and pesticides to up to 40 US\$ ha^{-1} yr^{-1} (Bouman *et al*., 1998). Finally, and related to the low labor requirements, supervision costs are also relatively low. Consequently, pasture-based beef production allows farmers and cattle ranchers to operate distant and large pasture areas at a relatively low financial risk.

In sum, cattle allows the development of agricultural activities in agrarian frontier areas where markets are not yet existing or distant, while pasture-based beef production allows the development of distant and large pasture areas. This provided the incentive to traditional and, especially, (well-employed) investment ranchers to establish large cattle ranches, as they had relatively good access to credit while prices of land at the agrarian frontier were relatively low (Kaimowitz, 1996; Faminow, 1998).

2.4.2 Increased demand for beef products

Section 2.3.2 explained that Latin American demand for beef products increased since the mid-1970’s, due to population growth and decreasing real beef prices. This increased demand for beef products is considered to have contributed to the expansion of cattle ranching in Latin America for a number of reasons.

First of all, and not particularly surprising, the increased demand for beef products needed to be balanced by the supply of beef products (Seré and Jarvis, 1992; Kaimowitz, 1996; Faminow, 1998). Section 2.3.2 described that the supply of beef products was mainly increased through an increase in domestic beef production (over 99% of domestic beef consumption was met by domestic beef supply). The increase in domestic beef production was mainly attained through expansion of the pasture area, as relative price shares favored the extensive use of low-cost land (Faminow, 1998).

Secondly, local domestic demand for livestock products increased due to government migration programs and spontaneous migration (Faminow, 1997). In combination with the relatively high transport costs between developed and migration areas, this increase in local demand for beef products led to an enormous (temporary) increase in local beef prices. This clearly boosted local investment in pasture-based beef production. Moreover, production systems adopted in the migration areas were relatively extensive in terms of land use as compared to the traditional beef production areas, because land prices were relatively low while external input prices were relatively high (transport costs).

In summary, increased Latin American demand for beef products in general, and increased local demand for beef products in particular, led to a considerable expansion of cattle ranching in Latin America. The so called “hamburger connection”[6] seems to have been of little relevance to Latin America as a whole because only a small and decreasing part of the total Latin American beef production was destined for the export market (see Section 2.3.2). Finally, beef production increased despite the considerable decrease and variability in real beef prices since the mid-1970’s (see Figure 2.1). In Chapter 5, we will take a closer look at the effect of decreasing and uncertain beef prices on investment decisions by cattle ranchers.

---

[6] Myers (1981) introduced this term to describe how the expanding U.S. market for Central American beef products resulted in an expansion of the beef cattle herd and subsequent deforestation in the region.

2.4.3 Government policies

During the past decades, governments in Latin America (with the help of international development agencies) promoted cattle ranching enthusiastically (Ledec, 1992) and this may have contributed to the expansion of cattle ranching in a number of ways.

In the first place, governments provided livestock credit from the 1960's till the beginning of the 1980's, which was heavily subsidized and went predominantly to cattle ranchers (Kaimowitz, 1996; Faminow, 1998). Livestock credit promoted cattle ranching as it helped cattle ranchers to overcome credit constraints which otherwise would have limited pasture and herd expansion, while it also made cattle ranching an attractive investment option compared to alternative investment options (Kaimowitz, 1996). Ledec (1992) and Faminow (1998), however, show that the role of subsidized credit in the expansion of cattle ranching is generally overstated (see also Chapter 6).

Secondly, road construction in agrarian frontier and forest areas without doubt promoted the conversion of forest into pasture (Jones, 1990; Ledec, 1992; Kaimowitz, 1996; Faminow, 1998). Roads promote the expansion of cattle ranching directly through the physical access it facilitates and the reduction in transport costs it results in, and indirectly through the potential returns from land speculation (see also Section 2.4.4 and Chapter 6).

Thirdly, governments recognized private property rights (land titles) to invaded national forest land that had been improved by clearing for pasture and farmland (Kaimowitz, 1996; Faminow, 1998). Jones (1990) argues that, consequently, deforestation of squatted land in favor of pasture establishment not only provided returns from beef production, but also demonstrated that the land was actively being used (squatters often had to prove that they had used the invaded land for a number of years).

Finally, government migration programs and spontaneous migration led to the development of local markets for livestock products (Kaimowitz, 1996; Faminow, 1997). This process was furthermore encouraged by colonization schemes in which the government sold land to cattle ranchers at a price well below the market value (Kaimowitz, 1996).

In sum, subsidized livestock credit, infrastructure development, land titling of invaded areas, and migration programs are government policies that all contributed to the expansion of cattle ranching in Latin America. According to Faminow (1998), the combined effect of these factors resulted in an increased demand for food products in the region, and the cattle ranchers took advantage of this situation.

2.4.4 Land speculation

Land speculation by cattle ranchers is often considered the principal cause of deforestation in Latin America, especially in combination with the interest rate subsidies that were widely provided to cattle ranchers until the beginning of the 1980's (Van Hijfte, 1989; Hecht, 1992; Kaimowitz, 1996; Smith *et al*, 1997). Cattle ranching is viewed as the easiest vehicle for securing the land while waiting for land prices to rise, and at the same time it also provides economic returns in the form of beef production (Hecht, 1992; Faminow, 1998). Consequently, it is argued, cattle ranchers hold more pasture-land for beef production than what would be optimal from a productive point of view (Kaimowitz, 1996; Jansen *et al*, 1997; Smith *et al*, 1997).

The development of land prices in Latin American agrarian frontier areas is an important issue of debate in the literature. Fearnside (1990), Diegues (1992) and Kaimowitz (1996) argue that real land prices in Central America have risen considerably over the last decades, for a number of reasons. First, real land prices have risen at a rate greater than or equal to the opportunity cost of capital due to infrastructure development, favorable livestock product prices during the 1960's and 1970's, as well as population growth and urbanization. Second, Ledec (1992) states that deforested lands usually sell at much higher prices than forested lands. Faminow (1998), however, considered the real land prices as not having risen at all. He shows that annual rates of returns to land speculation in the Brazilian Amazon are greater than the opportunity cost of capital in only 32% of the cases and even negative in 34% of the cases. For the year 1986, however, annual rates of return ranged between 4% and 87%, a result that would plead in favor of the argument of land speculation.

Summarizing, the debate about the role of land speculation in Latin American deforestation largely comes down to whether or not land prices tend to rise over time. In Chapter 6, we will take a closer look at this issue, thereby specifically differentiating between the effects of rising and of fluctuating land prices on investment decisions by cattle ranchers.

2.4.5 Resource degradation

Many cattle ranching systems in Latin America are rapidly degrading their resource base (Kaimowitz, 1996; Faminow, 1998). This resource degradation is mainly attributed to soil erosion and nutrient depletion, and eventually leads to pasture degradation and declining pasture yields (Haynes and Williams, 1993; Myers and Robbins, 1991; Williams and Chartres, 1991). Consequently, resource degradation is considered to contribute to the expansion of cattle ranching into agrarian frontier forest areas in two ways. First, with progressive pasture degradation cattle ranching becomes less and less profitable, degraded pasture-land will be abandoned, and cattle ranchers start buying virgin forest areas to take advantage of their initially high fertility levels (Haynes and Williams, 1993; Kaimowitz, 1996). Second, more land is required to produce a certain amount of beef on degraded than on non-degraded land (Kaimowitz, 1996).

In contrast, the literature has only sparsely, and mostly qualitatively, investigated the role of resource degradation on the expansion of cattle ranching in Latin America. The following section contains a more detailed description of the environmental issues related to cattle ranching in Latin America, and Chapter 7 analyzes the effects of resource degradation on investment and production decisions by cattle ranchers.

2.5 Environmental implications

Pasture for cattle ranching has been the most common replacement for cleared tropical forest areas in Latin America (Downing *et al.*, 1992; Kaimowitz, 1996; Faminow, 1998). The most important environmental effects related to the conversion of tropical forest areas into pasture-land are: 1) increased emission of trace and greenhouse gases, 2) resource degradation, and 3) loss of biodiversity. Each of these issues will be discussed briefly in the following subsections.

2.5.1 Emission of trace and greenhouse gases

Trace and greenhouse gases such as carbon dioxide (CO_2), nitrous oxide (N_2O) and nitric oxide (NO) play an important role in climate change, as they block solar radiation reflected by the surface of the earth as infrared radiation (Plant, 1999). Moreover, N_2O contributes to the destruction of stratospheric ozone (O_3) and, consequently, leads to increased levels of UV-B radiation at the earth's surface.

Tropical forest clearing in favor of cattle ranching increases CO_2 emission in three ways. First, there is the direct effect of burning the forest cover to make way for natural pastures (Faminow, 1998). Next, cattle produces methane (CH_4), which is partly converted into CO_2 through atmospheric oxidization (Johnson and Johnson, 1995). Finally, Plant and Keller (1999) and Veldkamp (1994) show that between 35% and 70% of the soil organic carbon (C) is lost from the system (in the form of CO_2) due to the conversion of tropical forest into pasture.

The effect of tropical forest clearing on soil-atmosphere emission of N_2O and NO has been studied extensively. Keller *et al.* (1993), Keller and Reiners (1994) and Veldkamp *et al.* (1999), for example, show that the emission of N_2O and NO measured in young pastures (*i.e.* between 2 and 10 years old) is 5 to 8 times larger than the emission of N_2O and NO measured in tropical forests. Ten years after pasture establishment, however, pasture N_2O and NO emissions fall below forest levels. Consequently, land use changes and pasture age are essential factors in controlling N oxide emissions in the tropics of Latin America.

2.5.2 Resource degradation

As already mentioned in Section 2.4.5, resource degradation in cattle ranching is mainly attributed to soil erosion and nutrient depletion, and leads eventually to pasture degradation and declining pasture yields (Haynes and Williams, 1993; Myers and Robbins, 1991; Williams and Chartres, 1991). There are, however, more factors involved in the degradation of pastures, and Kaimowitz (1996) differentiates between social and environmental factors.

Social factors that have contributed to reduced pasture management and subsequent pasture degradation in Latin America include, for example, decreasing real beef prices, increasing labor costs, reduced access to credit for cattle ranching, import taxes on agricultural inputs, and physical insecurity due to military conflicts and banditry (Kaimowitz, 1996).

Environmental factors that determine pasture degradation include weed invasion, soil compaction, soil erosion, and nutrient depletion (Myers and Robbins, 1991; Hernández *et al.*, 1995; Kaimowitz, 1996; Faminow, 1998). Weed invasion takes place by annual and perennial weed types (Filho, 1990). The annual weed type produces a lot of seeds, develops rapidly, and quickly competes for water, nutrients, space and light, while the perennial weed type grows more slowly but lasts for years. Soil compaction occurs due to the pasture preparation process and subsequent stamping by cattle (Faminow, 1998). Compaction negatively affects pasture root development, increases soil moisture levels and thereby reduces the capacity of the soil to absorb rainfall. Soil erosion is, according to the universal soil loss equation (USLE), determined by rainfall erosivity, soil erodibility, length and degree of slope, vegetative cover and conservation practices (Faminow, 1998). Erosion negatively affects pasture production, due to the loss of the fertile topsoil and the occurrence of landslides. Finally, nutrients are lost from the system (Haynes and Williams, 1993) when leaching, denitrification, volatilization and animal (by-)products (*e.g.* manure and beef) exceed the gain of nutrients from rain, fixation and external sources (*e.g.* fertilizer and feed supplements).

2.5.3 Loss of biodiversity

Tropical forests are not only home to people, but also to a diverse range of plant and animal species. Deforestation of tropical forest areas in favor of pasture establishment for cattle ranching is often considered to lead to extinction of numerous plant and animal species, which results in a loss of species diversity (Ledec, 1992; May, 1992; Swanson, 1992).

From an economic point of view, tropical forest biodiversity has a use as well as a nonuse value. Direct use values of biodiversity received a lot of attention from economists and ecologists. They consider biodiversity as a valuable source of (new) medicines as well as plant and animal genetics (Ledec, 1992; Van Kooten and Bulte, 2000). Moreover, it enables the production of distinctive tropical forest fruits (*e.g.* Brazilian nuts), while it also attracts ecotourism (Ledec, 1992). Indirect use values of biodiversity include ecosystem stability as it may be positively linked to biodiversity (Van Kooten and Bulte, 2000). Finally, the nonuse value of tropical forest biodiversity is determined by the satisfaction an individual derives from the mere preservation of biodiversity for present and future generations.

According to Van Kooten and Bulte (2000), the direct use value of tropical forest biodiversity is no more than US$ 25 per hectare, while the nonuse value is between US$ 36 and US$ 90 per hectare. Including all other forest functions (*e.g.* watershed protection, prevention of soil erosion and flood prevention), the total value of tropical forest conservation equals, on average, about US$ 1568 per hectare. This value is, however, much lower than the net economic benefits obtained from alternative land uses, such as commercial logging and agriculture (on average about US$ 2620 and US$ 2580 per hectare, respectively). Consequently, Van Kooten and Bulte (2000) conclude that, from an economic point of view, it may not yet be globally optimal to stop tropical deforestation and land use conversion.

2.6 Conclusions

This chapter outlines the most important issues put forward in the Latin American cattle ranching debate are discussed. As seen, livestock production in Latin America is performed by small farmers, traditional ranchers and investment ranchers. Investment ranchers and, to a minor extent, traditional ranchers are generally described as *cattle ranchers* who maximize profit and produce beef by grazing one type of animal on large tracts of natural pastures. Cattle ranchers play an important role in Latin American agriculture, as they own most of the agricultural land and cattle stock. Moreover, pasture expansion in favor of cattle ranching is considered the principal cause of deforestation in the tropics of Latin America.

FAO figures on land use, production and productivity for the period 1961 to 1999 confirm the relative importance of cattle ranching in Latin America. On average, permanent pastures accounted for no less than 80% of the agricultural area. Moreover, the share of permanent pastures in the total area increased from about 25% in 1961 to 30% in 1999, and was mainly created through a decrease in the forest and woodland area. The subsequent increase in beef production was largely facilitated by an increase in Latin American demand for beef products. The so called “hamburger connection” seems of little relevance to Latin America as a whole because only a small and decreasing part of Latin American beef production was exported. Beef production per animal head and per hectare increased with 33% and 120% over the past four decades, and this is explained by the almost doubled stocking rate in combination with declining beef prices and the adoption of more productive cattle and pasture species.

The expansion of cattle ranching in Latin America is generally attributed to five factors. First, cattle ranching is an agricultural activity that can (profitably) be developed in remote agrarian frontier areas where markets do not yet exist or are distant. Second, the increased Latin American demand for beef products in general, and the increased local demand for beef products in particular are obvious factors. Third, cattle ranchers took advantage of government policies, such as subsidized livestock credit, infrastructure development, land titling of invaded areas, and migration programs. Fourth, land speculation played a role, as it could provide economic returns over and above the returns gained from beef production. Finally, resource degradation contributed to the expansion of cattle ranching, as more land was required to maintain beef production and because virgin forest areas were converted into pasture to take advantage of their initially high fertility levels.

Deforestation of tropical forest areas in favor of pasture establishment for cattle ranching has important environmental consequences. First, it leads to an increase in the emission of trace and greenhouse gases, which play an important role in climate change and UV-B radiation at the earth’s surface. Second, nutrient depletion and soil erosion result in resource degradation, and, eventually, to pasture degradation and declining pasture yields. Finally, the conversion of tropical forest areas into pastureland may lead to a loss of species diversity, with subsequent use and nonuse costs.

The debate concerning the sources of expansion of cattle ranching in Latin America is, however, mostly qualitative and incomplete in a number or respects. First, it remains unclear why beef production increased despite the considerable decrease and variability in real beef prices since the mid-1970’s. In Chapter 5 we will take a closer look at the effect of decreasing and uncertain beef prices on investment decisions by cattle ranchers. Second, the role of land speculation as a contributor to deforestation in Latin America is highly debated, and the discussion largely comes down to whether or not land prices tend to rise over time. In Chapter 6 and 7, we will investigate this issue, thereby specifically differentiating between the effects of rising and of fluctuating land prices on investment decisions by cattle ranchers. Finally, the role of resource degradation on the expansion of cattle ranching in Latin America is sparsely and mostly qualitatively dealt with in the literature. Chapter 7 assesses the consequences of resource degradation on investment and production decisions by cattle ranchers.

3 Investment theories: overview and tools

3.1 Introduction

An investment can be defined as a change in the fixed capital stock over a period of time, without consuming it or using it up entirely in this period (Nickell, 1978).[7] The decision by a firm to undertake an investment is of particular importance because: 1) the consequences of the decision to invest will last for a number of years, 2) the investment may be partly or totally irreversible, and 3) the firm faces an uncertain future (Nickell, 1978; Dixit and Pindyck, 1994). Moreover, the firm not only decides on the desired rate of investment flow but also on the desired fixed capital stock.

During the past decades, three major streams of investment theories emerged. First, benefit-cost analysis (BCA) was developed by Jules Dupuit in 1848 and later formalized by Alfred Marshall (Watkins, 2003). BCA forms the basis for the evaluation of investment projects, in which benefits and costs of an investment project are compared on the basis of a number of procedures (Zerbe and Dively, 1994). Next, Jorgenson and Tobin developed the Neoclassical and q-theory of investment, respectively, in the 1960's. These investment theories are based on benefit-cost analysis in general and the net present value (*NPV*) rule in particular. Both theories rely on a marginal approach, which states that investments in fixed capital should continue up to the point where marginal costs of the investment are equal to marginal returns of this investment. Finally, the option approach was devised by, for example, Dixit and Pindyck in the course of the 1980's. The option approach relaxes the implicit *NPV* assumptions that either an investment is reversible or that an irreversible investment cannot be delayed. This approach adjusts the *NPV* rule in the sense that the marginal costs of the investment not only includes the purchase and installation costs but also the opportunity cost of keeping the investment option alive (Dixit and Pindyck, 1994).

Consequently, investment problems are concerned with the determination of the investment path that maximizes the sum of all annual profit streams over time, given the (uncertain) costs and returns that result from the decision to invest and occur at different points in time over the lifetime of the investment project (Chiang, 1992; Stefanou, 1992). The combination of two types of mathematical tools is useful in solving these kinds of investment problems. Dynamic optimization enables us to determine the optimal investment path that maximizes the discounted sum of annual profit streams over time. Stochastic calculus provides the opportunity to characterize the development of uncertain variables that affect the decision to invest.

This chapter's purpose is to provide an overview of the most important investment theories and the mathematical tools that are applied in the development of these theories, as both are extensively used throughout this study. It covers the basics of investment theory, dynamic optimization and stochastic calculus. Section 3.2 gives an overview of the most important investment theories, which include benefit-cost analysis, the Neoclassical and q-theory of investment, and the option approach. Section 3.3 deals with the mathematical tools that are extensively used in these investment theories.

---

[7] Consequently, investment is a flow variable and fixed capital is a stock variable.

3.2 Investment theories of the firm

This section discusses the three major theories of investment that have been developed over the past decades. Section 3.2.1 contains an overview of the most important procedures that are used in benefit-cost analysis. Section 3.2.2 presents the essentially equivalent Neoclassical investment theory and Tobin's q-theory. Finally, Section 3.2.3 covers the option approach.

3.2.1 Benefit-cost analysis

Benefit-cost analysis (BCA) was first developed by the French engineer Jules Dupuit in 1848 and later formalized by Alfred Marshall. It wasn't until the 1950's that economists started to develop procedures to define and compare benefits and costs that are attributable to the installation of an investment project (Zerbe and Dively, 1994). Financial analysis helps to identify attractive investment projects that increase wealth. The most important procedures for making financial decisions include: 1) net present value, 2) payback period, 3) benefit-cost ratio, 4) internal rate of return, and 5) wealth-maximizing rate (Zerbe and Dively, 1994).

Before turning to the discussion of these BCA procedures, it is worthwhile to mention the four main principles underlying benefit-cost analysis (Pass *et al.*, 2000). First, all costs and benefits of the project should be specified and ranked according to their remoteness from the main purpose of the project. Second, all costs and benefits of the project have to be valued. Third, all costs and benefits of the project need to be discounted, by using an unambiguously defined discount rate. Finally, relevant constraints should be taken into account.

Net present value

The net present value NPV is defined as the discounted sum of the differences between benefits B_t and costs C_t, that are attributable to the installation of the project and occur in each period t over the entire lifetime of the project T (Zerbe and Dively, 1994). Formally, the NPV is given by

$$NPV = \sum_{t=0}^{T} \frac{B_t}{(1+r)^t} - \sum_{t=0}^{T} \frac{C_t}{(1+r)^t} \qquad (3.1)$$

where r is the time discount rate. The NPV rule states that investment in a project should take place in the case of $NPV > 0$. Proper use of the NPV approach requires that the discount rate is given and that capital is readily available (Zerbe and Dively, 1994).

The NPV approach holds a number of advantages compared to the other approaches presented in this section (Zerbe and Dively, 1994). First, it produces correct financial decisions in all cases. Second, the calculations are relatively easy. Third, it applies to financial as well as non-financial problems. Consequently, the NPV is often called the fundamental financial equation of benefit-costs analysis. However, the NPV rule can only be applied to compare projects with identical life spans.

Payback period

The payback period p is defined as the time required for a project's total discounted benefits to exceed its total discounted costs, where benefits B_t and costs C_t are attributable to the installation of the project and occur in each period t (Zerbe and Dively, 1994). The equation for the payback period is given by

$$\sum_{t=0}^{p}\frac{B_t}{(1+r)^t}-\sum_{t=0}^{p}\frac{C_t}{(1+r)^t}\geq 0 \qquad (3.2)$$

with r is the time discount rate. The payback period approach has two major disadvantages compared to the *NPV* technique (Zerbe and Dively, 1994). First, the decision to accept or reject a project on the basis of the payback period alone is completely arbitrary. Second, the payback period approach ignores benefits and costs that occur beyond the payback period. In conjunction with other techniques, the payback period approach provides valuable information.

Benefit-cost ratio

The discounted benefit-cost ratio *BCR* is defined as the ratio of the present value of total benefits and the present value of total costs, where benefits B_t and costs C_t are related to the installation of the project and occur in each period t over the entire lifetime of the project T (Zerbe and Dively, 1994). The *BCR* shows

$$BCR=\sum_{t=0}^{T}\frac{B_t}{(1+r)^t}\Bigg/\sum_{t=0}^{T}\frac{C_t}{(1+r)^t} \qquad (3.3)$$

where r is the time discount rate. Essentially, the *BCR* and the *NPV* lead to identical decisions about projects, as the only difference between the two approaches is the operation used to compare benefits and costs (Zerbe and Dively, 1994). Investment in a project should take place in the case of $BCR > 1$, which is similar to $NPV > 0$. Proper use of the *BCR* requires that the discount rate is given and that capital is readily available.

The *BCR* approach holds a number of disadvantages (Zerbe and Dively, 1994). First, the value of the *BCR* is sensitive to the definition of benefits and costs. Second, the *BCR* is subject to problems of scale. Moreover, the *BCR*-approach can only be used to compare projects if: 1) benefits and costs are defined consistently for all projects, 2) the life-span is (made) equal for all projects, and 3) the outlay basis is (made) equal for all projects.

Internal rate of return

The internal rate of return *IRR* is defined as the discount rate for which the present value of total benefits balances the present value of total costs, where benefits B_t and costs C_t are linked to the installation of the project and occur in each period t over the entire lifetime of the project T (Zerbe and Dively, 1994). The *IRR* is found by using

$$\sum_{t=0}^{T} \frac{B_t}{(1+IRR)^t} = \sum_{t=0}^{T} \frac{C_t}{(1+IRR)^t} \tag{3.4}$$

For single projects with initial negative cash flows that are followed by a series of nonnegative cash flows, the *IRR* and the *NPV* lead to identical results (Zerbe and Dively, 1994). The *IRR* states that investment in a project should take place if $IRR > r$, as the project earns returns at a rate higher than the interest rate. Use of the *IRR* requires that capital is readily available.

The *IRR* approach has several disadvantages (Zerbe and Dively, 1994). First, calculations can become complex and time-consuming if cash flows become more complicated. Second, the *IRR* approach may produce multiple solutions if negative cash flows occur later in the project. Third, a weak assumption in the *IRR* approach is that the project can borrow and lend at the internal rate of return. Finally, the *IRR* approach can only be used to compare projects if: 1) the life-span is (made) equal for all projects, and 2) the outlay basis is (made) equal for all projects.

Wealth-maximizing rate

The wealth-maximizing rate *WMR* is defined as the compounded rate of return obtained from an original investment C_0, which yields benefits B_t that are attributable to the installation of the project and occur in each period t over the entire lifetime of the project T (Zerbe and Dively, 1994). The *WMR* is found by using

$$C_0(1+WMR)^T = \sum_{t=0}^{T} B_t(1+BAAR)^{T-t} \tag{3.5}$$

where *BAAR* is the best rate of return available outside the project. The *l.h.s.* of Eq. (3.5) is the fundamental formula for compound interest and the *r.h.s.* of Eq. (3.5) is the future value of the project. The latter takes into account the stream of benefits B_t, and the amount of interest earned from benefits B_t accomplished before the project is terminated. Given that the *BAAR* is equal to the loan rate, the *WMR* states that investment in a project should take place if $WMR > BAAR$. The use of the *WMR* requires that capital is readily available.

As with the *IRR* approach, disadvantages of the *WMR* approach are that calculations can become complex in the case that cash flows become more complicated, and that multiple solutions may be produced if negative cash flows occur later in the project. A major advantage of the *WMR* approach, compared to the *IRR* approach, is that it allows external reinvestment at the *BAAR* instead of the *IRR*. The *WMR* approach can only be applied to compare projects if: 1) the life span is (made) equal for all projects and 2) the initial cost basis C_0 is (made) equal for all projects.

3.2.2 The Neoclassical theory of investment

Jorgenson (1963) first developed the Neoclassical investment theory for the firm. The theory starts from the firm's optimization behavior, thereby maximizing the present value of net income streams subject to a Neoclassical production function. Jorgenson assumes, however, an exogenous mechanism (a distributed lag function) that determines the rate at which the actual capital stock grows towards the desired capital stock.[8] Difficulty of interpreting this exogenous adjustment mechanism led to the introduction of so-called adjustment costs, which capture the notion that it is more costly to expand the capital stock rapidly than to expand it slowly (Abel, 1990). This adaptation of the Neoclassical investment theory was formalized by Eisner and Strotz (1963) and later used by Lucas (1967), Gould (1968), Treadway (1969), and Mussa (1977).

The point of departure of the Neoclassical investment model is that investment and employment decisions are made by the firm, and, consequently, demand for productive capital is a derived demand by firms (Abel, 1990). The firm is engaged in production $Q(L_t, K_t)$, by using the factors of production labor L_t (variable input) and capital K_t (fixed capital input), while facing decreasing returns to scale. The firm produces a net income stream π_t, which is defined as the difference between revenues and costs at each point in time t. Investments I_t in the fixed capital input take place in order to assure the supply of capital services and are subject to investment costs $C(I_t)$ that include purchase and adjustment costs of the fixed capital input. The net annual income stream is given by

$$\pi_t(L_t, K_t, I_t) = pQ(L_t, K_t) - p_L L_t - p_K K_t - C(I_t) \tag{3.6}$$

where p represents the product price, p_L is the price of labor (wage), p_K is the price of capital operation, and where the investment cost function is convex in the rate of investment I_t. The firm maximizes the present value of net income streams over an infinite horizon. The optimal control problem is formulated as

Maximize $$V(K_0) = \max_{L_t, I_t} \int_0^{\infty} [\pi_t] e^{-rt} dt \tag{3.7}$$

subject to $\dot{K}_t = I_t$ (equation of motion for K)

$K_0 > 0$ and $I_0 = 0$ (initial conditions)

$K_t \geq 0$ and $L_t \geq 0$

Here, r is the time discount rate, and a dot over a variable denotes the derivative of that variable with respect to time. The equation of motion provides the mechanism by which the control variable I_t is translated into the movement pattern of the state variable K_t. To solve the maximization problem of the firm, the amount of labor L_t and the rate of investment in capital I_t must be chosen to maximize the Hamiltonian H (see Section 3.3.1, on *Optimal control*). The Hamiltonian is given by

$$H_t(L_t, K_t, I_t, \lambda_t) = \left(pQ(L_t, K_t) - p_L L_t - p_K K_t - C(I_t)\right) e^{-rt} + \lambda_t I_t \tag{3.8}$$

---

[8] Distributed lags can be interpreted as expectational lags, delivery lags, or a combination of both (Abel *et al.*, 1986).

where λ_t is the costate variable that, like the Lagrange multiplier, measures the shadow price of the associated state variable (Chiang, 1992). The maximum principle requires maximization of the Hamiltonian with respect to I_t. This implies that the firm must balance, over time, the prospective gains in the current profit against prospective losses in future profits (Chiang, 1992). The maximum principle conditions are given by

$$\lambda_t = C_I(I_t)e^{-rt} \qquad \text{(first order condition for } I\text{)} \qquad (3.9)$$

$$p_L = pQ_L(L_t, K_t) \qquad \text{(first order condition for } L\text{)} \qquad (3.10)$$

$$\dot{\lambda}_t = \left(p_K - pQ_K(L_t, K_t)\right)e^{-rt} \qquad \text{(costate equation)} \qquad (3.11)$$

where $C_I = \partial C/\partial I$, $Q_L = \partial Q/\partial L$ and $Q_K = \partial Q/\partial K$. Eq. (3.9) states that the firm chooses a rate of investment such that the value of an additional unit of installed capital is equal to the present value marginal investment cost of the fixed capital input (Abel, 1990). Further differentiation of the optimality condition with respect to I_t, shows whether the extremum is a maximum ($\partial^2 H_t / \partial I_t^2 < 0$) or a minimum ($\partial^2 H_t / \partial I_t^2 > 0$). Eq. (3.10) states that the firm employs labor up to the point where the marginal revenue product of labor is equal to the marginal cost of labor. Eq. (3.11), finally, says that the rate of change in the shadow price of the capital input equals the marginal contribution of this capital input to current profit (Chiang, 1992).

Another way of interpreting Eq. (3.11) is by observing that it is a differential equation with the stationary solution

$$\lambda_t = \int_t^\infty \left[pQ_K(L_s, K_s) - p_K\right]e^{-r(s-t)}ds \qquad (3.12)$$

Eq. (3.12) gives the shadow price of a unit of capital as equal to the present value of the stream of marginal returns attributable to this unit of capital that is installed at time *t* over all future dates *s*. Substituting Eq. (3.9) into Eq. (3.12) yields

$$C_I(I_t)e^{-rt} = \int_t^\infty \left[pQ_K(L_s, K_s) - p_K\right]e^{-r(s-t)}ds \qquad (3.13)$$

which states that the present value marginal investment cost of capital is equal to the present value of the stream of marginal returns attributable to this unit of capital that is installed at time *t* and that is productive over all future dates *s*.

The presented Neoclassical investment model with adjustment costs is based on a number of assumptions (Nickell, 1978; Abel, 1990). First, the production function employs two production factors (one variable and one fixed factor of production) to produce one single output, is twice differential, and exhibits strictly decreasing returns to scale. Second, the variable input (labor *L*) can be adjusted costlessly and instantaneously. Third, the fixed capital input (capital *K*) can be adjusted and is subject to an investment cost function that is convex in the rate of investment. Fourth, the fixed capital input (capital *K*) maintains its productivity forever (no depreciation). Fifth, all factor, output and capital markets function perfectly. Finally, there is perfect certainty about the present and future.

3.2.3 The *q*-theory of investment

The *q*-theory of investment, introduced by Tobin (1969), formalizes the notion that the incentive to purchase capital depends on the market value of this capital (*i.e.* future production value) relative to its purchase costs (Abel, 1990). The greater the amount by which the market value of capital exceeds its purchase cost, the larger the incentive to invest. Tobin relates the rate of investment to the variable *q*, which he defines as the market value of capital relative to its replacement costs.

The *q*-theory of investment can be derived from the Neoclassical adjustment cost model of investment (presented in the previous subsection). The firm is engaged in production $Q(L_t, K_t)$ by using the factors of production labor L_t and capital K_t, investments in capital I_t are subject to investment costs $C(I_t)$ that include purchase and adjustment costs, and the firm maximizes the present value of net income streams π_t over an infinite horizon. The optimization problem is given by

Maximize $$V(K_0) = \max_{L_t, I_t} \int_0^\infty [\pi_t] e^{-rt} dt \qquad (3.14)$$

subject to $\pi_t(L_t, K_t, I_t) = pQ(L_t, K_t) - p_L L_t - p_K K_t - C(I_t)$

$\dot{K}_t = I_t$ (equation of motion for *K*)

$K_0 > 0$ and $I_0 = 0$ (initial conditions)

$K_t \geq 0$ and $L_t \geq 0$

Here, *r* is the time discount rate, *p* is the product price, p_L is the wage rate, p_K is the price of capital operation, and the investment cost function is convex in the rate of investment I_t. The Hamiltonian *H* is given by

$$H_t(L_t, K_t, I_t, \lambda_t) = (pQ(L_t, K_t) - p_L L_t - p_K K_t - C(I_t))e^{-rt} + \lambda_t I_t \qquad (3.15)$$

where λ_t is the costate variable. First-order conditions are given by

$$\lambda_t = C_I(I_t) e^{-rt} \qquad \text{(first-order condition for } I\text{)} \qquad (3.16)$$

$$p_L = pQ_L(L_t, K_t) \qquad \text{(first-order condition for } L\text{)} \qquad (3.17)$$

$$\dot{\lambda}_t = (p_K - pQ_K(L_t, K_t))e^{-rt} \qquad \text{(costate equation)} \qquad (3.18)$$

where $C_I = \partial C/\partial I$, $Q_L = \partial Q/\partial L$ and $Q_K = \partial Q/\partial K$. As explained before, Tobin's *q* is defined as the market value of capital relative to its replacement costs. The replacement cost of capital is given in the optimality condition, which states that the shadow price of a unit of capital is equal to the present value marginal investment costs of this unit of capital. The market value of capital can be derived from the costate equation for *K*, which is a differential equation with the stationary solution

$$\lambda_t = \int_t^{\infty} \left[pQ_K(L_s, K_s) - p_K \right] e^{-r(s-t)} ds \tag{3.19}$$

Eq. (3.19) states that the shadow price or market value of a unit of capital is equal to the present value of the stream of marginal returns attributable to this unit of capital that is installed at time *t* and that is productive over all future dates *s*. Tobin's marginal *q* is now given by

$$q = \frac{\int_t^{\infty} \left[pQ_K(L_s, K_s) - p_K \right] e^{-r(s-t)} ds}{C_I(I_t) e^{-rt}} \tag{3.20}$$

This *q* is called the marginal *q*, as it refers to the market value of an *additional* unit of capital relative to its replacement cost. This version of the *q*-theory is not operational as long as the marginal *q* is not observable. Consequently, most empirical work is based on the observable average *q*, which is defined as the market value of *existing* capital relative to its replacement cost (Hayashi, 1982).[9] Tobin's marginal *q* indicates that a firm will increase its capital stock for $q > 1$, decrease its capital stock for $q < 1$, and will (dis)invest until *q* reaches its equilibrium value $q = 1$ (Tobin, 1969).

Lucas and Prescot (1971) first indicated and Hayashi (1982) later showed that the Neoclassical investment theory and Tobin's *q*-theory are equivalent. Comparing Eq. (3.13) and Eq. (3.20) makes clear that in both theories, investment decisions are based on the comparison of marginal costs and marginal returns of capital. In fact, the only difference between the two theories is the operation used to compare marginal benefits and marginal costs of the fixed capital input. Investment takes place when marginal returns of capital exceed marginal costs, dis-investment takes place when marginal costs of capital exceed marginal returns, and no investment takes place when marginal returns of capital equal marginal costs.

---

[9] Hayashi (1982) shows that the marginal *q* equals average *q*, in the case that the firm is a price taker with constant returns to scale in production (*i.e.* production function is homogenous of degree one in *K* and *L*) and installation (*i.e.* adjustment cost function is homogenous of degree one in *I* and *K*).

3.2.4 The option approach

The Neoclassical and q investment theory are both founded on the basic net present value (*NPV*) rule, which assumes that either the investment is reversible or the investment is irreversible and the investment timing is fixed. However, numerous studies show that the ability of delaying an irreversible investment can profoundly affect investment decisions (Dixit and Pindyck, 1994). Moreover, this result undermines the basic *NPV* rule and, in turn, the Neoclassical investment and Tobin's q-theory.

Irreversibility and flexibility in investment timing prove to be important characteristics in actual investment practice (Dixit and Pindyck, 1994) and require some further explanation. Irreversibility of an investment refers to the partial or total inability to recover the initial cost of an investment, and can arise because of a number of reasons (Pindyck, 1991). First, firm-specific capital cannot be employed productively by another firm as, for example, investments in marketing and advertising are firm-specific. Second, non-firm-specific capital can only be sold well below its purchase cost as one is unable to evaluate the quality of the capital item ("lemons" problem). Finally, irreversibility of an investment may also arise because of government regulations or institutional arrangements, such as capital controls and reversion costs.

Flexibility in investment timing refers to the ability to delay an irreversible investment option (Dixit and Pindyck, 1994). Making an irreversible investment expenditure implies losing the option to invest later, which may be preferred in the light of new information obtained after waiting. This lost option to invest is called the opportunity cost of investing, and should form part of total investment costs (Dixit and Pindyck, 1994). However, firms do not always have the opportunity to delay investments, due to, for example, strategic considerations.

3.3 Mathematical tools

A couple of mathematical tools are useful in solving investment problems, in which (uncertain) costs and (uncertain) returns occur at different points in time during the lifetime of the investment project. First of all, dynamic optimization techniques are required to determine the optimal investment path, which maximizes the discounted sum of all annual profit streams over time (Section 3.3.1). Secondly, stochastic calculus is required to characterize the development of uncertain variables that have to be taken into account when making investment decisions (Section 3.3.2).

3.3.1 Approaches to dynamic optimization

The fundamental problem of dynamic optimization is the balancing of marginal costs from current decisions against marginal benefits from future profitability (Chiang, 1992; Stefanou, 1992). A dynamic optimization problem poses the question of what would be the optimal magnitude of a choice variable in each period of time within the planning period. The solution of this problem will yield the optimal time path for every choice variable. An optimal time path is one that maximizes the path value $V[y_t]$ over time, where the objective functional $V[y_t]$ is the value of the project corresponding with the state of y_t at each moment in time t. Approaches to solve this kind of optimization problems in economics and management include: 1) calculus of variations, 2) optimal control, and 3) dynamic programming (Kamien and Schwartz, 1991; Chiang, 1992; Stefanou, 1992). These approaches will be discussed in the following subsections.

Calculus of variations

The basis for calculus of variation dates back to the 17th century and is attributed to the mathematicians John and James Bernoulli as well as Newton, while the general mathematical theory was developed by Euler and Lagrange (Kamien and Schwartz, 1991). The fundamental problem of calculus of variations can be represented by the following general formulation

$$\text{Maximize} \quad V[K_0] = \max_{K_t} \int_0^T F\left[t, K_t, \dot{K}_t\right] dt \qquad t \in [0, T] \tag{3.21}$$

$$\begin{aligned} \text{subject to} \quad & K_0 = k_0 && \text{(initial condition)} \\ & K_T = k_T && \text{(terminal condition)} \end{aligned}$$

Here, k_0 and k_T are given, K_t is the stock or state variable which reflects all additions and removals of K up to time t, and a dot over a variable denotes the derivative of that variable with respect to time. The basic first-order necessary condition for an extremal in the calculus of variations problem is the *Euler-Lagrange* equation, which is given by[10]

$$F_K - \frac{dF_{\dot{K}}}{dt} = 0 \qquad \text{for all } t \in [0, T] \tag{3.22}$$

where $F_K = \partial F / \partial K$ and $F_{\dot{K}} = \partial F / \partial \dot{K}$. Applying the chain rule and noting that F and $F_{\dot{K}}$ are a function of the arguments t, K and $\dot{K}$, a more explicit version of the Euler equation becomes

$$F_{\dot{K}\dot{K}} \ddot{K} + F_{K\dot{K}} \dot{K} + F_{t\dot{K}} - F_K = 0 \qquad \text{for all } t \in [0, T] \tag{3.23}$$

which is a second-order non-linear differential equation, in which $F_{\dot{K}\dot{K}} = \partial^2 F / \partial \dot{K}^2$, $F_{K\dot{K}} = \partial^2 F / \partial K \partial \dot{K}$ and $F_{t\dot{K}} = \partial^2 F / \partial t \partial \dot{K}$. Its general solution contains two arbitrary constants, and can be definitized by using the initial and terminal condition. Solving Eq. (3.23) yields the optimal time state variable path K_t^*. To find an extremal, the functional $V[K_t]$ must be integrable, continuous, and continuously differentiable.

The calculus of variations approach holds several drawbacks (Chiang, 1992; Stefanou, 1992). First, the Euler equation often results in second-order non-linear differential equations, for which a solution may not

---

[10] Extremal is defined as the smooth K_t path that yields an extremum (maximum or minimum) for the functional $V[K_t]$ (Chiang, 1992).

exist for all values of t and k. Second, the integrand F must be a function of the arguments t, K and $\dot{K}$ where the control of the system must be an explicit time rate of change of the state variable K. Finally, the calculus of variations approach has considerable problems with functions that are linear in $\dot{K}$ and with inequality constraints on $\dot{K}$.

Optimal control

Contrary to the calculus of variations approach, where the aim is to find the optimal time path for the state variable K_t, the aim of the optimal control approach is to determine the optimal path for a control variable u_t (Chiang, 1992). The control variable regulates the state variable, which is only the case if the decision on the control path u_t will unambiguously determine the state variable path K_t. The optimal control problem therefore contains a so-called *equation of motion* or *state equation*

$$\dot{K}_t = f\left[t, K_t, u_t\right] \tag{3.24}$$

which shows how the state variable is driven over time, given the moment in time t, the value of the state variable K_t, and the planner's choice of the control variable u_t. The fundamental optimal-control problem can be represented by the following general formulation

Maximize $\quad V\left[u_t\right] = \max_{u_t} \int_0^T F\left[t, K_t, u_t\right] dt \qquad t \in [0, T] \qquad$ (3.25)

subject to $\quad \dot{K}_t = f\left[t, K_t, u_t\right] \qquad$ (equation of motion for K)

$K_0 = k_0 \qquad$ (initial condition)

and where k_0 is given, K_t is the stock or state variable, and u_t the control variable. The maximum principle of optimal control requires the formation of the *Hamiltonian*, which equates the cost of the current decision to the subsequent benefits from future flows attributable to this current decision. The Hamiltonian H is given by

$$H\left[t, K_t, u_t, \lambda_t\right] = F\left[t, K_t, u_t\right] + \lambda_t f\left[t, K_t, u_t\right] \qquad \text{for all } t \in [0, T] \tag{3.26}$$

where λ_t is the so-called *costate variable*, which looks like the Lagrange multiplier and measures the shadow price of an associated state variable. For this optimal-control problem and the given Hamiltonian, the maximum principle conditions are

$H_u = 0 \qquad$ (optimality condition)

$H_\lambda = \dot{K} \qquad$ (equation of motion for K or state equation)

$H_K = -\dot{\lambda} \qquad$ (equation of motion for λ or costate equation)

$\lambda(T) = 0$ (transversality condition)

where $H_u = \partial H/\partial u$, $H_\lambda = \partial H/\partial \lambda$ and $H_K = \partial H/\partial K$, and which must hold for all for all $t \in [0, T]$. Solving this set of equations yields the optimal control path u_t^*, which, given the equation of motion, is used to determine the optimal time path for the state variable, K_t^*.

The optimal control approach holds a number of advantages compared to the calculus of variations approach (Chiang, 1992; Stefanou, 1992). First, the definition of the control variable u_t in terms of $\dot{K}$ allows for a broad range of functional forms between controls and states, including jump discontinuities (as long as the control path u_t is piecewise continuous and does not involve infinite values of u_t), direct constraints on the control variable (by using the Kuhn-Tucker conditions), and costs related to the control variable. Second, the use of optimal control requires that the state path K_t is continuous and piecewise differentiable, while the use of calculus of variations requires that the state path K_t is continuous and continuously differentiable. Finally, the fundamental optimal control problem has a free terminal state ($T = \infty$), while the fundamental problem of calculus of variations requires a fixed terminal state.

Dynamic programming

The dynamic programming approach focuses on the optimal value of the functional V^* rather than on the optimal state path K_t^* (as in calculus of variations) or the optimal control path u_t^* (as in optimal control). Dynamic programming, pioneered by Bellman (1957), embeds the control problem in a family of control problems, where the sequence in which the problem is solved actually solves the whole family of problems. Primary attention is given to the optimal value of the functional V^* for each of the members of the family. In fact, an optimal value function (assigning an optimal value to each of the individual members of the family) is used as a characterization of the solution. The problem is solved iteratively, in line with Bellman's *principle of optimality*. This principle states that if one cuts off the first part of the value function V^*, the remaining part of the value function must still be optimal in its own right, given the optimal path from the initial to the terminal point (Kamien and Schwartz, 1991; Chiang, 1992; Stefanou, 1992).

To formalize this concept, let $F[s, K_s, u_s]$ be the incremental gain from a given control action u_s with initial state K_s at time s. The fundamental dynamic-programming problem can be represented by the following general formulation

Maximize $$V[K_t, t] = \max_{u_s} \int_t^T F[s, K_s, u_s] ds \qquad s \in [t, T] \tag{3.27}$$

subject to $\dot{K}_s = f[s, K_s, u_s]$ (equation of motion)

$K_t = k_t$ (initial condition)

and where k_t is given, K_s is the stock or state variable, and where u_s is the control variable. It follows from the principle of optimality and Eq. (3.27) that

$$V[K_t,t]=\max_{u_s}\left[\int_t^{t+\Delta t}F[s,K_s,u_s]ds+V[K_{t+\Delta t},t+\Delta t]\right] \tag{3.28}$$

where $$V[K_{t+\Delta t},t+\Delta t]=\max_{u_s}\int_{t+\Delta t}^{T}F[s,K_s,u_s]ds \tag{3.29}$$

and subject to the equation of motion. Eq. (3.28) states that the value of the function V equals the immediate gain $F(s, K_s, u_s)$ that is obtained from the optimal choice of control u_s over the period of time $(t, t+\Delta t)$ and given the initial state K_t, plus the continuation value given the resulting new stock $K^*_{t+\Delta t}$ at time $(t+\Delta t)$ over the remaining time period $(t+\Delta t, T)$.

As Δt is very small, the control u_s can be considered constant over the period of time $(t, t+\Delta t)$. Assuming that V is a twice continuously differentiable function, and Taylor-expanding the second term on the *r.h.s.*, Eq. (3.28) can be rewritten as

$$V[K_t,t]=\max_{u}\left(F[t,K_t,u_t]\Delta t+V[K_t,t]+V_K[K_t,t]\Delta K+V_t[K_t,t]\Delta t+h.o.t.\right) \tag{3.30}$$

where *h.o.t.* are the higher-order terms in Δt, and where $V_K=\partial V/\partial K$. By subtracting $V[K_t, t]$ from each side, dividing by Δt, and letting $\Delta t \rightarrow 0$, while using the equation of motion, the following *Hamilton-Jacobi-Bellman* equation results

$$-V_t[K_t,t]=\max_{u}\left(F[t,K_t,u_t]+V_K[K_t,t]f[t,K_t,u_t]\right) \tag{3.31}$$

given that *h.o.t.* → 0 as $\Delta t \rightarrow 0$. The optimal u (in terms of t, K_t and V_K) is found by differentiation of Eq. (3.31) with respect to u (optimality condition), which is then substituted back into Eq. (3.31) to find the partial differential equation that can be solved by using the boundary conditions. The optimal control path u_t^* can be determined over the entire time horizon (t, T), by using backward induction (Leonard and Van Long, 1992). Comparison of Eq. (3.26) and (3.31) shows that the Hamiltonian looks very much like the expression on the *r.h.s.* of Eq. (3.31), apart from the fact that $V_K[K_t, t]$ plays the role of λ. Given the interpretation of λ as the shadow price of the associated state variable K_t, it is indeed correct to conclude that $\lambda_t = V_K[K_t, t]$.

The major advantage of dynamic programming, compared to the calculus of variations and optimal control approaches, is its strength in dealing with discrete problems where underlying functions are not smooth and "nice" (Kamien and Schwartz, 1991). It is, however, less suited for analytical purposes (Leonard and Long, 1992) and the problem may be highly nontrivial if the initial state variable K_t is multidimensional (Conrad and Clark, 1987).

3.3.2 Stochastic calculus

Stochastic calculus is widely used when considering uncertainty in investment projects (Dixit and Pindyck, 1994). This Section starts with a discussion on stochastic processes, which form the basis of stochastic calculus. Next is the continuous-time Wiener process or Brownian motion, which is an important building block for a broad range of variables that vary continuously and stochastically over time. Brownian motion can be generalized to the so-called Ito process or Generalized Brownian motion, which is a wide-ranging continuous-time stochastic process that is often used to represent variables that evolve stochastically over time. Finally, jump processes, which are characterized by infrequent and discrete jumps, are introduced.

Stochastic processes

A stochastic process is defined by a variable that evolves over time in a way that is in part random, or, more formally, by a probability law for the evolution of x_t of a variable x over time t (Dixit and Pindyck, 1994). The stochastic process can be *stationary* or *nonstationary*,[11] and is either *continuous* or *discrete* in time.[12] An important property that can greatly simplify the analysis of stochastic processes, is the *Markov property*. Satisfaction of this property implies that the probability distribution for all future values of the process depends only on the current value x_t, and is unaffected by past values of the process or by any other current information (Dixit and Pindyck, 1994).

The simplest example of a stochastic process that satisfies the *Markov* property is the *discrete-time discrete-state random walk*. Let x_t be a random variable with a known initial value x_0, that takes a jump of size u (either up or down), at each moment in time t, and with the probability p of an upward jump and the probability $1-p$ of a downward jump. The dynamics of x_t are given by

$$x_t = x_{t-1} + \varepsilon_t \tag{3.32}$$

where ε_t is a random variable with probability distribution prob($\varepsilon_t = u$) = p and prob($\varepsilon_t = -u$) = $1-p$. Note that x_t is a nonstationary process, as the range of possible values that x_t can take increases with t, as does the variance of x_t. The process is called a *random walk* in the case that $p = ½$ (as the probability of an upward or downward shift is ½, at time $t = 0$ the expected value of x_t is x_0 for all t), and a *random walk with drift* if $p \neq ½$ (as the probability of an upward or downward shift is not equal to ½, at time $t = 0$ the expected value of x_t is greater than x_0 for all $t > 0$ and increases with t).

---

[11] A stationary process implies that the statistical properties of the variable are constant over long periods of time, while a nonstationary process implies that the expected value of the variable can grow without bound (Dixit and Pindyck, 1994).

[12] A continuous-time stochastic process implies that the variable's time index t is a continuous variable in time, while a discrete-time stochastic process implies that the variable's time index t changes at discrete points in time (Dixit and Pindyck, 1994).

Brownian motion

The *Brownian motion*, or *Wiener process*, is a continuous-time stochastic process with the following three important properties: 1) it is a Markov process, 2) it has independent increments, which implies that the probability distribution for the change in the process over any time interval is independent of any other (non-overlapping) time interval, and 3) changes in the process over any finite interval over time are normally distributed, with a variance that increases linearly with the time interval (Dixit and Pindyck, 1994). The Wiener process forms the basis for a range of variables that vary continuously and stochastically over time.

If z_t is a Wiener process, then the increment of the Wiener process *dz* over an infinitely small period of time *dt* (*i.e.* in continuous time) is represented by

$$dz = \varepsilon_t \sqrt{dt} \tag{3.33}$$

where ε_t is a normally distributed random variable with zero mean and unit standard deviation, that is not serially correlated. Note that the variance of the change in a Wiener process grows linearly over time. Furthermore, the Wiener process is nonstationary, which implies that its variance tends to infinity as $t \rightarrow \infty$. Finally, note that the Wiener process has no time derivative, in the conventional sense.

A generalization of the Wiener process is the *Brownian motion with drift*, which is given by

$$dx = \alpha dt + \sigma dz \tag{3.34}$$

where *dz* is the increment of a Wiener process as defined in Eq. (3.33), α the drift parameter, and σ the variance parameter. Over any time interval *dt*, every change in the current state *dx* is normally distributed and has the expected value $E[dx] = \alpha dt$ and variance $V(dx) = \sigma^2 dt$. It can be observed from Eq. (3.34) that the trend is the dominant determinant of the Brownian motion in the long run, whereas the volatility of the process is the dominant determinant in the short run.

Generalized Brownian motion

The *generalized Brownian motion*, or *Ito process*, is a more general version of the Brownian motion discussed in the preceding section. A variety of stochastic variables can be modeled by using the generalization of the Brownian motion with drift, which is given by

$$dx = a(x,t)dt + b(x,t)dz \tag{3.35}$$

where *dz* is the increment of a Wiener process as given in Eq. (3.33), and where $a(x, t)$ and $b(x, t)$ are known (nonrandom) drift and variance functions, respectively that are functions of the current state *x* and time *t*. The continuous-time stochastic process $x(t)$ presented in Eq. (3.35) is called an *Ito process*. Given $E[dz] = 0$, the expected value $E[dx] = a(x, t)dt$, and, in turn, it can be shown that the variance $V[dx] = b^2(x, t)dt$.

The *Geometric Brownian Motion with drift* is a special case of the generalized Brownian motion presented in Eq. (3.35). In this case, $a(x, t) = \alpha x$ and $b(x, t) = \sigma x$, so that Eq. (3.35) becomes

$$dx = \alpha x dt + \sigma x dz \tag{3.36}$$

where α and σ are constants. Given a starting value x_0, it can be shown that the expected value $E[x_t] = x_0 e^{\alpha t}$ and that the variance $V[x_t] = x_0^2 e^{2\alpha t}(e^{\sigma^2 t} - 1)$. This result can be used to calculate the expected present discounted value of x_t over some period of time, for example,

$$E[\int_0^\infty x_t e^{-rt} dt] = \int_0^\infty x_0 e^{-(r-\alpha)t} dt = x_0 /(r - \alpha) \tag{3.37}$$

given that the discount rate r exceeds the growth rate α. Brownian motions tend to wander far from their starting points, which may be realistic for economic variables like speculative asset prices. However, if one expects prices to be somehow related to long-run marginal production costs, then these prices should be modeled as a *mean-reverting process*.

The *Ornstain-Uhlenbeck process*, also a special case of the generalized Brownian motion, is an example of a mean-reverting process. In this case, $a(x, t) = \eta(\bar{x} - x)$ and $b(x, t) = \sigma$, so that Eq. (3.35) becomes

$$dx = \eta(\bar{x} - x)dt + \sigma dz \tag{3.38}$$

where η is the speed of reversion, and $\bar{x}$ is the level to which x tends to revert to (*i.e.* the "normal" level). Given a starting value x_0, it can be shown that the expected value $E[x_t] = \bar{x} + (x_0 - \bar{x})e^{-\eta t}$ and that the variance $V[x_t - \bar{x}] = \sigma^2(1 - e^{-2\eta t})/2\eta$. The expected value $E[x_t]$ converges to $\bar{x}$ as $t \rightarrow \infty$, and the variance $V[x_t - \bar{x}]$ converges to $\sigma^2 / 2\eta$ as $t \rightarrow \infty$.

In practice, it is relatively difficult to determine whether a variable is best modeled as a geometric Brownian motion or as a mean-reverting process, because it requires extensive time series to determine with any degree of confidence whether a variable is mean-reverting (Dixit and Pindyck, 1994). For analytical tractability, the geometric Brownian motion is preferred over the mean-reverting process. In fact, solving for an optimal investment rule is relatively easy when the stochastic variable is modeled as a geometric Brownian motion, while it is virtually impossible when the stochastic variable is modeled as a mean-reverting process. Given the limited size of the time series and the focus on the analytical tractability of the model, we model beef prices (Chapter 5) as well as land prices (Chapter 6) as a geometric Brownian motion.

Jump processes

Often, it is required to model an economic variable as a process that makes infrequent but discrete jumps, contrary to the diffusion (*i.e.* continuous) processes discussed in the previous subsections. A *Poisson process* is a process subject to jumps (*i.e.* events) of fixed or random size, for which the arrival time follows a Poisson distribution. If λ denotes the mean arrival time of an event during time interval *dt*, then the probability that an event occurs is given by $\lambda\, dt$ and the probability that an event will not occur is indicated by $1 - \lambda\, dt$. Let *q* denote a Poisson process by analogy with the Wiener process, so that

$$dq = \begin{cases} 0 & \text{with probability } (1-\lambda)dt \\ u & \text{with probability } \lambda dt \end{cases} \tag{3.39}$$

where *u* is the jump size. Writing the stochastic process for the variable *x* as a combination of a Poisson process and an Ito process leads to (in analogy with the generalized Brownian motion)

$$dx = a(x,t)dt + b(x,t)dz + g(x,t)dq \tag{3.40}$$

where a(*x*, *t*), *b*(*x*, *t*) and *g*(*x*, *t*) are known (nonrandom) functions. Suppose that *H*(*x*, *t*) is some (differentiable) function of *x* and *t*, and that we want to derive an expression for the expected change in *H*, that is, *E*[*dH*]. The expectation of the differential of *H* is given by

$$E[dH] = \left[\frac{\partial H}{\partial t} + a(x,t)\frac{\partial H}{\partial x} + \tfrac{1}{2}b^2(x,t)\frac{\partial^2 H}{\partial x^2}\right]dt + E_u\{\lambda[H(x+g(x,t)u,t) - H(x,t)]\}dt \tag{3.41}$$

The first term on the *r.h.s.* of Eq. (3.41) reflects the continuous part of the process (drift and variance), while the second term on the *r.h.s.* of Eq. (3.41) reflects the stochastic part of the process (jump, which is defined as a difference in values of *H* at discretely different points in time).

4 A deterministic investment model for cattle ranchers in Latin America

4.1 Introduction

Cattle ranching is a specialized form of livestock production, in which beef is produced by grazing one type of animal on large tracts of natural pastures (see Chapter 2, Section 2.2). To gain a greater understanding of the processes underlying the investment and production decisions of cattle ranchers in Latin America, their specific characteristics should be taken into account. Cattle ranchers can be described as profit maximizers, who are not only interested in recurrent returns from beef production, but also in the returns that can be obtained from rising land prices and land speculation (Barbier *et al*, 1991; Browder, 1988; Fearnside, 1989; Hecht, 1985, 1992; Kaimowitz, 1996). Put differently, they see land as both a productive resource and as an investment object.

The economics of cattle ranching have been extensively described and analyzed during the past decades. A great number of biologically strong, though economically weak, beef cattle production models have been developed. See for example Spreen and Laughlin (1986), Ridder *et al.* (1986), and Korver and Arendonk (1988) for an overview, and also Torell *et al.* (1991), Jansen *et al.* (1997) and Bouman *et al.*, (1999a). These models strongly focus on the relationship between forage production, animal growth and reproduction to improve herd management and productivity. Although these studies show the (technical) superiority of alternative production systems, management and marketing strategies, in practice cattle ranchers have not at all or hardly adopted these options as these studies do not consider the specific objectives and constraints faced by cattle ranchers (Bourdon and Brinks, 1986; Ledec, 1992).

Crotty (1980), Jarvis (1986) and Simpson (1988) recognized the need for economically stronger, so-called 'whole farm' cattle ranching models. They suggested integrating the biological and the economic models into one bio-economic model, in which the cattle rancher maximizes his specific objective(s) over a specific time horizon and subject to the biological constraints. This integration does, however, lead to highly non-linear dynamic optimization problems, which are difficult or even impossible to solve (see Chapter 3). Benefit-cost approaches appeared to be a flexible tool in dealing with relatively complex bio-economic relations, although they do not include optimizing behavior of the cattle rancher (*e.g.* Browder, 1988; Hecht *et al.*, 1988; Smith *et al.*, 1997). Dynamic optimization approaches proved to be more restrictive in dealing with complex bio-economic relations, but do take the optimizing behavior of the cattle rancher into account (*e.g.* Standiford and Howitt, 1992; Nicholson *et al.*, 1994; Costanza and Neuman, 1997; Bulte *et al.*, 2000). These approaches have in common, however, that they assume a fixed farm size and do not consider uncertainty.

The objective of this chapter is to develop a farm-economic model for cattle ranchers in Latin America, in which the cattle rancher is considered a profit maximizer who uses land as a productive resource as well as an investment object.[13] A dynamic reversible investment model for cattle ranchers is developed on the basis of the Neoclassical investment theory with adjustment costs (*e.g.* Eisner and Strotz, 1963; Lucas,

---

[13] This model forms the basis for the models presented in Chapters 5 through 7.

1967; Gould, 1968). The cattle rancher is engaged in natural-pasture-based beef production (beef cattle fattening), thereby using cattle and land to produce beef according to a constant returns-to-scale production function that is quadratic in the stocking rate. Land is considered a stock variable as purchase and productive implantation of forested land for grazing is subject to investment costs, while cattle is considered a variable input as it is a nearly liquid source of capital (Faminow and Vosti, 1998; Bouman *et al.*, 1998, 2000). The model is solved analytically and a numerical example of the model is given for an average cattle ranch in the Atlantic Zone (AZ) of Costa Rica, a humid tropical lowland area where about 70% of the agricultural area is dedicated to cattle ranching (Bouman *et al.*, 2000).

The remainder of this chapter is structured as follows. Section 4.2 provides a theoretical discussion on the determinants of pasture-based beef production, followed by the empirical estimation of a production function for pasture-based beef production in the AZ of Costa Rica, and completed by a discussion on returns to scale in agriculture in general and beef cattle production in particular. Similarly, Section 4.3 provides a theoretical discussion on the determinants of investment costs faced by a firm, followed by the empirical estimation of an investment cost function faced by beef cattle ranches in the AZ of Costa Rica. In Section 4.4, a dynamic reversible investment model for beef cattle ranches in the humid tropics is developed, and solved analytically. Section 4.5 presents results of the numerical application of the theoretical model and thereby focuses on the adjustment path and the steady state, followed by a sensitivity analysis. Finally, Section 4.6 offers concluding remarks and observations.

4.2 Production function for pasture-based beef production

4.2.1 Theoretical discussion

Soil conditions, climate, pasture and animal species, diseases, and management influence animal production from grazed pastures (Morley, 1981; Holmes, 1987). The cattle rancher is the driving force behind the system, and makes his management decisions on the basis of biophysical and economic considerations. Management options that determine animal production from grazed pastures and are available to the cattle rancher include: 1) herd management, 2) pasture management, 3) feed management, and 4) animal care (Morley, 1981; Holmes, 1987; Baker *et al.*, 1992).

Herd management involves decisions on the stocking rate and the composition of the grazing population. *Stocking rate* is the major determinant of animal production per hectare as more animals supply more produce. On the other hand, higher stocking rates lead to a reduction in animal production per head, for a number of reasons (Morley, 1981; White, 1987). First, high stocking rates impair the stability of the pasture system, as pasture growth rates will decrease to levels below those sufficient to maintain the cattle stock (Noy-Meir, 1975). Second, high stocking rates lead to a decrease in pasture availability, as a larger part of the pasture is consumed and trampled. Third, high stocking rates may lead to soil erosion, as the leaf area of the pasture decreases. Fourth, high stocking rates may provoke animal stress from under-nutrition. Finally, higher stocking rates negatively affect the botanical composition of the pasture. The *composition of the grazing population* can, largely, be controlled by the cattle rancher. Single-species fattening systems are, generally, less vulnerable than single-species breeding systems,[14] while combined fattening and breeding systems are susceptible to competition for feed.[15] However, competition for feed not only takes place between livestock species, but also with wildlife, pests and predators, which, in turn, may influence livestock composition, number and behavior.

Pasture management involves decisions on pasture species and fertilizer use. *Pasture species* are selected on the basis of a number of criteria. First, feed production should be high and steady over a long period of time, in order to reduce costs of pasture re-establishment. Second, the pasture species should be resistant to mismanagement and disasters, such as floods, fire and drought. Third, the pasture species should grow well enough during the potential growing season, and provide useful residue outside the growing season. Finally, the choice of the pasture species depends on the performance of the livestock that graze the pasture. *Fertilizer use* (nitrogen, potassium and phosphorus) has a positive effect on pasture productivity if drainage and soil acidity are favorable (Holmes, 1987). The response of grassland production to nitrogen application is linear at low nitrogen application rates, then reaches a maximum and declines at high rates of application (Marsh, 1975; Morrison, 1987). Several studies have shown that an inverse quadratic model fits results of field experiments best (Holmes, 1974; Morrison, 1987). The yield response of pastures to nitrogen application depends, however, on the climate and seasonal conditions, the amount of nitrogen in soil organic matter, the pasture species and presence of legumes, and the frequency of defoliation and grazing (Morrison, 1987).

Feed management involves decisions on the grazing system, feed conservation and supplementary feeding. *Grazing systems* (*i.e.* pasture subdivision) facilitate separation of different kinds of livestock, improved livestock handling, and rotational grazing. Continuous stocking systems promote dense pasture, which requires more maintenance, while rotational systems lead to more productive open pasture, which is more sensitive to trampling (Holmes, 1980). On the other hand, experimental investigations show that continuous stocking systems are at least as productive as any rotational system. In addition, there is no evidence that rotational grazing affects the removal of infective stages of internal parasites, as parasites survive for periods far longer than that of the rotation length (Donald *et al*., 1978). *Feed conservation* from pastures usually takes place when pasture is most abundant (Bishop and Birrel, 1975). Benefits from feed conservation depend on the degree to which the conserved feed can compensate for pasture deficiency. Costs from feed conservation include the making of the hay or silage, storage, and feeding it to the animals. The importance of conserved feed as drought reserves is doubtful, as the amounts required are very large and the reserves are susceptible to losses. The success of *supplementary feeding* (*i.e.* improved nutrition of the grazing animals), depends on biological and logistic variables. Biological elements of supplementary feeding are concerned with the physiological state and anticipated needs of the animal, the present condition and health of the animal, and the consequences of not giving supplements. Logistic elements of supplementary feeding are

---

[14] Breeding can be adversely affected repeatedly because: 1) bad condition of the female animal may inhibit fertilization, 2) low nutrition at parturition may be fatal for the offspring and the dam, and 3) at weaning, the animal is vulnerable to low-quality nutrition and diseases (Morley, 1981).

[15] Young beef cattle requires high-quality feed and, therefore, breeding cows may have to be fed with low-quality feed.

concerned with obtaining feed, storing it, and feeding it to the animals in accordance with their needs. Feed to grazing animals can only be rationed precisely if complex and costly equipment is available.

Animal care involves decisions on the timing of joining and weaning, and disease control. The *date of joining* is not only determined by fertility of the animals but also by the quantity and quality of feed supplied by the pasture. For example, in beef cattle production, feed supply after parturition should be increased to permit good growth of calves. *Weaning* is only feasible when the young animal is able to consume sufficient pasture to maintain itself. Early weaning is a compromise between assuring survival and growth of the young animals, on the one hand, and survival and productivity of the dam, on the other hand. Pathogenic organisms, parasites, intoxication, and malnutrition can cause *diseases* in grazing animals. Preventive medicine is considered most important in maintaining the health of grazing animals, as some diseases are difficult to prevent while other diseases are rapidly transmitted through contaminated water supplies. Moreover, clinical treatment of sick animals only is very expensive due to the labor involved in identifying, gathering and transporting the sick animals.

4.2.2 Empirical estimation

The stocking rate, *i.e.* the number of animals per unit area of land, is considered the most important management tool available to cattle ranchers that focus on pasture-based beef production (McMeekan, 1956; Morley, 1981; White, 1987). As already mentioned, more animals per hectare produce more beef, though also lead to a reduction in animal growth.

The quantitative relation between animal production and stocking rate is often discussed. Postulated relations between production per animal and stocking rate include linear and curvilinear functional forms (White, 1987). In general, production per animal will decrease if the stocking rate increases, while animal production per hectare will follow a parabolic curve with a maximum when production per animal is about half the maximum (Jones and Sandland, 1974).

A linearly decreasing relation between production per animal and stocking rate has been frequently suggested (Riewe, 1964; Chisholm, 1965; Langlands and Bennet, 1973) and first proven on the basis of experimental data by Jones and Sandland (1974). The linear relationship between production per animal and stocking rate is based on a number of assumptions. First, the pasture is taken to be homogeneous and the quantity of feed available to be proportional to the pasture area (Byrne, 1968). Second, the relationship between weight gain per animal and available feed per animal approximates a rectangular hyperbola, while the relationship between stocking rate and available feed is an inverse one (Willoughby, 1959; Arnold and Dudzinski, 1967). Finally, linearity implies that the quality and quantity of the feed throughout the year do not significantly affect this linear relationship (White, 1987). Major advantage of this linear functional form is that it leads to a continuous quadratic expression for animal production per unit of land. The linear relation between production per animal Q_S and stocking rate SR is given by

$$Q_S(SR) = a + bSR \tag{4.1}$$

where a and b are equation parameters, the former positive and the latter negative. In turn, animal production per hectare Q_A is just the gain per animal Q_S times the stocking rate SR, so that

$$Q_A(SR) = aSR + bSR^2 \tag{4.2}$$

which implies a quadratic relationship between animal production per hectare and stocking rate.

A linearly decreasing relation between production per animal and stocking rate cannot be assumed over a wide range of stocking rates, except in environments with small differences in bio-physical circumstances between seasons (White, 1987).[16] Given the agro-ecological circumstances in the study region (the AZ of Costa Rica) described hereafter, it seems reasonable to use a linearly decreasing relation between production per animal and stocking rate and, consequently, a quadratic relation between animal production per hectare and stocking rate.

Cattle ranching in the AZ of Costa Rica is mainly performed on very unproductive naturalized and native pastures, such as carpet grass (*Axonopus compresus*), ratana grass (*Ischaemum ciliare*), brachiaria grass (*Brachiaria radicans*) and *Paspallum* spp. (Ibrahim, 1994), while use of feed supplements is almost absent (Van Loon, 1997). Productivity of natural pastures in the AZ of Costa Rica is mainly determined by herd and pasture management, and soil type (Ibrahim, 1994; Bouman *et al*., 1998). Average annual rainfall is between 3500 mm and 5000 mm without dry months, and the average temperature is between 25°C and 27°C (Nieuwenhuyse *et al*., 2000). The most important soil types in the AZ are: 1) young alluvial well drained volcanic soils of relatively high fertility, classified as soil fertile well drained (SFW), 2) old, well drained soils developed on fluvio-laharic sediments having relatively high acidity and low fertility, classified as infertile well drained (SIW), and 3) young, poorly drained alluvial soils of relatively high fertility, classified as fertile poorly drained (SFP) (Wielemaker and Vogel, 1993).

A production function for natural-pasture-based beef production is estimated for the three soil types, with the aid of input-output data generated by the PASTOR system (Bouman *et al*., 1998). PASTOR (Pasture and Animal System Technical coefficient generatOR) is an agronomic model that generates input-output coefficients for cattle systems in the humid tropics, and is calibrated for the AZ of Costa Rica. As PASTOR input-output data are given per hectare, presented production function estimates are valid on the plot level. As outlined above, beef production per hectare Q_A (*i.e.* total weight of all animal units (AU) at the end of the year in kg ha^{-1}) is considered a function of the stocking rate SR (in AU ha^{-1}). Eq. (4.2) gives the functional form of the Quadratic production function, where a and b are regression coefficients. Table 4.1 shows estimation results for the natural-pasture-based beef production function per soil type.

---

[16] This conclusion is confirmed by experiments performed by Bennet *et al.* (1970) and Morley *et al.* (1978), who show that the relation between animal production and stocking rate may be non-linear in a specific season due to compensatory growth and changes in botanical composition of the pasture, while it is almost linear for the entire year.

Table 4.1 **Stocking rate dependent production function estimates per soil type for natural-pasture-based beef production in the AZ of Costa Rica**[1]

	Soil type[2]	
	SFW	SFP/SIW
Explanatory variables[3]		
Coefficient *a*	391.770 ***	354.260 ***
Coefficient *b*	-73.747 ***	-70.980 ***
Performance indicators		
Adjusted R^2	0.886	0.642
White test (prob.)	0.017	0.023
Number of observations	37	37

Notes: [1] Dependent variable is total weight of animals in kg ha^{-1}.

[2] SFW = soil fertile well drained; SFP = soil fertile poorly drained; SIW = soil infertile well drained.

[3] Significant at the at the 10% level (*), the 5% level (**), and the 1% level (***).

The parameter coefficients of the production function all have the expected sign, and are significantly different from zero at the 1% level (according to the *t*-test) for all soil types. Beef production is lower on the SIW and SFP compared to the SFW, due to acidity and drainage problems, respectively (Bouman *et al.*, 1998). Adjusted R^2 levels are high, especially for the SFW soil, indicating that the regression is strong in explaining the variation of the dependent variable in the sample. Initial problems of heteroskedasticity, as indicated by the White test, are solved by using White's heteroskedasticity consistent covariance estimators (White, 1980). Parameter estimates of the production function for the SFW soil type will be used in the numerical applications of the model presented in this and the following chapters.

4.2.3 Returns to scale in cattle ranching

In order to determine whether there are returns to scale in cattle ranching, one needs to look at the sources of economies of scale in agriculture, which include: 1) economies of scale in processing, 2) the use of lumpy inputs, and 3) advantages in credit access and risk diffusion (Binswanger *et al.*, 1995). Economies of scale in processing are only related to the organization of the farm, if coordination is required between harvesting on the one hand and processing or marketing on the other hand. Good coordination between the two can either be achieved through the establishment of plantations or through contract farming (Hayami and Otsuka, 1993). The use of lumpy inputs (*e.g.* farm machinery) implies that the optimum operational farm size increases with the introduction of the lumpy input, given that there is no rental market for this input. Use of lumpy inputs leads to an initial segment of the production function that is characterized by increasing returns to scale, while these economies of scale disappear when farm size is increased beyond the optimal scale of the lumpy input or when rental markets make lumpy inputs turn into variable inputs. Advantages in credit access arise because of the excellent potential of land as collateral. In general, the loan size increases with the amount of land owned, while the unit cost of borrowing declines with loan size.[17]

A vast amount of literature demonstrates that imperfections in at least two markets are required to explain a systematic relationship between farm size and productivity (Srinivasan, 1972; Feder, 1985; Eswaran and Kotwal, 1986; Carter and Kalfayan, 1989), as it leads to farm prices that differ systematically with the size of the farm holding. Imperfections in a single market can be compensated by transactions on perfectly functioning markets, and will result in a farm structure in which yields are equalized over farms of different operational size (Binswanger *et al*., 1995). General conclusions from studies relating farm size and productivity include: 1) the productivity advantage of small farms over large farms increases with the difference in size, 2) the highest productivity is achieved by the second-smallest, full-time farm size class, 3) plantation crops do not exhibit a negative relation between farm size and productivity; and 4) the negative relation between farm size and productivity is weakened when land is adjusted for quality, and through the introduction of green revolution technology (Binswanger *et al*., 1995).

Table 4.2 Factor production elasticities and returns to scale in Cobb-Douglas production function studies

Source	Location of sample	Function for	Elasticity of production[1]			
			Land	Labor	Capital	Sum
Antle, 1983	Developing countries	aggregate	0.44***	0.19***	0.17	0.80
Kawagoe *et al*., 1985	Developing countries	aggregate	-0.07	0.56***	0.55*	1.04
Cornia, 1985	Mexico	aggregate	0.16	0.13	0.39	0.68
	Barbados	aggregate	0.16	0.33	0.46	0.95
	Peru	aggregate	0.52*	0.23*	0.40	1.15
Kutcher and Scandizzo, 1981	Northeast Brazil[2]					
	West	aggregate	0.10***	0.77***	0.19	1.06
	South-east	aggregate	0.44***	0.43***	0.09	0.96
	Agreste	aggregate	0.08***	0.78***	0.15	1.01
Heady and Dillon, 1961	Eastern Kalahari	cattle ranching	0.28**	0.13**	0.55**	0.96*
	United States	cattle ranching	0.23**	0.18	0.53**	0.95
	Canada	cattle ranching	0.20**	0.37**	0.39**	0.97*

Notes: [1] Significant at the at the 10% level (*), the 5% level (**), and the 1% level (***).

[2] Data refer to non-family farms in regions where cattle ranching is the dominant activity.

Empirical Cobb-Douglas production function studies have been performed on different levels (cross-country, nation and region) and scales (aggregate or single product), and provide information on factor productivity and returns to scale in agriculture (see Table 4.2). Aggregate cross-country production function studies (where world agriculture is represented by a single mode of production) point towards decreasing returns to scale in

---

[17] The unit cost of borrowing declines with loan size as the fixed costs involved in establishing the loan (*e.g.* administration costs) are spread out over a larger loan size.

agriculture for all developing countries (Trueblood, 1989). Returns to scale from conventional inputs (land, labor and capital) range between 0.80 (Antle, 1983) and 1.04 (Kawagoe *et al.*, 1985). Aggregate country-specific production function studies (where national agriculture is represented by a single mode of production) also point towards decreasing returns to scale in agriculture for a number of Latin American countries. Returns to scale range from 0.68 in Mexico to 1.15 in Peru (Cornia, 1985). An aggregate regional production function study for Northeast Brazil provides mixed evidence on the relation between farm size and productivity (Kutcher and Scandizzo, 1981), though focusing on non-family farms in regions where cattle ranching is the dominant activity reveals almost constant returns to scale. Cattle ranching and country specific production function studies summarized in Heady and Dillon (1961) show that returns to scale are about constant in developed as well as in developing countries.

Summarizing, it seems fair to assume that cattle ranching exhibits constant returns to scale. Cattle ranchers neither profit from economies of scale in processing nor from the use of lumpy inputs, although they do benefit from advantages in credit access (see Chapter 2, Section 2.4.3). Moreover, empirical studies clearly point towards constant returns to scale in cattle ranching.

4.3 The investment cost function

4.3.1 Theoretical discussion

Gross investments I_t incur three types of cost components: 1) fixed costs, 2) purchase costs, and 3) adjustment costs (Nickell, 1978; Abel and Eberly, 1994, 1997). Fixed costs are independent of the level of investment and thus constant over all levels of investment when the rate of investment is nonzero (Abel and Eberly, 1994). Purchase costs are the costs of buying uninstalled capital at a fixed price per unit, which are positive in the case of positive gross investments and negative (thus representing proceeds to the firm) in the case of negative gross investments (Abel and Eberly, 1994, 1997). Adjustment costs are defined as the costs associated with the purchase, sale and productive implementation of the fixed capital input over and above the purchase price of this fixed capital input, and are considered nonnegative, continuous and strictly convex in I_t (Nickell, 1978; Abel and Eberly, 1994, 1997). The existence of adjustment costs may be justified for a number of situations: 1) if the firm's demand for the fixed capital input increases and forms a significant proportion of total demand, then the price of the capital input will rise,[18] 2) if there are costs associated with the installation of the fixed capital input, such as reorganization of product lines and training of workers, and 3) if installation of the fixed capital input becomes more expensive when installation is done quicker (Nickell, 1978). The investment cost function $C(I_t)$ is given by

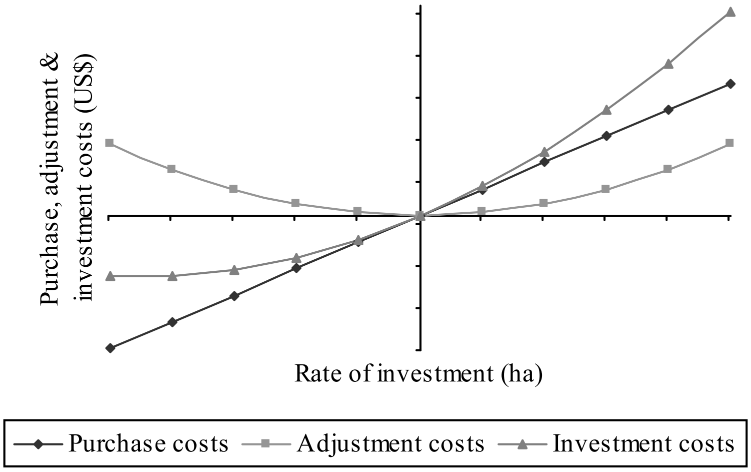
$$C(I_t) = c_1 + c_2 p_I I_t + c_3 I_t^{\beta} \qquad \text{where } \beta = n/(n\text{-}1) \text{ and } n \in \{2, 4, 6, \ldots\} \qquad (4.3)$$

---

[18] Eisner and Strotz (1963) argue that the incentive to expand applies not just to one firm but to all firms in a certain industry. Firms realize this and recognize that they actually face an upward sloping supply curve for the capital input.

where c_1 is the fixed cost parameter for $I \neq 0$, c_2 is the purchase cost scale parameter, p_I is the price of the fixed capital input, c_3 is the adjustment cost scale parameter, and where β is the adjustment cost elasticity.[19] The purchase, adjustment and investment cost functions, as specified in Eq. (4.3), are illustrated in Fig. 4.1.

Figure 4.1 **Purchase, adjustment and investment costs**



The purchase cost function $(c_2 p_I I_t)$ is strictly linear, continuous and increasing in I_t. The adjustment cost function $(c_3 I_t^{\beta})$ is strictly convex, continuous and nonnegative in I_t, given that $\beta = n/(n\text{-}1)$ with n an even positive integer. The investment cost function, given by the sum of purchase and adjustment costs, is strictly convex and continuous in I_t, negative for $\left(-c_2 p_I / c_3\right)^{1/(\beta-1)} < I_t < 0$, and positive otherwise.

Investment models that only include purchase costs in the investment cost function, *i.e.* when $c_1 = 0$, $c_2 \neq 0$ and $c_3 = 0$ (*e.g.* Fisher, 1930; Hirshleifer, 1965), assume that the fixed capital input stock can be adjusted costlessly and instantaneously. Consequently, the firm can respond to relevant parameter changes through instantaneous adjustments in the fixed capital input stock, the firm can ignore the future when making optimal investment decisions, and the firm can buy and sell fixed capital inputs for the purpose of capital gains (Nickell, 1978). In this case, the investments are reversible, as initial investment costs can be recovered completely (Dixit and Pindyck, 1994).

Investment models that only include adjustment costs in the investment cost function, *i.e.* when $c_1 = 0$, $c_2 = 0$ and $c_3 \neq 0$ (*e.g.* Abel, 1983, 1985), implicitly assume that a positive rate of investment is always optimal as purchase costs of fixed capital are not included and marginal adjustment costs are specified as zero at zero investment (Abel and Eberly, 1997). Consequently, the price of the fixed capital input and the interest rate do not determine the steady state solution, though do determine the speed at which the fixed capital input

---

[19] Abel and Eberly (1997) show that the adjustment cost function is real-valued and convex for negative as well as positive I_t if $\beta = n/(n\text{-}1)$, with n an even positive integer.

stock grows towards its steady-state level. In this case, the investments are irreversible as initial investment costs cannot be recovered.

Investment models that include purchase as well as adjustment costs in the investment cost function, *i.e.* when $c_1 = 0$, $c_2 \neq 0$ and $c_3 \neq 0$ (*e.g.* Eisner and Strotz, 1963; Lucas, 1967; Gould, 1968; Treadway, 1969), implicitly introduce the possibility of disinvestment. In the case of disinvestment, $-C(I_t)$ may be positive and reflects the revenue that may be obtained as the fixed capital input is sold off (Gould, 1968). Consequently, zero or negative levels of investment may be optimal to the firm when, realistically, assuming a positive purchase price of capital (Abel and Eberly, 1997). In this case, the investments are partially reversible, as initial investment costs cannot be recovered completely (adjustment costs form a sunk cost for the firm).

4.3.2 Empirical estimation

Investment costs faced by beef cattle ranchers in the AZ of Costa Rica are linked to the purchase (or sale) and clearing of forested land for pasture-based beef production. Purchase costs (or sale returns) related to (dis)investments in land are a function of land price, the latter being determined by location, available infrastructure and soil characteristics of the plot. Adjustment costs related to investments in land are considered a function of labor requirements for forest clearing, while taking into account that wages increase when labor demand rises because cattle ranchers in the zone face an upward-sloping labor supply curve.

Purchase costs

Consistent data on land transactions and land prices in Costa Rica are not readily available. The most important institutions concerned with land include the Institute of Agricultural Development (IDA) and the Ministry of Housing. The *Instituto de Desarrollo Agropecuario* (IDA), which was concerned with the registration, distribution and sale of land, maintained a (largely incomplete) database of land transactions during the period 1973 till 1991. The *Dirección de Tributación Directa* of the Ministry of Housing is occupied with the taxing of real estate, and uses actual land prices for the taxing of land.

In this study, land price data from the Ministry of Housing are used to determine the price of land in the AZ of Costa Rica. The 1995 data set contains 49 observations for the canton of Pococí, and includes information on the land price per hectare in US$ (value), location of the plot (district 1 to 6), type of road bordering the plot (tarmac or dirt), type of service (electricity, telephone, waterworks and illumination), drainage quality (good or bad), and soil quality (good or bad). In the estimation of rural land prices, plots in urban areas are excluded by eliminating the data for plots that have illumination.

A linear regression model is developed, in which the per hectare land price (dependent variable) is equated to district, type of road, type of service, drainage quality and soil quality (explanatory variables). Full model results (see Table 4.3) show that proximity of the plot to the main road positively and significantly influences the land price, given that district 1 (Colorado) is farthest and district 6 (Guápiles) closest to the main road.[20] Road quality negatively though not significantly influences the land price, as it is reported that both tarmac and dirt roads can be used throughout the year by all kinds of vehicles. Availability of electricity, telephone and waterworks positively and significantly influence the land price, as these services improve productive (*e.g.* machinery, information and hygiene) and non-productive (*e.g.* housing) use of the land. Good soil drainage positively and significantly influences the land price, as the drainage characteristics of the soil highly determine the land's agricultural potential (Wielemaker and Vogel, 1993). Good soil quality positively though insignificantly influences the land price, as soil quality is mostly determined by soil drainage characteristics. This is also reflected by the high correlation (70%) between soil drainage and soil quality variables. Adjusted R^2 levels are high, indicating that the regression is strong in explaining the variation in land prices. The White test indicates that there is no problem of heteroskedasticity.

Table 4.3 Estimation results of the linear regression model for rural land prices in Pococí[1]

	Full model	Reduced model
Explanatory variables[2]		
District	209.97 ***	179.95 ***
Tarmac road	-64.22	-
Electricity	562.62 *	805.12 ***
Telephone	666.80 *	665.09 **
Waterworks	1072.45 ***	1113.42 ***
Good soil drainage	729.91 *	899.40 ***
Good soil quality	361.91	-
Performance indicators		
Adjusted R^2	0.759	0.758
White test (prob.)	0.119	0.404
Number of observations	39	39

Notes: [1] Dependent variable is land price in US\$ ha^{-1}.

[2] Significant at the at the 10% level (*), the 5% level (**), and the 1% level (***).

Reduced model results (see Table 4.3) are obtained by stepwise deletion of least significant variables from the linear regression model, by using the *t*-test. Variables that are significantly different from zero at the 5% level and determine the land price are district, availability of electricity, telephone and waterworks, and soil drainage. District shows that the base land price is about 180 US\$ ha^{-1} for a plot most distant from the main road, and about 1080 US\$ ha^{-1} for a plot closest to the main road. In all districts, the plots can be reached by either tarmac or dirt road. Availability of electricity, telephone and waterworks increase the land price with approximately 800 US\$ ha^{-1}, 660 US\$ ha^{-1} and 1100 US\$ ha^{-1}, respectively. Good soil drainage increases the

---

[20] District is a proxy for the distance to the main road that connects the capital (San Jose) and the main port (Limón) of Costa Rica.

land price with almost 900 US$ ha^{-1}, as agricultural potentials increases significantly. Adjusted R^2 levels are high and there is no problem of heteroskedasticity.

Adjustment costs

Beef cattle ranches in the AZ of Costa Rica face adjustment costs when purchasing as well as selling land. Adjustment costs related to the purchase of land are determined by labor requirements for forest clearing, and amount up to 9.1 labor days (LD) per hectare (Van Leeuwen and Hofstede, 1995; Marciano, 1999).[21] Given the 1995 agricultural wage rate of 8.9 US$ LD^{-1} (Bouman *et al*., 2000), adjustment costs related to the purchase of land are about 81 US$ ha^{-1}. Adjustment costs linked to the sale of land may be determined by the work involved in searching a potential buyer and legal administration, which is performed by the cattle rancher or his legal representative against opportunity wage.

While production decisions by individual cattle ranches do not affect factor prices, on the regional level, total factor demand of all cattle ranches may affect equilibrium prices. In the AZ, especially labor is of considerable importance in production decisions (Bouman *et al*., 2000). Given a total of 803 beef cattle ranches in the AZ (DGEC, 1987), a labor supply elasticity of 0.2 (Bosworth *et al*., 1996) and a total agricultural labor force of $9.0*10^6$ LD in 1995 (Bouman *et al*., 2000), a ten-hectare expansion of the farm area by each cattle ranch in the region would lead to an increase in the agricultural wage from 8.9 US$ LD^{-1} to about 9.3 US$ LD^{-1}.

As outlined in Section 4.3.1, adjustment costs C^{adj} can be approached by a functional form that is strictly convex, continuous and nonnegative in I_t. This implies that there are diseconomies of scale associated with more rapid changes in the land stock. The simplest form with these characteristics is the quadratic

$$C^{adj}(I_t) = c_3 I_t^2 \qquad (4.4)$$

An important assumption made by using this adjustment cost function is that the adjustment costs related to investments in land are equal to the adjustment costs related to disinvestments in land.[22] On the basis of the total number of beef cattle ranches, labor requirements for forest clearing, the labor supply elasticity and the agricultural labor force in the AZ, adjustment costs can be calculated for different levels of adjustment in the land stock. In turn, a quadratic functional form is used to approach these adjustment costs. Table 4.4 shows estimation results for the quadratic adjustment cost function, thereby differentiating for simultaneous investments by 100%, 75%, 50% and 25% of all beef cattle ranches in the AZ.

---

[21] Labor demand by beef cattle ranches in the AZ of Costa Rica is not so much related to beef cattle fattening itself but rather to land clearing for pasture establishment. Labor requirements for pasture establishment and maintenance as well as cattle maintenance are about 2.5 LD ha^{-1} yr^{-1} (Bouman *et al*., 1998), while labor requirements for land clearing amount up to almost 10 LD ha^{-1} (Van Leeuwen and Hofstede, 1995; Marciano, 1999).

[22] In Chapter 6, this assumption will be relaxed and the investment cost function that is quadratic in the rate of investment will be compared with an investment cost function that is exponential in the rate of investment.

Table 4.4 Adjustment cost estimates for different shares of all cattle ranches investing simultaneously[1]

	100% of ranches	75% of ranches	50% of ranches	25% of ranches
Dependent variable[2]				
Coefficient c_3	7.378***	7.202***	7.032***	6.864***
Performance indicators				
Adjusted R^2	0.807	0.794	0.781	0.767
White test (prob.)	0.285	0.288	0.290	0.292
Number of observations	121	121	121	121

Notes: [1] Dependent variable is adjustment cost in US$.

[2] Significant at the at the 10% level (*), the 5% level (**), and the 1% level (***).

Parameter coefficients of the quadratic adjustment cost function are significantly different from zero at the 1% level (according to the *t*-test) for all shares of cattle ranches investing simultaneously. Compared to the situation where all cattle ranches invest simultaneously, the adjustment costs coefficient c_3 is about 7% lower when only 25% of all cattle ranches invest simultaneously. Adjusted R^2 levels are high, indicating that the quadratic functional form approaches the adjustment cost function relatively well. Note, however, that adjusted R^2 levels are higher when the share of cattle ranches that invest simultaneously is higher.[23] The White test indicates that there is no problem of heteroskedasticity.

4.4 Model specification: a dynamic reversible investment model for cattle ranchers

A model for cattle ranchers in Latin America is developed on the basis of the dynamic Neoclassical investment theory with adjustment costs (Eisner and Strotz, 1963; Gould, 1968; Treadway, 1969; Mussa, 1977; Abel, 1990). The model assumes that: 1) the production function employs one variable and one fixed factor of production, produces one single output, is twice differentiable and reflects constant returns to scale, 2) the variable input can be adjusted costlessly and instantaneously, 3) the fixed capital input can be adjusted and is subject to an investment cost function that is convex in the rate of investment, 4) the fixed capital input is subject to depreciation, 5) all factor, output and capital markets function perfectly, and 6) there is perfect certainty concerning the present and future.

The cattle rancher is engaged in pasture-based beef production (fattening), thereby using cattle S_t and natural pasture-land A_t to produce beef according to a production function $Q(S_t, A_t)$ that is quadratic in the stocking rate S_t/A_t, while assuming constant returns to scale (see Section 4.2). Land is considered a fixed capital input, as it is relatively fixed and subject to relatively large purchase and adjustment costs (see Section 4.3). Cattle is considered a variable input, as any number of beef cattle can be bought and sold at any moment

---

[23] A larger share of cattle ranches (dis)investing simultaneously leads to higher labor demand, higher labor prices, and, consequently, more rapidly rising adjustment costs. As a result, adjustment costs become more convex in I_t and are better approached by the quadratic functional form.

in time (Faminow and Vosti, 1998) and beef cattle is held for a relatively short period of time (Bouman *et al.*, 1998).[24] Consequently, an assumption in this model is that the cattle rancher can adjust his level of beef production in response to (for example) a change in beef prices by adjusting the cattle stock and not by selling cattle at a lower or higher age. This may seem a restriction, but data from the Costa Rican National Production Board (CNP) for the period 1984 to 1997 confirm that cattle ranchers mainly respond to changes in beef prices by adjusting the cattle stock.[25] This notion is consistent with Jarvis (1986) and Kaimowitz (1996), who state that ranchers tend to adjust their farm size and/or cattle stock in response to changed market conditions.

The cattle ranch produces an annual net income stream π_t, defined as the returns from beef production net of variable costs related to the use of cattle and land as well as investment costs, at each point in time t. Investments in land I_t take place to assure feed supply (*i.e.* capital service) and are subject to convex increasing investment costs $C(I_t)$ that include purchase and adjustment costs (see Section 4.3). The annual net income stream π_t is given by

$$\pi(S_t, A_t, I_t) = pQ(S_t, A_t) - p_S S_t - p_A A_t - C(I_t) \qquad (4.5)$$

with $Q(S_t, A_t) = A_t Q_A(SR_t) = aS_t + bS_t^2 A_t^{-1}$ where $SR_t = S_t/A_t$, $a > 0$ and $b < 0$ (4.6)

$$C(I_t) = p_{I,t} I_t + c_3 I_t^{\beta} \qquad (4.7)$$

Here, p represents the beef price, p_S is the price of cattle purchase and maintenance, p_A is the price of pasture maintenance, p_I is the price of pasture-land, c_3 is the adjustment cost scale parameter, and β is the adjustment cost elasticity. The cattle rancher maximizes the present value of net income streams over time, subject to the equation of motion for land.[26] The optimal control problem is formulated as follows

Maximize $$V(A_0) = \max_{I_t, S_t} \left\{ \int_0^{\infty} [\pi_t] e^{-rt} dt \right\} \qquad (4.8)$$

subject to $\dot{A}_t = I_t - \delta A_t$ (equation of motion for A_t)

---

[24] A beef cattle fattening system is characterized as system where young animals are bought, fattened over a relatively short period of time (between 1 and 2 years), and then sold (Bouman *et al.*, 1998).

[25] Unpublished CNP data for the period 1984 to 1997 indicate that the correlation coefficient between beef prices and the number of slaughtered animals is about 0.34, while the correlation coefficient between beef prices and the weight of the animal offered for slaughter is about –0.12.

[26] This formulation implies that the cattle rancher is considered a risk-neutral individual, who prefers the alternative with the highest expected monetary returns despite the probability of gains or losses (Robinson *et al.*, 1984). Put differently, the expected utility obtained from the expected monetary income is linearly increasing in the expected monetary income

and $A_0 > 0$ and $I_0 = 0$ (initial conditions)

$A_t \geq 0$ and $S_t \geq 0$

where r is the time discount rate, and where a dot over a variable denotes the derivative of that variable with respect to time t. The equation of motion for land is determined by gross investments in land I_t as well as depreciation of land δ. Depreciation of land is taken into account, as it is generally acknowledged that pasture-land is abandoned or has to be recuperated after 7 to 12 years after pasture establishment as a result of resource degradation (Faminow, 1998; Bulte *et al.*, 2000).[27] The value function in Eq. (4.8) satisfies the Hamilton-Jacobi-Bellman equation

$$rV(A_t) = \max_{I_t, S_t}\left[pQ(S_t, A_t) - p_S S_t - p_A A_t - C(I_t) + (I_t - \delta A_t)V_A\right] \tag{4.9}$$

where $V_A = \partial V / \partial A$. This optimality condition requires that, over an infinitely small time interval, the instantaneous net income equals the required return $rV(A_t)$. Using Eq. (4.6) and (4.7), maximization of Eq. (4.9) with respect to I_t and S_t, respectively yields the *f.o.c.*'s

$$V_A = p_I + c_3 \beta I_t^{\beta - 1} \quad \text{or} \quad I_t = \left(\frac{V_A - p_I}{c_3 \beta}\right)^{1/(\beta-1)} \tag{4.10}$$

$$p_S = p\left(a + 2bS_t A_t^{-1}\right) \quad \text{or} \quad S_t = \frac{(p_S - pa)A_t}{2pb} \tag{4.11}$$

Eq. (4.10) states that the optimal rate of investment is such that marginal valuation of land V_A is equal to the marginal costs of investment in land, *i.e.* the sum of purchase and adjustment costs. Further differentiation of Eq. (4.9) with respect to I_t shows that the extremum is a maximum ($\partial V^2 / \partial I_t^2 < 0$), given that $c_3 > 0$ and $\beta > 1$. Eq. (4.11) says that the cattle rancher employs cattle up to the point where marginal costs equal marginal returns. Subsequent substitution of the optimal I_t and S_t into Eq. (4.9) results in

$$rV(A_t) = (h - \delta V_A)A_t + \left(V_A - p_I\right)^{\beta/(\beta-1)}\Gamma \tag{4.12}$$

(Hardaker *et al.*, 1997). This is a reasonable assumption, given the fact that cattle ranchers are characterized as profit maximizers who are not dependent on the income they obtain from cattle ranching (see Chapter 2, Section 2.2).

[27] Depreciation is a relatively simple way to model resource degradation, with two peculiarities in this setting. First, the specific effect of resource degradation on production is not considered. Second, depreciated land just evaporates from the farm. In Chapter 7, resource degradation will be modeled in a more sophisticated way.

where $$h = \frac{2p_S pa - p^2 a^2 - p_S^2 - 4p_A pb}{4pb}$$

$$\Gamma = \left(\frac{1}{c_3\beta} \right)^{1/(\beta-1)} - c_3 \left(\frac{1}{c_3\beta} \right)^{\beta/(\beta-1)}$$

Note that V_A is the marginal valuation or shadow value of installed land, in correspondence with Tobin's marginal q (Tobin, 1969). To find an analytical solution of Eq. (4.12), we take $V(A_t)$ to be a linear function of the land stock A_t, thus

$$V(A_t) = qA_t + C \tag{4.13}$$

where C and $q = V_A$ are constants to be determined. Substitution of Eq. (4.13) into Eq. (4.12) yields

$$rqA_t + rC = (h - \delta q)A_t + (q - p_I)^{\beta/(\beta-1)}\Gamma \tag{4.14}$$

which holds for all values of A_t. Consequently, the term multiplying A_t on the *l.h.s.* must equal the term multiplying A_t on the *r.h.s.*, and, similarly, the term not involving A_t on the *l.h.s.* must equal the term not involving A_t on the *r.h.s.*. This yields, while solving for q and C, respectively

$$q = \frac{h}{r+\delta} = \frac{2p_S pa - p^2 a^2 - p_S^2 - 4p_A pb}{4pb(r+\delta)} \tag{4.15}$$

$$C = r^{-1}(q - p_I)^{\beta/(\beta-1)}\Gamma = r^{-1}(q - p_I)^{\beta/(\beta-1)} \left[\left(\frac{1}{c_3\beta} \right)^{1/(\beta-1)} - c_3 \left(\frac{1}{c_3\beta} \right)^{\beta/(\beta-1)} \right] \tag{4.16}$$

Therefore, taking $V(A_t)$ to be a linear function of A_t leads to a solution of Eq. (4.12). This means that q is independent of the land stock A_t, in line with the assumption that the cattle rancher faces a constant returns to scale production function and exogenous prices.[28] Substitution of q and C back into Eq. (4.13) and (4.10), respectively, yields the fundamental value of the farm $V(A_t)$ and the optimal rate of investment I_t. So

$$V(A_t) = qA_t + r^{-1}(q - p_I)^{\beta/(\beta-1)} \left[\left(\frac{1}{c_3\beta} \right)^{1/(\beta-1)} - c_3 \left(\frac{1}{c_3\beta} \right)^{\beta/(\beta-1)} \right] \tag{4.17}$$

---

[28] Abel (1983) shows that q equals the present value of marginal revenue products of land.

$$I_t = \left(\frac{q - p_I}{c_3 \beta} \right)^{1/(\beta - 1)} = \left(\frac{2 p_S pa - p^2 a^2 - p_S^2 - 4 p_A pb - 4 p_I pb(r + \delta)}{4 pb(r + \delta) c_3 \beta} \right)^{1/(\beta - 1)} \tag{4.18}$$

As assumed in Eq. (4.13), it is also clear from Eq. (4.17) that the fundamental value of the farm is a linear function of the land stock A_t, given that q is independent of the land stock. The value of the farm will increase for positive and negative differences between the shadow price of land q and the purchase price of land p_I, as land can be bought for future productive returns and sold for immediate sales returns.[29] According to Eq. (4.18), the optimal rate of investment is an increasing function of q, and independent of A and t. When the shadow price of land q is greater (smaller) than the purchase price of land p_I, the cattle rancher buys (sells) land and gross investment is positive (negative).[30]

Using the equation of motion for A_t (see Eq. 4.8), the land stock path A_t is obtained by solving the differential equation $\partial A_t / \partial t + \delta A_t = I_t$. Direct substitution verifies that the specific solution to this nonhomogeneous linear differential equation is given by

$$A_t = \left[A_0 - \frac{I_t}{\delta} \right] e^{-\delta t} + \frac{I_t}{\delta} \tag{4.19}$$

where A_0 is the initial land stock. Eq. (4.19) shows that the steady state land stock A^* equals I_t/δ, and that the land stock grows (falls) in an exponential fashion towards this equilibrium level given that the initial land stock lies below (above) this equilibrium.

The model is solved qualitatively by the construction of a phase diagram, in which I_t is plotted against A_t (see Fig. 4.2). The demarcation curves $\dot{A}_t = 0$ and $\dot{I}_t = 0$, describe the subsets of points in the A_t - I_t space where the variable in question can be stationary. The point of intersection of the two demarcation curves (*i.e.* where $\dot{A}_t = 0$ and $\dot{I}_t = 0$), determines the unique intertemporal equilibrium or steady state of the entire system (Chiang, 1992). The demarcation curves $\dot{A}_t = 0$ and $\dot{I}_t = 0$ are found using Eq. (4.8) and (4.18), respectively, and are given by

$$I_t = \delta A_t \qquad (\dot{A}_t = 0 \text{ curve}) \tag{4.20}$$

$$I_t = \left(\frac{2 p_S pa - p^2 a^2 - p_S^2 - 4 p_A pb - 4 p_I pb(r + \delta)}{4 pb(r + \delta) c_3 \beta} \right)^{1/(\beta - 1)} \qquad (\dot{I}_t = 0 \text{ curve}) \tag{4.21}$$

---

[29] Note that $\beta / (\beta - 1)$ is even for $n \in \{2, 4, 6, \ldots\}$, so that $(q - p_I)^{\beta/(\beta-1)} > 0$ for all $q - p_I$..

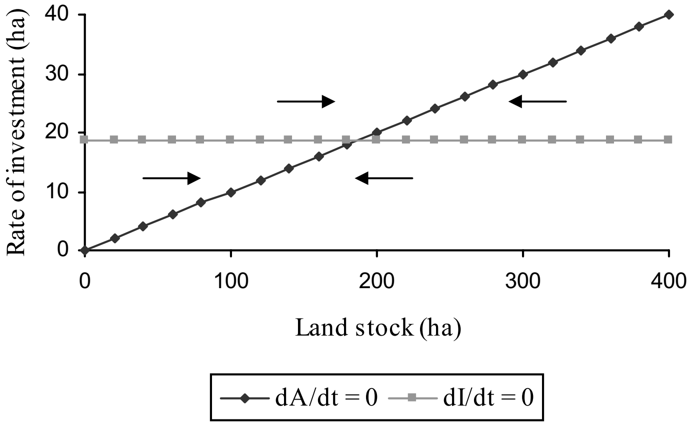
[30] Note that $1 / (\beta - 1)$ is odd for $n \in \{2, 4, 6, \ldots\}$, so that $I > 0$ for $q > p_I$ and $I < 0$ for $q < p_I$..

The direction of movement of points in the A_t - I_t space that are not on the demarcation curves are indicated by the directional arrows in Fig. 4.2. Directional arrows are obtained by differentiation of Eq. (4.8) and Eq. (4.18) with respect to I_t, which yields, respectively

$$\partial \dot{A}_t / \partial I_t = 1 \qquad \text{and} \qquad \partial \dot{I}_t / \partial I_t = 0 \tag{4.22}$$

The positive sign of $\partial \dot{A}_t / \partial I_t$ implies that $\dot{A}_t$ is negative below the $\dot{A}_t = 0$ curve, and that $\dot{A}_t$ is positive above the $\dot{A}_t = 0$. So, A_t is falling at every point below the $\dot{A}_t = 0$ curve, and A_t is increasing at every point above the $\dot{A}_t = 0$ curve. The fact that $\partial \dot{I}_t / \partial I_t = 0$ implies that $\dot{I}_t$ is zero below and above the $\dot{I}_t = 0$ curve. So, I_t is constant at every point below and above the $\dot{I}_t = 0$ curve.

Figure 4.2 **Phase diagram**



The steady-state solution of the model is found at the point of intersection of the $\dot{A}_t = 0$ and the $\dot{I}_t = 0$ curve, *i.e.* when all net investment or expansion of the pasture area is completed. Substituting Eq. (4.21) in (4.20) and solving for A_t yields the steady-state land stock A^*. Further substitution of A^* in Eq. (4.11) and (4.6) yields steady states for cattle S^*, beef production Q^*, and the stocking rate SR^*, as given by

$$A^* = \left(\frac{2p_S pa - p^2a^2 - p_S^2 - 4p_A pb - 4p_I pb(r+\delta)}{4pb(r+\delta)c_3\beta} \right)^{1/(\beta-1)} \Big/ \delta \tag{4.23}$$

$$S^* = \frac{(p_S - pa)A^*}{2pb} \tag{4.24}$$

$$Q^* = \frac{(p_S - pa)(p_S + pa)A^*}{4p^2b} \tag{4.25}$$

$$SR^* = \frac{S^*}{A^*} = \frac{p_S - pa}{2pb} \tag{4.26}$$

Steady-state factor demand (A^* and S^*) and product supply (Q^*) are: 1) continuous, 2) convex and increasing in p, 3) convex and decreasing in p_S, 4), linear and decreasing in p_A and p_I, and 5) homogeneous of degree one in all prices (*i.e.* simultaneously input, output and land prices). The steady-state stocking rate SR^* is: 1) continuous, 2) concave and increasing in p, 3) convex and decreasing in p_S, and 4) homogenous of degree zero in p_A, p_I and all prices.

4.5 Model results

The deterministic investment model developed in the previous section is applied to an average cattle ranch in the AZ of Costa Rica, while using the production and investment cost functions as determined in Section 4.2.2 and 4.3.2, respectively. First, the adjustment path is established in order to analyze investment and income dynamics over time. Next, the steady-state solution is considered and compared to the actual situation of 1984. Finally, a comparative static sensitivity analysis is performed with respect to output, input and capital prices, as well as adjustment costs.

Model base run results are obtained on the basis of 1995 data. The price of beef (p = 1.41 US\$ kg^{-1}), cattle purchase and maintenance (p_S = 213.2 US\$ AU^{-1}) and pasture maintenance (p_A = 55.0 US\$ ha^{-1}) are obtained from the PASTOR system, which is calibrated for the AZ of Costa Rica for the year 1995 (Bouman *et al.*, 2000). The base price of land with road access, poor soil drainage and no further facilities for an average beef cattle ranch in the AZ (p_I = 630.0 US\$ ha^{-1}) is obtained from the *Dirección de Tributación Directa* of the Ministry of Housing (see Section 4.3.2). The rate of land depreciation is set at δ= 0.10, in line with Faminow (1998) and Bulte *et al.* (2000) who state that pasture-land is abandoned or recuperated in about 7 to 12 years after pasture establishment. Quadratic adjustment costs related to investments in land are determined on the basis of secondary data regarding labor supply, costs and requirements (see Section 4.3.2), thereby assuming that 25% of all beef cattle ranches invest simultaneously (c_3 = 6.864 and β= 2). The World Development Indicators (World Bank, 1999) provided the time discount rate (r = 6.9% yr^{-1}), which was calculated as the geometric mean of the real interest rates over the period 1984 to 1997, and the official exchange rate (179.73 Colones US\$$^{-1}$). Production function parameter estimates for pasture-based beef production on poorly drained soil types in the AZ of Costa Rica are determined on the basis of input-output coefficients generated by the PASTOR system (see Section 4.2.2). Returns to scale are assumed constant, in line with secondary data on cattle ranching systems (see Section 4.2.3).

4.5.1 The adjustment path

The deterministic reversible investment model, as presented in Section 4.4, is used to analyze the investment and income dynamics of an average beef cattle ranch in the AZ of Costa Rica. Figure 4.3 shows the rate of gross investment in pasture-land, the corresponding levels of net and replacement investments, and the total land stock over time. Similarly, Figure 4.4 depicts gross investment costs, recurrent returns from beef production, annual net income, and the cumulative discounted net income over time.

The rate of gross investment in land I_t is constant over time, in correspondence with Eq. (4.18). As such, the rate of gross investment does not provide much information. However, solving the equation of motion for land (Eq. 4.8), with respect to I_t produces

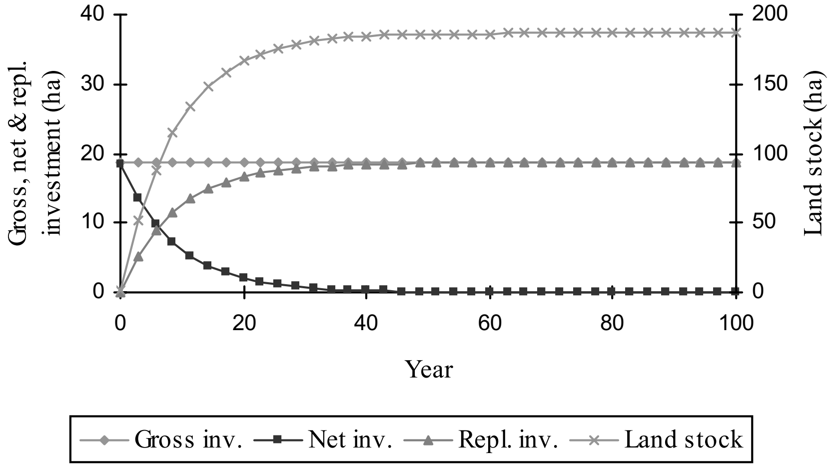
$$I_t = \dot{A}_t + \delta A_t \tag{4.27}$$

which states that gross investments I_t can be separated into net investments ($\dot{A}_t$) and replacement investments (δA_t), where the former refers to an expansion of the land stock and the latter to the recuperation of depreciated land. If there is no further expansion of the land stock, according to Eq. 4.20, the steady-state land stock A^* requires a level of replacement land δA_t^* to maintain itself. Hence, in equilibrium the level of gross investment, I_t equals replacement investments δA_t^*, and Eq. (4.27) becomes (solving for $\dot{A}_t$)

$$\dot{A}_t = \delta\left(A_t^* - A_t\right) \tag{4.28}$$

Consequently, net investments $\dot{A}_t$ are directly proportional to the difference between the desired land stock A^* and the current land stock A_t.

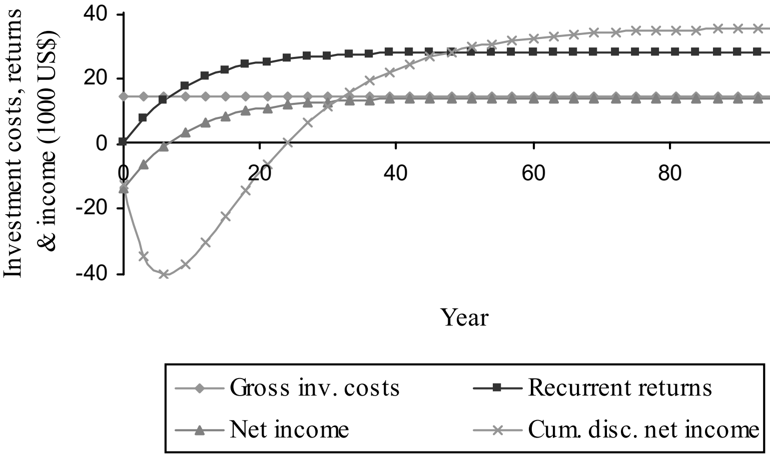
Figure 4.3 **Gross investments, net investments, replacement investments, and land stock over time**



With the above discussion in mind, it is clear from Figure 4.3 that net investments decrease in an exponential fashion towards zero over time, leading to the convergence of the land stock towards the optimal land stock A^*. As gross investments are the sum of net and replacement investments, replacement investments increase in an exponential fashion towards the depreciation level δA^*, corresponding to the steady state land stock A^*. To get an idea of the speed of adjustment of the land stock: 25% of total investments are completed after 3 years, 50% after 7 years, and 75% of total investments are completed after 13 years.

A steady-state solution is obtained by assuming depreciation of pasture-land over time, together with the assumption of convex investment costs. The steady state arises because investment costs increase at the margin, and consequently replacement investment costs limit the size of the farm. The optimal land stock A^* is that quantity of land that provides a current marginal net profit that just equals the marginal investment costs corresponding to the replacement investment associated to this optimal land stock (Nickell, 1978).

Figure 4.4 **Gross investment costs, recurrent returns, net income, and cumulative discounted net income over time**



Given the level of gross investment and the land stock path over time, gross investment costs, recurrent returns, net income levels, and the cumulative discounted net income can be determined (see Figure 4.4).[31] Gross investment costs are positive and constant over time, in line with the rate of gross investment determined in Eq. (4.18). Recurrent returns from beef production are positive, concave and increasing over time, in correspondence with the land stock path depicted in Eq. (4.19), as pasture-land allows for the fattening of beef cattle with subsequent variable costs and returns. Net income, which is the sum of recurrent returns and gross investment costs, is concave and increasing over time and becomes positive in the 7th year of production. Finally, the cumulative discounted net income is negative and decreasing till the 7th year of production, negative and increasing from the 7th till the 25th year of production, and is positive, concave and increasing from the 25th year of production. Note that the cumulative discounted net income grows towards the steady-state value of the farm of $35.5*10^3$ US$.

---

[31] Gross investment costs are calculated from Eq. (4.7), recurrent returns are defined as the gross returns from beef production Q net of variable input costs related to the use of cattle S and pasture-land A, net income levels are calculated with Eq. (4.5), and the cumulative discounted net income is calculated by using Eq. (4.8).

4.5.2 The steady-state solution

The steady state solution is compared with the actual situation in 1984, the year in which the latest agricultural census in Costa Rica was held (DGEC, 1987). Table 4.5 gives the steady-state solution for an average beef cattle ranch in the AZ of Costa Rica as well as the actual situation in 1984 in which cattle ranchers in the AZ of Costa Rica are stratified according to farm size.[32] Indicators include the value of the farm, resource stock, rate of investment, beef production and the stocking rate.

Table 4.5 Steady-state solution for an average beef cattle ranch and the actual situation for beef cattle ranches stratified according to farm size, in the AZ of Costa Rica

	Unit	Steady state	Actual situation[1]			
			50-100 ha	100-300 ha	> 300 ha	Average
Value of the farm	US$	35,456.8	-	-	-	-
Resource stock						
Land	ha yr^{-1}	186.6	70.6	159.7	674.2	197.7
Cattle	AU yr^{-1}	266.9	94.3	163.6	695.2	212.7
Rate of investment	ha yr^{-1}	18.7	-	-	-	-
Beef production	tons yr^{-1}	31.1	-	-	-	-
Stocking rate	AU ha^{-1}	1.43	1.34	1.02	1.03	1.08
Number of ranches	#	-	364	355	84	-

Note: [1] Actual situation in 1984 is obtained from DGEC (1987).

The steady-state solution indicates that an average beef cattle ranch in the AZ encompasses about 187 ha of pasture-land and 267 AU of beef cattle, which implies a stocking rate of about 1.4 AU ha^{-1}. The rate of investment amounts 18.7 ha per year, which is required to replace the depreciated land. Annual beef production is just over 31 tons yr^{-1}, which implies a productivity of 116.4 kg AU^{-1} yr^{-1}. The value of the farm is about $35.5*10^3$ US$ over the concerned infinite time horizon.

The actual situation in 1984 indicates that land is not equally distributed over the cattle ranchers in the AZ. On average, 45% of the cattle ranchers own between 50 and 100 ha of pasture (18% of the total pasture area), 44% of the cattle ranchers possess between 100 and 300 ha of pasture (41% of the total pasture area), and 11% of the cattle ranchers own more than 300 ha of pasture (41% of the total pasture area). Note that the stocking rate falls as the farm size increases.

Comparison of the steady-state solution (generated for the year 1995) and the average actual situation in 1984 indicates that the former underestimates land use by only 6% while it overestimates cattle use by about 25%. This deviation is probably the result of differences in beef, input and land prices, as well as interest rates between the concerned years. The stocking rate turns out to be overestimated by 33% compared to the average actual situation in 1984. This can be explained by the fact that the production function

---

[32] Cattle ranches are defined to have more than 50 ha of pasture-land and more than 50 AU of beef cattle.

parameter estimates are based on 1995 data for the top ten best cattle ranches in the AZ as well as on experimental field data (Hengsdijk *et al*., 2000). Moreover, the effect of pasture degradation on the carrying capacity of the pasture-land has not specifically been taken into account here, but will be in Chapter 7.

4.5.3 Sensitivity analysis

Table 4.6 shows price elasticities for an average beef cattle rancher in the AZ of Costa Rica, in response to a 1% increase in the price of beef, inputs (cattle maintenance, pasture maintenance and land) and capital (time discount rate), as well as a 1% increase in adjustment costs (c_3 in Eq. 4.7). Results refer to the steady-state solution and, again, indicators include the value of the farm, resource stock, rate of investment, beef production and the stocking rate.

Table 4.6 Price elasticities for an average beef cattle ranch in the AZ of Costa Rica, for a 1% increase in output, input and capital prices, and adjustment costs[1]

	1% increase in price of:					
	Beef	Cattle Maintenance	Pasture maintenance	Land	Discount rate	Adjustment costs
Value of the farm	10.9	-1.4	-2.5	-4.7	-3.7	-1.0
Resource stock						
Land	5.4	-0.7	-1.3	-2.5	-1.4	-1.0
Cattle	5.5	-0.8	-1.3	-2.5	-1.4	-1.0
Rate of investment	5.4	-0.7	-1.3	-2.5	-1.4	-1.0
Beef production	5.4	-0.7	-1.3	-2.5	-1.4	-1.0
Stocking rate	0.1	-0.1	0.0	0.0	0.0	0.0

Note: [1] Price elasticities reflect the percentage change in indicator value compared to the base run steady state solution (see Section 4.5.2).

A 1% increase in the price of beef leads to positive and relatively elastic response reactions. The value of the farm increases with almost 11%, the resource stock, rate of investment and level of beef production increase with over 5%, while the stocking rate shows only a minor increase. Eq. 4.23 confirms that the steady-state land stock A^* is increasing in the beef price p, which is explained by the fact that the shadow value of land q is increasing in p (see Eq. 4.15), the rate of investment I_t is increasing in q (see Eq. 4.18), and the land stock A_t is increasing in I_t (see Eq. 4.19). Eq. (4.17) gives the value of the farm V as a linear function of the land stock A_t and the shadow value of land q, plus a constant C. Given that C (see Eq. 4.16) as well as q are increasing in p, it is clear that the value of the farm V is increasing in p.

A 1% increase in input (cattle maintenance, pasture maintenance and land) and capital (discount rate) prices, leads to negative and relatively elastic response reactions. Response reactions are smallest for an increase in cattle maintenance costs, and largest for an increase in land prices. The value of the farm decreases with 1.4% to 4.7%, the resource stock, rate of investment and level of beef production decrease with 0.7% to 2.5%, while the stocking rate shows only a minor or no decrease. Eq. (4.17), (4.18) and Eq. (4.23) to (4.25), respectively, show that V, I^*, A^*, S^* and Q^* are decreasing in input and capital prices. Also, the stocking rate is not influenced by a change in the price of pasture maintenance, land and the discount rate (see Eq. 4.26).

Finally, a 1% increase in adjustment costs leads to a 1% decrease in the value of the farm, resource use and beef production. From Eq. (4.15) it is clear that the shadow value of land does not depend on the adjustment costs scale parameter c_3. However, Eq. (4.17), (4.18) and Eq. (4.23) to (4.25), respectively, reveal that V, I^*, A^*, S^* and Q^* are directly proportional to c_3, as the rate of investment I_t is directly proportional to c_3 (see Eq. 4.18). The stocking rate is independent of adjustment costs (see Eq. 4.26).

4.6 Conclusions

In this chapter we developed a dynamic reversible investment model for cattle ranchers in Latin America on the basis of the Neoclassical investment theory (see Chapter 3, Section 3.2.2). In line with the general characterization of cattle ranchers (see Chapter 2, Section 2.2), we consider the cattle rancher to be a profit maximizer who is not only engaged in natural pasture based beef production (beef cattle fattening), but who also views land as an investment object. The model differs from previous dynamic cattle ranching and livestock models (*e.g.* Standiford and Howitt, 1992; Nicholson *et al.*, 1994; Costanza and Neuman, 1997; Bulte *et al.*, 2000) in the sense that the farm size is not assumed fixed. Consequently, this model not only enables us to determine the optimal stocking rate, but also permits us to determine the optimal farm size and rate of investment. This feature is particularly important in the consideration of uncertainty in beef prices (Chapter 5), land speculation (Chapter 6) and resource degradation (Chapter 7).

Analytical results indicate that the shadow value of land is constant and independent of the land stock, in line with the assumption that cattle ranchers face a constant returns to scale production function and exogenous prices. The optimal rate of investment is determined by comparison of the shadow value of land and the marginal investment costs of land (*i.e.* purchase and adjustment costs), and cattle ranchers buy land when the former exceeds the latter (and *vice versa*). In turn, the optimal (steady-state) land stock is determined by the quotient of the rate of investment and the rate of land depreciation. Finally, analytical results indicate that the fundamental value of the farm is linear in the farm size, in line with the assumption of constant returns to scale and exogenous prices.

The model is applied to the case of an average cattle rancher in the Atlantic Zone (AZ) of Costa Rica, econometric methods are used to determine the appropriate investment cost and production functions, while necessary parameter values are taken from secondary data sources. The production function for natural-pasture-based beef production is determined on the basis of input-output data that are generated by an agronomic model for cattle systems in the humid tropics (PASTOR, by Bouman *et al.*, 1998). In line with production function studies for cattle ranching, the pasture-based beef production function is quadratic in the stocking rate (*e.g.* Riewe, 1964; Jones and Sandland, 1974) and exhibits constant returns to scale (*e.g.* Heady and Dillon, 1961; Kutcher and Scandizzo, 1981). Investment costs are given by the sum of purchase and adjustment costs of land, and are determined on the basis of 1995 land price data and labor requirements for forest clearing, respectively. Land prices are mainly determined by availability of services (waterworks, electricity and telephone), soil drainage, and distance to the main road (in order of importance).

Numerical results indicate that the steady state solution is relatively close to the average situation in 1984, although the stocking rate is overestimated by just over 30%. In the steady state, an average beef cattle ranch encompasses about 187 ha and 267 animal units (AU), which implies a stocking rate of about 1.4 AU ha^{-1}. Given the land depreciation rate of 10% yr^{-1}, the rate of investment amounts 18.7 ha yr^{-1}. Finally, the value of the farm is about $35.5*10^3$ US$ over the concerned infinite time horizon.

The sensitivity analysis indicates that the model is especially responsive to changes in beef and land prices. A 1% increase in the beef price leads to a 11% increase in the value of the farm and a more than 5% increase in farm size (and thus the rate of investment), while a 1% increase in the land price leads to an almost 5% decrease in the value of the farm and a 2.5% decrease in farm size. The model is less responsive to changes in other input (cattle maintenance and pasture maintenance) and capital (discount rate) prices, as well as adjustment costs. A 1% increase in these prices or costs, leads to a 1.4% to 3.7% decrease in the value of the farm and a 0.7% to 1.4% decrease in farm size. The effect on the stocking rate is relatively small (< 0.1%) in all cases, due to the assumption of constant returns to scale.

The presented model for cattle ranchers in Latin America holds a number of limitations. First, the presented approach is of a partial equilibrium nature, which implies that prices are not determined by aggregate supply and demand. Second, neither uncertainty in beef prices nor uncertainty in land prices are taken into account, although beef and land prices are considered principal factors in explaining the expansion of cattle ranching in Latin America (see Chapter 2, Section 2.4). This argument is strengthened by the presented model sensitivity analysis, which indicates that the model is especially responsive to changes in beef and land prices. In Chapter 5 and 6, we will take a closer look at the effect of uncertain beef and land prices, respectively, on investment decisions by cattle ranchers. Third, resource degradation is modeled in a rather artificial way by assuming that land depreciates over time. In Chapter 7 we will model resource degradation in a more sophisticated way, through the inclusion of a nitrogen-dependent beef production function and an equation of motion for nitrogen. Fourth, although Costa Rican National Production Board (CNP) data as well as Kaimowitz (1996) indicate that cattle ranchers mainly adjust their farm size and/or cattle stock in response to changed market conditions, the model would provide additional economic insight if it were to allow for the possibility to sell beef cattle at a lower or higher age. Finally, externalities related to deforestation, like the emission of trace and greenhouse gases, are not addressed in the present model.

5 Investment decisions under decreasing and fluctuating beef prices

5.1 Introduction

Real beef prices in Latin America have decreased considerably over the past decades (FAO, 2002). As a consequence, the profitability of cattle ranching in Latin America is often doubted. Numerous economic studies have shown that cattle ranching in the 1980's and 1990's was generally not profitable, if speculative returns from land and government subsidies were not taken into account (*e.g.* Edelman, 1985; Hecht *et al.*, 1988; Jarquín, 1990; Van der Kamp, 1990; Mattos and Uhl, 1994). Nevertheless, beef production in Latin America grew with no less than 2.6% yr^{-1} over the period 1961 to 1999 (FAO, 2002). Moreover, Faminow (1998) argues that this increase even occurred in the absence of speculative returns from land as well as government subsidies.

One of the factors (see Chapter 2) that causes expansion of cattle ranching in Latin America is the increased Latin American demand for beef products in general (Seré and Jarvis, 1992; Kaimowitz, 1996; Faminow 1998) and the increased local demand for beef products in particular (Faminow, 1997). Nowhere in this demand debate, however, the importance of speculative returns from beef production is emphasized, while in practice the cattle rancher can obtain short-term gains by adjusting the level of beef production in response to changing beef prices. Given the decrease and the relatively large fluctuations in Latin American real beef prices over the past decades (FAO, 2002), this hiatus in the literature is all the more surprising.

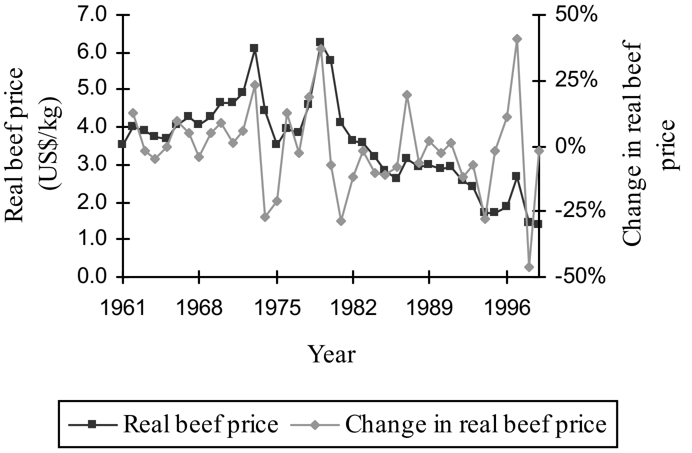
This chapter therefore examines the effect of levels, drifts and fluctuations in beef prices on investment decisions by cattle ranchers in Latin America. Based on the deterministic investment model with adjustment costs developed in Chapter 4, a stochastic reversible investment model with adjustment costs is developed in which beef prices are modeled as a geometric Brownian motion. The model is solved analytically and applied numerically for an average cattle rancher in the Atlantic Zone (AZ) of Costa Rica on the basis of 1995 data. Model simulations are carried out for various levels, growth rates (drifts) and fluctuations (standard deviations) in beef prices.

The remainder of this chapter is structured as follows. Section 5.2 starts with a discussion on the development of beef production, consumption and trade in Costa Rica, and this is followed by the empirical determination of the stochastic process underlying the development of beef prices between 1961 and 1999. In Section 5.3, the stochastic reversible investment model with adjustment costs for cattle ranchers is developed, in which beef prices are modeled as a geometric Brownian motion. Section 5.4 provides a numerical application of the model with uncertainty in beef prices to the case of Costa Rica. A comparative static sensitivity analysis with respect to levels, drifts and fluctuations in beef prices is carried out, and results are analyzed. Finally, Section 5.5 offers concluding remarks and observations.

5.2 The development of beef prices in Costa Rica

Chapter 2 (Section 2.3.2) contains an overview of the development of beef production, consumption and trade in Latin America from 1961 to 1999. This section does the same for the case of Costa Rica, compares the results with those for Latin America, examines whether beef prices in Costa Rica follow a Geometric Brownian motion, and presents the calculation of the appropriate parameter values for drift and standard deviation in beef prices for the numerical application of the model (Section 5.4).

Figure 5.1 **Real beef export prices in Costa Rica: levels and changes over the period 1961 - 1999**



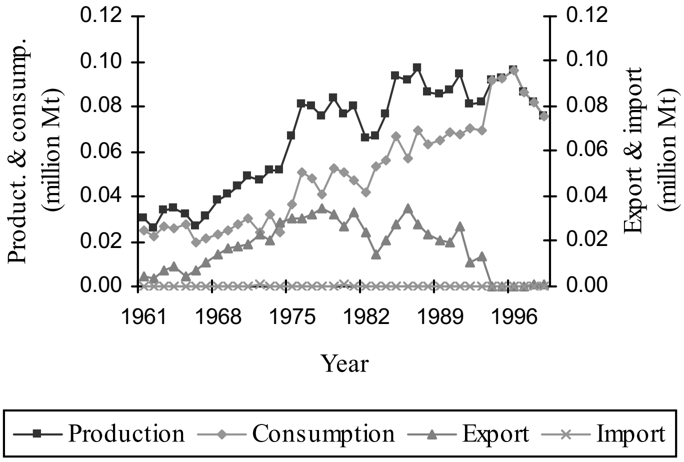
Source: FAO statistical database (2002).

Note: Prices in constant 1995 US$.

Figures 5.1 and 5.2 give the development of real Costa Rican beef export prices and the development of Costa Rican beef production, consumption, export and import over the period 1961 to 1999, respectively. Real beef prices were relatively high and stable till the mid-1970's, while they showed a general decrease and far larger fluctuations after the mid-1970's.

Compared to the Latin American average, the Costa Rican beef trade is large, relative to domestic production. Due to the fact that the Costa Rican market for beef products was relatively shallow (Kaimowitz, 1996), over 30% of total beef production was destined for the export market from 1961 to the mid-1970's, while only 0.5% of total beef consumption was met by beef imports. Real beef export prices were relatively high because demand for beef products by the U.S. (Costa Rica's most important export country) was large compared to global beef supply. As of the mid-1970's, Costa Rican beef exports first stabilized and later dropped. Still, however, almost 25% of total beef production was destined for the U.S. export market, while less than 0.2% of total beef consumption was met by beef imports. Real beef export prices fell as a result of the reduction in U.S. demand for imported beef products and the increase in world market beef supply (Kaimowitz, 1996).

Figure 5.2 **Beef production, consumption, export and import for Costa Rica over the period 1961 - 1999**



Source: FAO statistical database (2002)

Compared to the Latin American average, Costa Rican beef consumption grew relatively fast. From 1961 to the mid-1970's, Costa Rican beef consumption increased with 3.4% yr^{-1}, and with no less than 4.9% yr^{-1} since then. On average over the entire period, this is 1.4% yr^{-1} above the Latin American average. This relatively strong increase is not only explained by population growth levels of about 3% yr^{-1}, but also by an increase in per capita beef consumption (Kaimowitz, 1996; FAO, 2002). Contrary to many other Latin American countries, real income per capita in Costa Rica has risen since the 1960's.

Costa Rican beef production also grew relatively fast compared to the Latin American average. Between 1961 and the mid-1970's, beef production increased with no less than 5.6% yr^{-1} and with 2.0% yr^{-1} since then. On average over the entire period, this is just over 0.5% yr^{-1} above the Latin American average. Costa Rican beef production grew less rapidly since the mid-1970's, due to decreasing real export prices in combination with the relatively shallow domestic market.

In Section 5.3, we will develop a continuous time model of a competitive cattle ranch that sells beef at an exogenously given beef price p_t. We thereby assume that beef prices evolve according to a *geometric Brownian motion* (see Chapter 3, Section 3.3.2, *Generalized Brownian motion*), which is given by

$$dp_t / p_t = \mu dt + \sigma dz \qquad (5.1)$$

where μ is the instantaneous drift, σ is the instantaneous standard deviation, and where *dz* is a Wiener process with mean zero and unit variance. To determine the development in real beef prices, we need to test whether real beef prices follow a geometric Brownian motion.

Using the real Costa Rican beef export prices p_t (Figure 5.1), it can be tested whether $k_t = \ln(p_t)$ is consistent with Brownian motion, and, via Itô's Lemma, whether p_t is consistent with geometric Brownian motion (see for example Conrad, 1997). To test that k_t is consistent with Brownian motion requires running the unrestricted regression

$$(k_t - k_{t-1}) = \phi + \varphi t + (\gamma - 1)k_{t-1} + \eta(k_{t-1} - k_{t-2}) + \varepsilon_t \tag{5.2}$$

and the restricted regression

$$(k_t - k_{t-1}) = \phi + \eta(k_{t-1} - k_{t-2}) + \varepsilon_t \tag{5.3}$$

The null hypothesis is that k_t follows Brownian motion, or H_0: $\varphi = 0$, $\gamma = 1$. Regression results of the unrestricted and restricted models, as shown in Table 5.1, are used to calculate the F-statistic. The null hypothesis that k_t follows Brownian motion cannot be rejected, as the F-statistic is well below the Dickey-Fuller critical F^*-value at the 5% level for a sample size smaller than 50 ($F = 3.12 < F^* = 6.73$). In turn, it is proven that p_t is consistent with geometric Brownian motion.

Table 5.1 Estimation results for unrestricted and restricted regression models for real beef export prices

	Unrestricted		Restricted	
	Estimate	*t*-stat.	Estimate	*t*-stat.
Coefficients				
ϕ	0.546	2.238	-0.030	-0.983
φ	-0.010	-2.454		
$(\gamma - 1)$	-0.295	-2.131		
η	0.051	0.289	-0.060	-0.357
Sum of squared residuals (SSR)	0.998		1.187	
Number of observations	39		39	

Now that it is clear that k_t follows Brownian motion and, consequently, that p_t is consistent with geometric Brownian motion, we can proceed by estimating the mean m and standard deviation s of the series $\ln(p_{t+1}/p_t)$. These are found to be equal to $m = -0.0247$ and $s = 0.1812$, implying that $\mu = m + \frac{1}{2}s^2 = -0.0083$ and $\sigma = s = 0.1812$. For the numerical example given in Section 5.4, we will use these parameter values for drift and standard deviation in beef prices.

5.3 The stochastic model with uncertainty in beef prices

Based on the deterministic model presented in Chapter 4, a stochastic reversible investment model for cattle ranchers is developed in which uncertainty in beef pricesis modeled as a geometric Brownian motion.

Contrary to the deterministic model, this new model relaxes the assumption that there is perfect certainty concerning the level of present and future beef prices. All other assumptions remain unchanged.

As before, the cattle rancher uses cattle S_t and land A_t to produce beef according to a production function $Q(S_t, A_t)$ that is quadratic in the stocking rate S_t/A_t, while assuming constant returns to scale. The rancher undertakes gross investment I_t, while facing convex increasing investment costs $C(I_t)$. The annual net income stream π is

$$\pi(S_t, A_t, I_t) = p_t Q(S_t, A_t) - p_S S_t - p_A A_t - C(I_t) \tag{5.4}$$

with $Q(S_t, A_t) = A_t Q_A(SR_t) = aS_t + bS_t^2 A_t^{-1}$ where $SR_t = S_t/A_t$, $a > 0$ and $b < 0$ (5.5)

$C(I_t) = p_I I_t + c_3 I_t^{\beta}$ where $\beta = n/(n\text{-}1)$ and $n \in \{2, 4, 6, \ldots\}$ (5.6)

Here, p_t represents the beef price at a specific moment in time t, p_S is the price of cattle purchase and maintenance, p_A is the price of pasture maintenance, p_I is the price of land, c_3 is the adjustment cost scale parameter, and β is the adjustment cost elasticity. The cattle rancher maximizes the present value of net income streams over time, subject to the equation of motion for land and the beef price process over time. The optimization problem is formulated as follows

Maximize $V(A_0, p_0) = \max_{I_t, S_t} E_t \left\{ \int_0^{\infty} [\pi_t] e^{-rt} dt \right\}$ (5.7)

subject to $\dot{A}_t = I_t - \delta A_t$ (equation of motion for A_t)

$dp_t / p_t = \mu dt + \sigma dz_t$ (beef price process p_t)

and $A_0 > 0$ and $I_0 = 0$ (initial conditions)

$A_t \geq 0$ and $S_t \geq 0$

where r is the time discount rate, and where a dot over a variable denotes the derivative of that variable with respect to time t. The equation of motion for land is determined by gross investments in land I_t as well as depreciation of land δ. The beef price evolves according to a geometric Brownian motion, where μ is the instantaneous drift parameter, σ is the instantaneous standard deviation, and dz_t is an increment to the standard Wiener process with mean zero and unit variance. The value function in Eq. (5.7) satisfies the following Bellman equation

$$rV(A_t, p_t) = \max_{I_t, S_t} \left[p_t Q(S_t, A_t) - p_S S_t - p_A A_t - C(I_t) + E_t\{dV\}/dt \right] \tag{5.8}$$

This optimality condition requires that, over an infinitely small time interval, the instantaneous net income plus the expected capital gain $E_t\{dV\}/dt$ equals the required return $rV(A_t, p_t)$. The expected capital gain $E_t\{dV\}$ is calculated using Ito's lemma and the constraints in Eq. (5.7) that describe the evolution of A_t and p_t, so that

$$E_t\{dV\}/dt = (I_t - \delta A_t)V_A + \mu p_t V_p + \tfrac{1}{2}\sigma^2 p_t^2 V_{pp} \qquad (5.9)$$

where $V_A = \partial V/\partial A$, $V_p = \partial V/\partial p$ and $V_{pp} = \partial^2 V/\partial p^2$. Substituting Eq. (5.9) into Eq. (5.8) yields the basic condition for the stochastic optimal control problem in Eq. (5.7)

$$rV(A_t, p_t) = \max_{I_t, S_t}\left[p_t Q(S_t, A_t) - p_S S_t - p_A A_t - C(I_t) + (I_t - \delta A_t)V_A + \mu p_t V_p + \tfrac{1}{2}\sigma^2 p_t^2 V_{pp}\right] \qquad (5.10)$$

Using Eq. (5.5) and (5.6), maximization of Eq. (5.10) with respect to I_t and S_t produces the *f.o.c.*'s

$$V_A = p_I + c_3 \beta I_t^{\beta-1} \qquad \text{or} \qquad I_t = \left(\frac{V_A - p_I}{c_3 \beta}\right)^{1/(\beta-1)} \qquad (5.11)$$

$$p_S = p_t\left(a + 2bS_t A_t^{-1}\right) \qquad \text{or} \qquad S_t = \frac{(p_S - p_t a)A_t}{2p_t b} \qquad (5.12)$$

Eq. (5.11) states that the optimal rate of investment is such that marginal valuation of land V_A is equal to the marginal cost of investment in land, *i.e.* the sum of purchase and adjustment costs. Eq. (5.12) says that the cattle rancher employs cattle up to the point where marginal costs equal marginal returns. Substitution of the optimal I_t and S_t back into Eq. (5.10) yields a second-order differential equation in A_t and p_t, which is given by

$$rV(A_t, p_t) = h(p_t)A_t + \left(V_A - p_I\right)^{\beta/(\beta-1)}\Gamma - \delta A_t V_A + \mu p_t V_p + \tfrac{1}{2}\sigma^2 p_t^2 V_{pp} \qquad (5.13)$$

where
$$h(p_t) = \frac{2p_S p_t a - p_t^2 a^2 - p_S^2 - 4p_A p_t b}{4p_t b}$$

$$\Gamma = \left(1/c_3\beta\right)^{1/(\beta-1)} - c_3\left(1/c_3\beta\right)^{\beta/(\beta-1)}$$

Note that V_A is the marginal valuation or shadow value of installed land, corresponding to Tobin's marginal q. To find an analytical solution of Eq. 5.13, we take $V(A_t, p_t)$ to be a linear function of the land stock A_t, so

$$V(A_t, p_t) = qA_t + g \qquad \text{with } q \equiv q(p_t) \text{ and } g \equiv g(p_t) \qquad (5.14)$$

where $q = V_A$ and g are functions to be determined. The value function is comprised of two additive parts (Abel and Eberly, 1997). The first part, qA_t, represents the value of existing land, and equals the expected present value of the returns to the existing land stock. The second part, g, represents the value of the adjustment technology, and equals the present value of the expected rents accruing to the adjustment technology as represented by the investment cost function $C(I_t)$ in Eq. (5.6). Subsequent substitution of Eq. (5.14) into Eq. (5.13) yields

$$\begin{aligned} rqA_t + rg = {} & h(p_t)A_t + (q - p_I)^{\beta/(\beta-1)}\Gamma - \delta A_t q \\ & + \mu p_t q_p A_t + \mu p_t g_p + \tfrac{1}{2}\sigma^2 p_t^2 q_{pp} A_t + \tfrac{1}{2}\sigma^2 p_t^2 g_{pp} \end{aligned} \qquad (5.15)$$

where $q_p = \partial q/\partial p$, $q_{pp} = \partial^2 q/\partial p^2$, $g_p = \partial g/\partial p$ and $g_{pp} = \partial^2 g/\partial p^2$, and which holds for all values of A_t. So, the term multiplying A_t on the *l.h.s.* must equal the sum of terms multiplying A_t on the *r.h.s.*, and, similarly, the term not involving A_t on the *l.h.s.* must equal the sum of terms not involving A_t on the *r.h.s.*. This produces

$$q_{pp} + \frac{2\mu\sigma^{-2}}{p_t} q_p - \frac{2(r+\delta)\sigma^{-2}}{p_t^2} q = \frac{\frac{1}{2}a^2 b^{-1}\sigma^{-2}}{p_t} + \frac{(2p_A - p_S a b^{-1})\sigma^{-2}}{p_t^2} + \frac{\frac{1}{2}p_S^2 b^{-1}\sigma^{-2}}{p_t^3} \qquad (5.16)$$

$$g_{pp} + \frac{2\mu\sigma^{-2}}{p_t} g_p - \frac{2r\sigma^{-2}}{p_t^2} g = \frac{-2\sigma^{-2}(q - p_I)^{\beta/(\beta-1)}\Gamma}{p_t^2} \qquad (5.17)$$

The marginal value of installed land $q(p_t)$ can be found by solving the differential Eq. (5.16), and an analytical expression for the rate of investment I_t by using Eq. (5.11). Similarly, the intercept term g can be determined through Eq. (5.16) and Eq. (5.17), and an analytical expression for the value of the farm $V(A_t, p_t)$ derived from Eq. (5.14). This chapter only focuses on investment decisions by cattle ranchers and therefore does not produce an analytical solution for the value of the farm.[33] A general solution to the marginal value of installed land $q(p_t)$ is given by

---

[33] For $\beta = 2$, the particular solution to Eq. (5.17) is

$$\begin{aligned} g(p_t) = {} & -\frac{a^4 p_t^2}{64b^2 c_3 (r - \mu + \delta)(-r + 2\mu + \sigma^2)} - \frac{a^2 (2p_I b(r+\delta) + 2p_A b - p_S a)p_t}{4b^2 c_3 (r+\delta)(r - \mu + \delta)(-r + \mu)} \\ & + \left(\frac{p_S^2 a^2}{8b^2 (r + \mu + \delta - \sigma^2)(r - \mu + \delta)} + \left(-p_I - \frac{2p_A b - p_S a}{b(r+\delta)} \right)^2 \right) \Big/ r4c_3 \\ & + \frac{p_S^2 (2p_I b(r+\delta) + 2p_A b - p_S a)}{16b^2 c_3 (r+\delta)(r + \mu + \delta - \sigma^2)(r + \mu - \sigma^2)p_t} + \frac{p_S^4}{64b^2 c_3 (r + \mu + \delta - \sigma^2)(r + 2\mu - 3\sigma^2)p_t^2} . \end{aligned}$$

$$q(p_t) = C_0 p_t^2 + C_1 p_t + C_2 + \frac{C_3}{p_t} \qquad (5.18)$$

Direct substitution verifies that the particular solution to Eq. (5.18) is given by

$$q(p_t) = \frac{-a^2 p_t}{4b(r+\delta-\mu)} + \frac{a p_S - 2 p_A b}{2b(r+\delta)} - \frac{p_S^2}{4b\left(r+\delta+\mu-\sigma^2\right)p_t} \qquad (5.19)$$

Abel and Eberly (1997) note that $q(p_t)$ represents the present value of expected marginal revenue products, which is independent of the specification of the adjustment cost function. The expression for $q(p_t)$ differs from the q in the deterministic setting derived in Chapter 4, in the sense that the shadow value of land now depends on the beef price level p_t at a specific moment in time t, the drift in beef prices μ, and the standard deviation in beef prices σ.

The optimal rate of investment I_t is now obtained through substitution of $q(p_t)$ (which is equal to V_A) back into Eq. (5.11), and for $\beta = 2$ is given by

$$I(p_t) = \frac{q(p_t) - p_I}{2c_3} = \frac{-a^2 p_t}{8bc_3(r+\delta-\mu)} + \frac{a p_S - 2 p_A b}{4bc_3(r+\delta)} - \frac{p_S^2}{8bc_3\left(r+\delta+\mu-\sigma^2\right)p_t} - \frac{p_I}{2c_3} \qquad (5.20)$$

In contrast with the constant rate of investment I_t derived in Chapter 4, the rate of investment in this case fluctuates over time according to the beef price process depicted in Eq. (5.7), and gross investment $I(p_t)$ is positive (negative) when the shadow price of land $q(p_t)$ is greater (smaller) than the purchase price of land p_I. A closed form solution for the expected rate of investment $E(I_t)$ can be derived by rewriting Eq. (5.20), so that

$$E[I_t] = E\left[\frac{q(p_t) - p_I}{2c_3}\right] = \frac{E[q(p_t)]}{2c_3} - \frac{p_I}{2c_3} \qquad (5.21)$$

Consequently, the expected shadow value of land $E[q(p_t)]$ needs to be determined. Given that the beef price p_t evolves according to a geometric Brownian motion, over a finite time interval t, the change in the logarithm of p is normally distributed with mean $(\mu - \frac{1}{2}\sigma^2)t$ and variance $\sigma^2 t$ (Dixit and Pindyck, 1994). The expected value of p_t is given by

$$E[p_t] = p_0 e^{\mu t} \qquad (5.22)$$

where p_0 is the beef price in $t = 0$, and where μ is the drift in beef prices. The expected beef price increases (decreases) over time in an exponential fashion towards infinity (zero) in the case of $\mu > 0$ ($\mu < 0$). Substitution of Eq. (5.22) back into Eq. (5.19) yields the closed form solution for the expected shadow value of land $E[q(p_t)]$, which is approximated by

$$E\left[q(p_t)\right] = \frac{-a^2}{4b(r+\delta-\mu)} p_0 e^{\mu t} + \frac{ap_S - 2p_A b}{2b(r+\delta)} - \frac{p_S^2}{4b\left(r+\delta+\mu-\sigma^2\right)} \frac{1}{p_0 e^{\mu t}} \tag{5.23}$$

This approximation underestimates the exact $E[q(p_t)]$, as the last term on the *r.h.s.* is underestimated, given the expected positive sign of the parameters (only $b < 0$). This is an implication of Jensen's inequality (Dixit and Pindyck, 1994), which states that if p_t is a random variable and $f(p_t)$ is a convex function of p_t then $E[f(p_t)] > f(E[p_t])$. Note that the last term on the *r.h.s.* in Eq. (5.19) is convex in p_t given that only $b < 0$.

Subsequent substitution of Eq. (5.23) back into Eq. (5.21) yields the closed form solution for the expected rate of investment $E(I_t)$, which is given by

$$E\left[I_t\right] = \frac{-a^2 p_t}{8bc_3(r+\delta-\mu)} p_0 e^{\mu t} + \frac{ap_S - 2p_A b}{4bc_3(r+\delta)} - \frac{p_S^2}{8bc_3\left(r+\delta+\mu-\sigma^2\right)p_t} \frac{1}{p_0 e^{\mu t}} - \frac{p_I}{2c_3} \tag{5.24}$$

Given the expected positive sign of the parameters (only $b < 0$), the behavior of the investment function $E[I_t]$ with respect to μ and σ can be determined. The behavior of the investment function with respect to μ is relatively complex, due to the existence of asymptotes at ($\sigma^2 - r - \delta$) and ($r + \delta$). When only considering the part of the investment function that is relevant for this study, the rate of investment is revealed as continuous, convex and increasing in μ for $(\sigma^2 - r) < \mu < (r + \delta)$. Similarly, the behavior of the investment function with respect to σ is relatively complex, owing to the existence of an asymptote at $(r + \delta + \mu)^{1/2}$. When, again, considering only the relevant part of the investment function, the rate of investment is revealed as continuous, convex and increasing in σ for $0 < \sigma < (r + \delta + \mu)^{1/2}$.

Comparison of the deterministic model with constant beef prices (see Chapter 4) and the presented model with stochastic beef prices shows that the expected rate of investment in the stochastic case is larger than the rate of investment in the deterministic case for $0 < \mu < (r + \delta)$, and smaller for $(\sigma^2 - r) < \mu < 0$. In addition, the expected rate of investment in the stochastic case exceeds the rate of investment in the deterministic case for $0 < \sigma < (r + \delta + \mu)^{1/2}$. Finally, the rate of investment in the stochastic case is identical to the rate of investment in the deterministic case for $\mu = \sigma = 0$.

By using the equation of motion for land given in Eq. (5.7), the land stock path A_t now becomes a stochastic process defined as

$$A(p_t) = e^{-\delta t}\left(C + \int I(p_t)e^{\delta t}\,dt\right) \qquad (5.25)$$

where C is an arbitrary constant that can be obtained using the initial condition A_0. It is clear from Eq. (5.25) that a higher rate of investment I_t leads to a larger land stock A_t. Further substitution of A_t in Eq. (5.12) and (5.5) yields the cattle stock S_t, beef production Q_t and the stocking rate SR_t. Note that S_t, Q_t and SR_t are stochastic processes, as they are functions of the beef price p_t.

5.4 Model results

We now present a numerical application of the model with uncertainty in beef prices (see Section 5.3) for the case of Costa Rica. A comparative static sensitivity analysis is performed, to analyze the effect of various drifts as well as fluctuations in beef prices on optimal investment decisions by an average beef cattle rancher in the AZ of Costa Rica. In both cases, results are generated for a number of beef price levels.

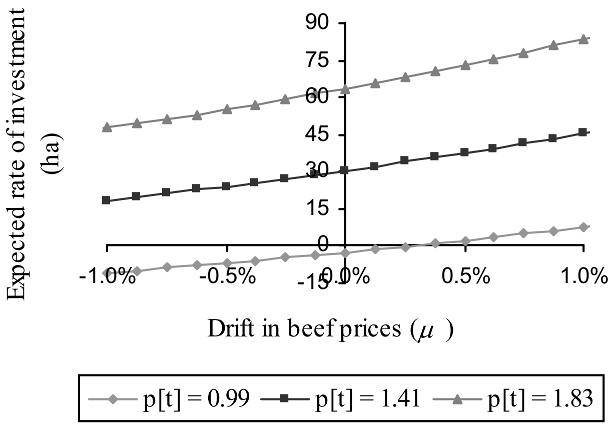
Model results are obtained on the basis of 1995 data. The base price of beef (p_0 = 1.41 US\$ kg^{-1}), the price of cattle and cattle maintenance (p_S = 213.2 US\$ AU^{-1}), and the price of pasture maintenance (p_A = 55.0 US\$ ha^{-1}) are obtained from the PASTOR system (Bouman *et al.*, 1998). Drift and standard deviation in real beef prices over the period 1961 to 1999 are determined in Section 5.2 ($\mu = -0.0083$ and $\sigma = 0.1812$). The price of land with road access, poor soil drainage and no further facilities in the AZ (p_I = 630.0 US\$ ha^{-1}) is obtained from the *Dirección de Tributación Directa* of the Ministry of Housing (see Chapter 4). The constant rate of land depreciation is set at $\delta = 0.10$, in line with Faminow (1998) and Bulte *et al.* (2000), who state that pasture-land is abandoned or needs to be recuperated 7 to 12 years after pasture establishment. Quadratic adjustment costs related to investment in land are determined on the basis of secondary data regarding labor supply, costs and requirements (see Chapter 4), thereby assuming that 25% of all beef cattle ranchers in the AZ invest simultaneously ($c_3 = 6.684$ and $\beta = 2$). The time discount rate (r = 6.9% yr^{-1}) and the official 1995 exchange rate (179.73 Colones US\$$^{-1}$) are obtained from the World Development Indicators (World Bank, 1999). The time discount rate is calculated as the geometric mean of the real interest rates over the period 1984 to 1997. Production function parameter estimates for pasture-based beef production on poorly drained soil types in the AZ of Costa Rica ($a = 354.3$ and $b = -70.9$) are determined on the basis of technical input-output coefficients generated by the PASTOR system (see Chapter 4).

5.4.1 Drifts in beef prices

When evaluating the effect of various drifts in beef prices μ as well as levels of beef prices p_t on the optimal rate of investment of an average beef cattle ranch in the AZ of Costa Rica, the standard deviation in beef prices σ is held constant at 18.1% yr^{-1}. Figure 5.3 shows the optimal rate of investment for various levels of μ and p_t. Drifts in beef prices range from –1% yr^{-1} to +1% yr^{-1} and levels of beef prices are given for 70%, 100% and 130% of the base beef price.

The expected rate of investment is positively related to the drift in beef prices and the level of beef prices. The relation between the expected rate of investment and the drift in beef prices is positive because the expected beef price $E[p_t]$ increases with the drift in beef prices μ (see Eq. 5.22), in turn, the expected shadow value of land $E[q(p_t)]$ is increasing in the expected beef price (see Eq. 5.23), and, finally, the expected rate of investment $E[I_t]$ is increasing in the expected shadow value of land (see Eq. 5.21 and 5.24). The same line of reasoning holds for the positive relation between the expected rate of investment and the beef price level, as the expected beef price $E[p_t]$ is increasing in the base beef price p_0.

Figure 5.3 **Expected rate of investment for various drifts in beef prices μ and beef prices p_t**



The numerical example in Figure 5.3 shows that the expected rate of investment is overestimated with more than one third, if beef prices are assumed constant instead of decreasing with 0.8% yr^{-1}. Furthermore, Figure 5.3 shows that a 30% increase in beef prices (*i.e.* from p_0 = 1.41 kg^{-1} to p_0 = 1.83 kg^{-1}) leads to a 150% increase in the expected rate of investment. Finally, the expected rate of investment becomes negative for large negative drifts in beef prices μ and/or low levels of base beef prices p_0.

The following conclusions can be drawn from these results. First, the expected rate of investment is overestimated (underestimated) if beef prices are assumed constant over time, while they actually tend to decrease (increase) over time. Second, the expected rate of investment can become negative if beef price levels are sufficiently low and when beef prices are expected to decrease sufficiently rapidly over time, as current and future beef prices do not provide sufficient present and future returns, respectively, to purchase land for pasture-based beef production. Finally, the expected rate of investment can be positive even when beef prices are expected to decrease over time, as current and near-future beef prices provide sufficient present and future returns, respectively, to purchase land for beef production.

5.4.2 Fluctuations in beef prices

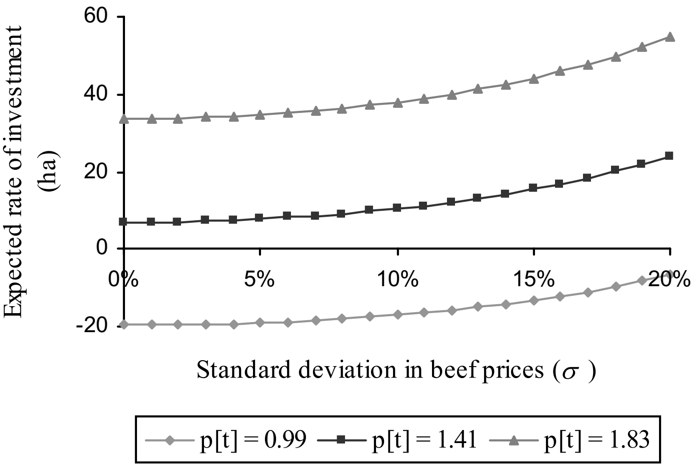
When evaluating the effect of various fluctuations in beef prices σ as well as levels of beef prices p_t on the optimal rate of investment of an average beef cattle ranch in the AZ of Costa Rica, the drift in beef prices μ is held constant at –0.8% yr^{-1}. Figure 5.4 shows the optimal rate of investment for various levels of σ and p_t.

Standard deviations in beef prices range from 0% yr^{-1} to 20% yr^{-1} and levels of beef prices are given for 70%, 100% and 130% of the base beef price.

The expected rate of investment is positively related to the standard deviation in beef prices and, not surprisingly and like before, the level of beef prices. The positive relation between the expected rate of investment and the standard deviation in beef prices is, however, less intuitive. Yet, examination of Eq. (5.23) shows that the expected shadow value of land $E[q(p_t)]$ is increasing in the standard deviation in beef prices σ, and, again, from Eq. (5.21) and (5.24), it follows that the expected rate of investment $E[I_t]$ is increasing in the expected shadow value of land.

The numerical example given in Figure 5.4 shows that the expected rate of investment is almost three times underestimated, in the case that beef prices are assumed constant instead of fluctuating with 18.1% yr^{-1}. As Figure 5.3, also Figure 5.4 shows that a 30% increase in beef prices leads to a 150% increase in the expected rate of investment. Finally, the expected rate of investment becomes negative for low standard deviations in beef prices σ and/or levels of base beef price p_0.

Figure 5.4 **Expected rate of investment for various standard deviations in beef prices σ and beef prices p_t**



A number of conclusions can be drawn from these results. First, the expected rate of investment is underestimated if beef prices are assumed constant over time, while they actually tend to fluctuate over time. Second, the expected rate of investment can become negative in the case that beef price levels are sufficiently low and when fluctuations in beef prices are sufficiently small, as current beef price levels and expected fluctuations in beef prices do not provide sufficient present and future as well as speculative returns, respectively, to purchase land for pasture-based beef production. Finally, the expected rate of investment can be positive even when beef prices are low, as fluctuations in beef prices provide sufficient speculative returns to purchase land for beef production.

5.5 Conclusions

On the basis of the deterministic model developed in Chapter 4, we developed a stochastic reversible investment model with adjustment costs in which beef prices are modeled as a geometric Brownian motion. This model provides insight in the effect of decreasing and fluctuating beef prices on investment decisions by cattle ranchers in Latin America. This is a particularly important issue given the general decrease in Latin American beef prices over the past decades, and the subsequent belief that cattle ranching is not profitable in the absence of speculative returns from land and government subsidies (*e.g.* Edelman, 1985; Hecht *et al*., 1988; Jarquín, 1990; Van der Kamp, 1990; Mattos and Uhl, 1994). Nevertheless, cattle ranching in Latin America has grown considerably since the 1960's, which is, amongst others (see Chapter 2), caused by the increased Latin American demand for beef products in general (Seré and Jarvis, 1992; Kaimowitz, 1996; Faminow, 1998) and the increased local demand for beef products in particular (Faminow, 1997). This chapter has shown, however, that cattle ranchers base their investment decisions not only on current beef prices (*i.e.* present returns) but also on expected drifts and fluctuations in beef prices (*i.e.* future and speculative returns, respectively).

The analytical results indicate that the expected shadow value of land is increasing in the level, drift and standard deviation in beef prices, due to larger present, future and speculative returns from beef production, respectively. The expected rate of investment is also increasing in the level, drift and standard deviation in beef prices, as the expected rate of investment is determined by comparison of the expected shadow value of land and the marginal investment costs of land.

The numerical results provide some interesting additional information regarding the effect of drifts and fluctuations in beef prices on investment decisions by an average beef cattle rancher in the Atlantic Zone (AZ) of Costa Rica. First, the expected rate of investment is underestimated (overestimated) if beef prices are assumed constant over time, while they actually tend to increase (decrease) or fluctuate over time. Second, the expected rate of investment can be negative when beef prices and subsequent present returns are too low. Sufficiently large expected drifts and fluctuations in beef prices, however, provide the economic incentive (*i.e.* future and speculative returns) to turn these negative investments into positive investments. Put differently, the expected rate of investment may be positive even when deterministic economic analysis (*i.e.*, which assumes all prices constant over time) indicates that beef prices are too low to purchase land for beef production. Finally, the rate of investment can be positive even when beef prices are expected to decrease over time. Sufficiently high current beef price levels and sufficiently large fluctuations in beef prices provide the economic incentive (*i.e.* present, future and speculative returns) to purchase land for beef production.

Summarizing, the expected rate of investment turns out to be inflated due to positive expected drifts and fluctuations in beef prices, with subsequent consequences for deforestation of agrarian frontier forest areas. Note, however, that future and speculative returns from expected drifts and fluctuations in beef prices, respectively, will only be fully achieved if the cattle rancher responds directly and adequately towards changes in beef prices. In practice, it can be expected that the cattle rancher will not take full advantage from the potential speculative returns, as beef price information is often not directly available and because timely adjustment of the pasture area and cattle stock would require continuous and rigorous management by the cattle rancher. Given that cattle ranchers are described as well-off professionals, businessmen or government officials (Kaimowitz, 1996), it is likely that the investment behavior of cattle ranchers would not be as sensitive towards fluctuations in beef prices.

Future research needs to address a number of topics not dealt with in this chapter (see Chapter 4). First, the approach presented here is of a partial equilibrium nature. Second, uncertainty in land prices and interest rates has not been taken into account (see Chapter 6). Third, in this approach, resource degradation was modeled artificially (see Chapter 7). Fourth, the model does not allow for the possibility to sell beef cattle at a lower or higher age in response to changed beef prices. Finally, externalities related to deforestation have not been taken into account.

6 Land speculation, interest rate subsidies and investment decisions

6.1 Introduction

Land speculation by cattle ranchers is often considered the principal cause of deforestation in Latin America, especially in combination with interest rate subsidies that were widely provided to cattle ranchers in the 1980's and 1990's (*e.g.* Hecht *et al*., 1988; Van Hijfte, 1989; Hecht, 1992; Kaimowitz, 1996; Smith *et al*, 1997; Faminow, 1998). Cattle ranching is viewed as the easiest vehicle to secure the land while waiting for land prices to rise and, at the same time, it also provides economic returns in the form of beef production (Hecht, 1992; Faminow, 1998). Therefore, it is argued, cattle ranchers hold more pasture-land for beef production than what would be optimal from a productive point of view (Kaimowitz, 1996; Jansen *et al*, 1997; Smith *et al*, 1997).

Proof for the hypothesis that land speculation leads to inflated levels of investment in land is, however, relatively limited and invariably related to the question whether land prices tend to rise over time. Fearnside (1990), Diegues (1992) and Kaimowitz (1996), for example, claim that real land prices have risen over the last decades due to infrastructure development, favorable livestock product prices during the 1960's and 1970's, population growth, and urbanization. Faminow (1998), on the other hand, states that empirical evidence is extremely limited, and shows that annual rates of return to land speculation in the Brazilian Amazon exceed the opportunity cost of capital to a limited extent and in only a small number of cases.

Speculators are, however, mostly interested in short-term gains that can be obtained through the purchase and sale of commodities of which the price changes rapidly (Pass *et al*., 2000). Consequently, this chapter not only examines the effect of expected growth rates in land prices, but also the effect of expected fluctuations in land prices and interest rate subsidies on investment decisions by cattle ranchers in Latin America. Based on the deterministic investment model with adjustment costs developed in Chapter 4, a stochastic reversible investment model is developed in which land prices are modeled as a geometric Brownian motion. The model is solved analytically for the case of quadratic as well as exponential investment costs, and a numerical example of the model is given for cattle ranchers in the Atlantic Zone (AZ) of Costa Rica on the basis of 1995 data. Model simulations are presented for varying levels of growth rates (drift) and fluctuations (standard deviation) in land prices, as well as varying levels of interest rate subsidy.

The chapter is structured as follows. Section 6.2 provides a discussion on the development in real land prices and interest rates in Costa Rica during the past decades, and is followed by an empirical determination of the stochastic process underlying the development in land prices, thereby correcting for fluctuations in interest rates. Section 6.3 presents the development of the stochastic reversible investment model with quadratic as well as exponential investment costs for cattle ranchers and in which land prices are modeled as a geometric Brownian motion. Section 6.4 provides a numerical application of the stochastic model with exponential investment costs to the case of Costa Rica. A comparative static sensitivity analysis with respect to drifts and fluctuations in land prices for different interest rates is performed, and results are analyzed. Finally, Section 6.5 offers concluding remarks and observations.

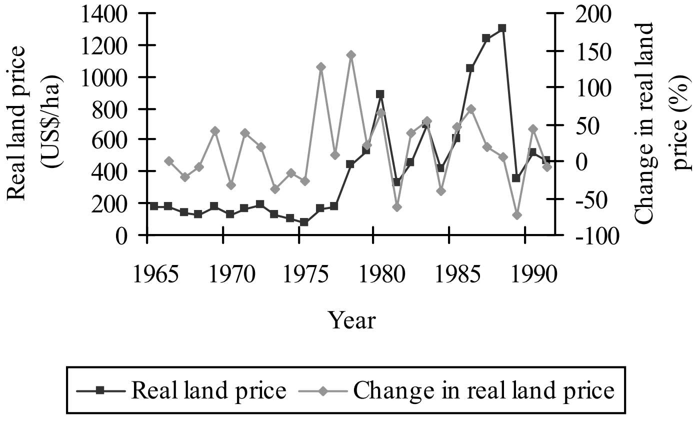
6.2 The development of land prices and interest rates in Costa Rica

This section starts with an overview of the debate on the development of real land prices in Latin America in general, and in the AZ of Costa Rica in particular. Next is a discussion of the development of real interest rates in Costa Rica over the 1980's and 1990's, while giving special attention to interest rates subsidies that were provided to specific sectors in the economy. This is followed by a test whether real land prices (corrected for fluctuations in interest rates) follow a geometric Brownian motion, and the appropriate parameter values are calculated for the numerical application of the model in Section 6.4.

6.2.1 Land prices

The development of land prices in Latin American agrarian frontier areas is an important issue of debate in the literature. Kaimowitz (1996), for example, argues that real land prices in Central America have risen considerably over the past decades, for a number of reasons. First, real land prices rose at a rate greater than or equal to the opportunity cost of capital due to infrastructure development, favorable livestock product prices during the 1960's and 1970's, as well as population growth and urbanization. Second, Kaimowitz states, deforested lands usually sell at a much higher price than forested lands. Faminow (1998), on the other hand, is of the opinion that real land prices did not rise at all. He shows that annual rates of returns to land speculation in the Brazilian Amazon were greater than the opportunity cost of capital in only 32% of the cases and even negative in 34% of the cases. For some years, however, he found annual rates of return that highly exceeded the opportunity costs of capital.

Figure 6.1 **Land prices in the AZ of Costa Rica: levels and changes over the period 1965 - 1991**



Source: Instituto de Desarrollo Agrícola (IDA).

Although there are no published data on land transactions and land prices in Costa Rica, the Institute of Agricultural Development (IDA), which was concerned with the registration, distribution and sale of land, (fortunately) also maintained a database of land transactions during the period 1965 to 1991. On the basis of these data, real land prices as well as the annual change in real land prices over the period 1965 to 1991 could be determined (see Figure 6.1).[34]

It is clear from Figure 6.1 that the real land prices varied considerably over time, while there is no visually evident general trend in land prices. Three distinct periods of changes in real land prices can, however, be identified. Till 1975, land prices were relatively low (on average 138 US$ ha^{-1}), decreasing (about 5% yr^{-1}) and stable (standard deviation of about 28% yr^{-1}). Land in agrarian frontier forest areas was abundantly available, and the Costa Rican government not only permitted but also actively promoted the privatization of these national forest lands (Kaimowitz, 1996). The period 1976 to 1979 can be considered as a transition period, in which land prices rose rapidly (over 70% yr^{-1}) and were elevated to a higher plane. The Costa Rican government started to play an active role in the protection of natural resources, through the establishment of natural parks and stricter control on deforestation in agrarian frontier forest areas (Salas *et al.*, 1983). Since 1980, land prices were relatively high (on average 690 US$ ha^{-1}), increasing (about 13% yr^{-1}) and unstable (standard deviation of about 50% yr^{-1}). This was not only a result of the government role in natural resource protection, but also of the rapid infrastructure development in the AZ. For example, between 1986 and 1988 a major highway was constructed that connects the capital (San José) with the major export harbor (Limón) and that passes right through the middle of the AZ (Nieuwenhuyse *et al.*, 2000).[35]

6.2.2 Interest rates

Figure 6.2 shows the development of real interest rates in Costa Rica over the period 1982 to 1997. There was a clear fluctuation in real interest rates, which were even negative at the beginning of the 1980's. Economic growth in Costa Rica, which was mainly agriculturally driven, slowed at the end of the 1970's due to a decrease in the growth of agricultural production (Nieuwenhuyse *et al.*, 2000). This resulted in an economic crisis at the beginning of the 1980's, with subsequent high levels of inflation (up to 90% in 1982) and currency depreciation (up to 130% in 1981, relative to the US$). Consequently, structural adjustment programs were developed that aimed at lowering the inflation, balancing the fiscal and external accounts, lowering trade barriers, as well as on reforming the financial and state sector (Nieuwenhuyse *et al.*, 2000).

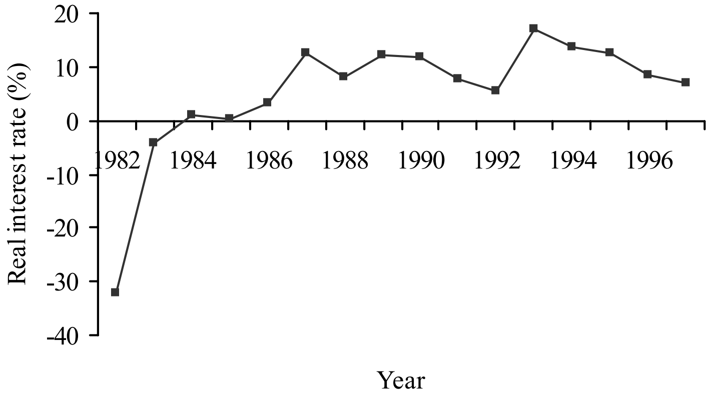
The gradual implementation of structural adjustment programs led to a relative stabilization of real interest rates, with a geometric mean of about 6.9% per year since 1984. However, the fluctuations in real interest rates remained relatively large. From 1993 to 1995, for example, the real interest rate was about 8% points above the average since 1984, leading to a reduction in investment combined with a contraction in consumption. This recession was (at least partially) caused by a government bailout of depositors associated with a major bank that collapsed in 1994 (Nieuwenhuyse *et al.*, 2000).

---

[34] Real land prices as calculated by using the 1995 consumer price index (World Bank, 1999).

[35] Note that at the end of the 1980's, also the "FODEA" law was passed, which canceled certain debts, provided longer payback periods, and lowered interest rates on past debts provided to, especially, cattle ranchers (Van Hijfte, 1989).

Figure 6.2 Real interest rates in Costa Rica over the period 1982 - 1997



Source: World Bank development indicators (1999).

Political support for the livestock industry in Latin America in the 1970's was reflected in the terms and availability of livestock credit (Kaimowitz, 1996; Faminow, 1998). Livestock credit provided in this period was heavily subsidized, went mostly to cattle ranchers, and was allocated to a relatively small group of cattle ranchers. Figure 6.3 shows the percentage difference in real interest rates charged on livestock and agricultural credit, in comparison to the national average credit interest rate over the period 1984 to 1996.[36] These data confirm the belief that real interest rates for livestock credit were subsidized in the past. Especially before 1992, interest rates on livestock and, to a minor extent, agricultural credit were well below the national average. Interest rates charged on livestock and agricultural credit were, respectively, 0.7% and 0.3% below the national average, with a peak in 1985 when the livestock and agricultural interest rate were, respectively, 2.7% and 1.4% below the national average. Comparison of the livestock and agricultural interest rates shows that the interest rate charged on livestock credit was, on average, 0.4% below the agricultural interest rate, with a peak of 1.3% in 1985 and 1995.

During the decade before the economic crisis at the beginning of the 1980's, livestock credit subsidies were even larger than those reported in Figure 6.3. Kaimowitz (1996), who refers to an unpublished report by Aguilar and Solís (1988), show that real interest rates for livestock credit were even negative between 1970 and 1983. After the economic crisis at the beginning of the 1980's, the gradual implementation of structural adjustment programs led to a reduction in the deviation of livestock and agricultural interest rates from the national average (see Figure 6.3). Put differently, public livestock credit has become less available and less subsidized since 1985.

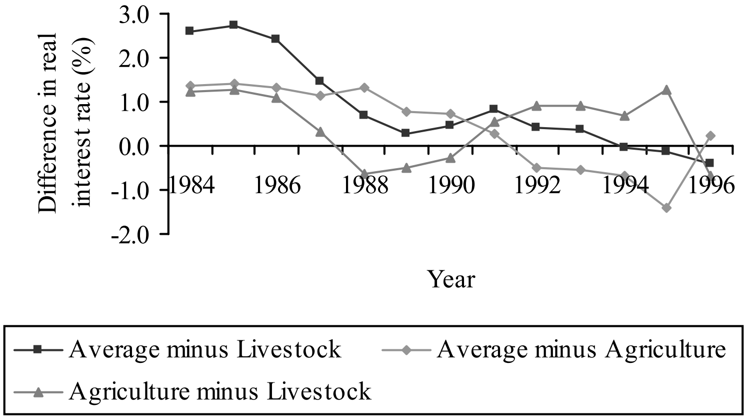
Subsidized livestock credit promoted cattle ranching in a number of ways (Kaimowitz, 1996; Faminow, 1998). First, credit helped cattle ranchers to overcome credit constraints which otherwise would have limited pasture and herd expansion. Second, credit subsidies made cattle ranching a relatively attractive

---

[36] The national average real interest rate includes the agricultural, livestock, construction, housing, and other sectors.

investment option. Finally, credit facilitated the transfer of cattle between ranchers. Hence, credit subsidies led to an allocation of scarce capital away from investments with higher returns, thereby reducing welfare.

Figure 6.3 **Percentage difference in real interest rates for livestock and agricultural credit compared to the national average over the period 1984 - 1996**



Source: Banco Nacional de Costa Rica (BNCR).

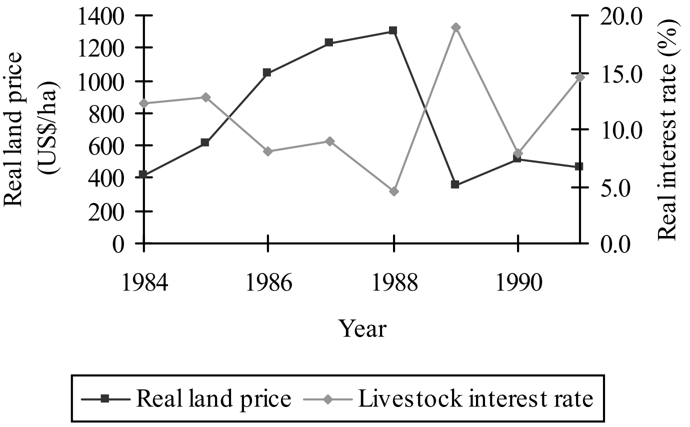
The role of subsidized livestock credit in the conversion of forest to pasture should, however, not be overstated. In his study on the impact of livestock credit on deforestation in Panama, Ledec (1992) demonstrates that less than 10% of deforestation could be attributed to livestock credit, that most of this deforestation took place in small forested areas outside the agricultural frontier, and that banks preferred to provide credit to large established cattle ranchers rather than to relatively small colonist cattle ranchers. Hence, livestock credit subsidies explain only part of the expansion of cattle ranching and subsequent deforestation in Latin America.

6.2.3 Relation between land prices and interest rates

Real land prices and real interest rates fluctuate strongly over time, as can be observed from Figure 6.1 and 6.2, respectively. According to the macro-economic theory, an increase in prices leads to a decrease in the interest rate, and *vice versa* (Branson, 1989). When real prices increase, real money supply decreases, an excess demand in the money market is created, and, for the money market to clear, the interest rate must increase given a certain income level.

Figure 6.4 displays the development of real land prices and livestock interest rates in Costa Rica for the period 1984 to 1991 – the longest period for which land prices and livestock interest rates were available for Costa Rica. It is clear from the figure that high land prices were accompanied by low interest rates, and *vice versa*. During the same period, fluctuations in beef and, especially, input prices were relatively low and mostly determined on the world market,[37] while labor costs for cattle and pasture maintenance were relatively low compared to other costs as a result of the labor extensive character of cattle ranching (Kaimowitz, 1996). Consequently, it is sufficient to correct the development in real land prices for fluctuations in real interest rates.

Figure 6.4 **Real land prices and livestock interest rates in Costa Rica over the period 1984 - 1991**



Source: Real land prices from the Instituto de Desarrollo Agrícola (IDA), and real interest rates from the Banco Nacional de Costa Rica (BNCR).

Section 6.3 develops a continuous time model of a competitive cattle ranch that buys and sells land at an exogenously given land price $p_{I,t}$. It assumed that land prices evolve according to a *geometric Brownian motion*,[38] which is given by

$$dp_{I,t} / p_{I,t} = \mu dt + \sigma dz \qquad (6.1)$$

where μ is the instantaneous drift, σ is the instantaneous standard deviation, and where dz is a Wiener process with mean zero and unit variance. To determine the development in real land prices while correcting for fluctuations in interest rates, the rental cost of land K_t needs to be calculated for the period 1984 to 1991.[39] Parameter values for drift and standard deviation in the rental costs of land reflect the net drift and standard deviation in land prices if interest rates are held constant. First, however, it must be tested whether the rental costs of land follows a geometric Brownian motion.

---

[37] Drift and standard deviation in real beef export prices in Costa Rica over the period 1961 to 1999, are about –0.8% and 18.1% per year, respectively (see Chapter 5).

[38] Geometric Brownian motion is generally used to model economic and financial variables (Dixit and Pindyck, 1994). Given the occurrence of a jump in real land prices over the period 1976 to 1979, it might have been more realistic to model land prices as a Poisson process. The available data on real land prices, however, do not permit an accurate estimation of the mean arrival time and size of the jump in real land prices.

[39] The rental cost of land is the interest payment on the value of land. So, $K_t = r_t * p_{I,t}$ where r_t is the livestock interest rate.

With annual rental costs of land data K_t, one can test whether $k_t = \ln(K_t)$ are consistent with Brownian motion, and, via Itô's Lemma, that K_t is consistent with geometric Brownian motion (see for example Conrad, 1997). To test that k_t is consistent with Brownian motion requires the running of the unrestricted regression

$$(k_t - k_{t-1}) = \phi + \varphi t + (\gamma - 1)k_{t-1} + \eta(k_{t-1} - k_{t-2}) + \varepsilon_t \tag{6.2}$$

and the restricted regression

$$(k_t - k_{t-1}) = \phi + \eta(k_{t-1} - k_{t-2}) + \varepsilon_t \tag{6.3}$$

The null hypothesis is that k_t follows Brownian motion, or H_0: $\varphi = 0$, $\gamma = 1$. Regression results of the unrestricted and restricted models, as shown in Table 6.1, are used to calculate the F-statistic. The null hypothesis that k_t follows Brownian motion cannot be rejected, as the F-statistic is well below the Dickey-Fuller critical F^*-value at the 5% level for a sample size smaller than 25 ($F = 3.25 < F^* = 7.24$). K_t is therefore consistent with geometric Brownian motion.

Table 6.1 Estimation results for unrestricted and restricted regression models for the rental costs of land

	Unrestricted		Restricted	
	Estimate	*t*-stat.	Estimate	*t*-stat.
Coefficients				
ϕ	455.769	2.202	-0.048	-0.277
φ	-0.226	-2.187		
$(\gamma - 1)$	-1.384	-2.131		
η	-0.385	-0.792	-0.576	-1.320
Sum of squared residuals (SSR)	0.167		0.708	
Number of observations	8		8	

Next comes estimating the mean m and standard deviation s of the series $\ln(K_{t+1}/K_t)$. These are found to be equal to $m = 0.0396$ and $s = 0.4457$, implying that $\mu = m + ½s^2 = 0.1389$ and $\sigma = s = 0.4457$.[40] For the numerical example given in Section 6.4, we will use these parameter values for drift and standard deviation in the rental cost of land, as they reflect the net drift and standard deviation in real land prices in the case where interest rates are held constant.

---

[40] We applied the same procedure to the real land prices for the period 1965 to 1991, shown in Figure 6.1. Results indicate that $p_{l,t}$ is consistent with geometric Brownian motion ($F = 3.25 < F^* = 7.24$, at the 5% level for a sample size smaller than 25), and that the drift in real land prices $\mu = 0.1648$ and the standard deviation $\sigma = 0.5029$.

6.3 Model specification

Based on the deterministic investment model presented in Chapter 4, a stochastic reversible investment model for cattle ranchers is developed in which land prices are modeled as a geometric Brownian motion. There are two different versions of this model, one in which investment costs are assumed quadratic (and thus symmetric) in the rate of investment (Section 6.3.1), and the other in which investment costs are assumed exponential (and thus non-symmetric) in the rate of investment (Section 6.3.2). It is shown that the form of the investment cost function determines whether (and to what extent) uncertainty in land prices affects investment decisions by cattle ranchers. For both versions of the model, reduced form equations for the expected rate of investment are derived analytically.

6.3.1 The stochastic model with uncertainty in land prices and quadratic investment costs

The model presented in this section is a stochastic version of the deterministic model of Chapter 4, in which investment costs are quadratic in the rate of investment and where land prices follow a process of geometric Brownian motion. The cattle rancher uses cattle S_t and land A_t to produce beef according to a production function $Q(S_t, A_t)$ that is quadratic in the stocking rate S_t/A_t, while assuming constant returns to scale. The rancher undertakes gross investment I_t, while facing convex increasing investment costs $C(I_t, p_{I,t})$. The annual net income stream π_t is

$$\pi(S_t, A_t, I_t) = pQ(S_t, A_t) - p_S S_t - p_A A_t - C(I_t, p_{I,t}) \qquad (6.4)$$

with $$Q(S_t, A_t) = A_t Q_A(SR_t) = aS_t + bS_t^2 A_t^{-1} \quad \text{where } SR_t = S_t/A_t,\ a > 0 \text{ and } b < 0 \qquad (6.5)$$

$$C(I_t, p_{I,t}) = p_{I,t} I_t + c_3 I_t^{\beta} \quad \text{where } \beta = n/(n-1) \text{ and } n \in \{2, 4, 6, \ldots\} \qquad (6.6)$$

and where p represents the beef price, p_S is the price of cattle purchase and maintenance, p_A is the price of pasture maintenance, $p_{I,t}$ is the price of land, c_3 is the adjustment cost scale parameter, and where β is the adjustment cost elasticity. The farm maximizes the present value of net income streams over time, subject to the equation of motion for land and the land price process over time. The optimization problem is formulated as follows

Maximize $$V(A_0, p_{I,0}) = \max_{I_t, S_t} E_t \left\{ \int_0^{\infty} [\pi_t] e^{-rt} dt \right\} \qquad (6.7)$$

subject to $\dot{A}_t = I_t - \delta A_t$ (equation of motion for A_t)

$dp_{I,t} / p_{I,t} = \mu dt + \sigma dz$ (land price process $p_{I,t}$)

and $A_0 > 0$ and $I_0 = 0$ (initial conditions)

$A_t \geq 0$ and $S_t \geq 0$

where r is the time discount rate, and where a dot over a variable denotes the derivative of that variable with respect to t. The equation of motion for land is determined by gross investments in land I_t as well as depreciation of land δ. The land price evolves according to a geometric Brownian motion, where μ is the instantaneous drift parameter, σ is the instantaneous standard deviation, and dz is an increment to the standard Wiener process with mean zero and unit variance. The value function in Eq. (6.7) satisfies the following Bellman equation

$$rV(A_t, p_{I,t}) = \max_{I_t, S_t}\left[pQ(S_t, A_t) - p_S S_t - p_A A_t - C(I_t, p_{I,t}) + E_t\{dV\}/dt\right] \qquad (6.8)$$

The optimality condition requires that, over an infinitely small time interval, the instantaneous net income plus the expected capital gain $E_t\{dV\}/dt$ equals the required return $rV(A_t, p_{I,t})$. The expected capital gain $E_t\{dV\}$ is calculated using Ito's lemma and the constraints in Eq. (6.7) that describe the evolution of A_t and $p_{I,t}$, so that

$$E_t\{dV\}/dt = (I_t - \delta A_t)V_A + \mu p_{I,t}V_{p_I} + \tfrac{1}{2}\sigma^2 p_{I,t}^2 V_{p_I p_I} \qquad (6.9)$$

where $V_A = \partial V/\partial A$, $V_{p_I} = \partial V/\partial p_I$ and $V_{p_I p_I} = \partial^2 V/\partial p_I^2$. Substituting Eq. (6.9) into Eq. (6.8) yields

$$rV(A_t, p_{I,t}) = \max_{I_t, S_t}\left[pQ(S_t, A_t) - p_S S_t - p_A A_t - C(I_t, p_{I,t}) + (I_t - \delta A_t)V_A + \mu p_{I,t}V_{p_I} + \tfrac{1}{2}\sigma^2 p_{I,t}^2 V_{p_I p_I}\right] \qquad (6.10)$$

Using Eq. (6.5) and (6.6), maximization of Eq. (6.10) with respect to I_t and S_t produces the *f.o.c.*'s

$$V_A = p_{I,t} + c_3\beta I_t^{\beta-1} \qquad \text{or} \qquad I_t = \left(\frac{V_A - p_{I,t}}{c_3\beta}\right)^{1/(\beta-1)} \qquad (6.11)$$

$$p_S = p\left(a + 2bS_t A_t^{-1}\right) \qquad \text{or} \qquad S_t = \frac{(p_S - pa)A_t}{2pb} \qquad (6.12)$$

which are identical to the first-order conditions in the deterministic case (see Chapter 4). However, the rate of investment I_t is now a stochastic process. Substitution of Eq. (6.11) and (6.12) into Eq. (6.10) yields

$$rV(A_t, p_{I,t}) = (h - \delta V_A)A_t + \left(V_A - p_{I,t}\right)^{\beta/(\beta-1)}\Gamma + \mu p_{I,t}V_{p_I} + \tfrac{1}{2}\sigma^2 p_{I,t}^2 V_{p_I p_I} \qquad (6.13)$$

where $$h = \frac{2p_S pa - p^2a^2 - p_S^2 - 4p_A pb}{4pb}$$

$$\Gamma = \left({}^{1}\!/_{c_3\beta} \right)^{1/(\beta-1)} - c_3 \left({}^{1}\!/_{c_3\beta} \right)^{\beta/(\beta-1)}$$

To find an analytical solution of Eq. (6.13), take $V(A_t)$ to be a linear function of the land stock A_t, so

$$V\left(A_t, p_{I,t}\right) = qA_t + g \qquad \text{with } q \equiv q(p_{I,t}) \text{ and } g \equiv g(p_{I,t}) \tag{6.14}$$

where q ($=V_A$) and g are functions to be determined. Substitution of Eq. (6.14) into Eq. (6.13) yields

$$\begin{aligned} rqA_t + rg = {} & hA_t + \left(q - p_{I,t}\right)^{\beta/(\beta-1)}\Gamma - \delta A_t q \\ & + \mu p_{I,t} q_{p_I} A_t + \mu p_{I,t} g_{p_I} + \tfrac{1}{2}\sigma^2 p_{I,t}^2 q_{p_I p_I} A_t + \tfrac{1}{2}\sigma^2 p_{I,t}^2 g_{p_I p_I} \end{aligned} \tag{6.15}$$

where $q_{p_I} = \partial q / \partial p_I$, $q_{p_I p_I} = \partial^2 q / \partial p_I^2$, $g_{p_I} = \partial g / \partial p_I$ and $g_{p_I p_I} = \partial^2 g / \partial p_I^2$, and which holds for all A_t. So, the term multiplying A_t on the *l.h.s.* must equal the sum of terms multiplying A_t on the *r.h.s.*, and, similarly, the term not involving A_t on the *l.h.s.* must equal the sum of terms not involving A_t on the *r.h.s.*. This yields

$$q_{p_I p_I} + \frac{2\mu\sigma^{-2}}{p_{I,t}} q_{p_I} - \frac{2(r+\delta)\sigma^{-2}}{p_{I,t}^2} q = \frac{\tfrac{1}{2} p^{-1} b^{-1} \sigma^{-2} \left(-2p_S pa + p^2 a^2 + p_S^2 + 4p_A pb\right)}{p_{I,t}^2} \tag{6.16}$$

$$g_{p_I p_I} + \frac{2\mu\sigma^{-2}}{p_{I,t}} g_{p_I} - \frac{2r\sigma^{-2}}{p_{I,t}^2} g = \frac{-2\sigma^{-2}\left(q - p_{I,t}\right)^{\beta/(\beta-1)}\Gamma}{p_{I,t}^2} \tag{6.17}$$

The marginal production value of land $q(p_{I,t})$ can be determined from Eq. (6.16), and an analytical expression for the rate of investment I_t is obtained through Eq. (6.11). The intercept term g can be determined with Eq. (6.16) and (6.17), and an analytical expression for the value of the farm $V(A_t, p_{I,t})$ by using Eq. (6.14). As this chapter only focuses on investment decisions by cattle ranchers, it is not necessary to derive an analytical solution for the value of the farm.[41] A general solution to the marginal value of installed land $q(p_{I,t})$ is given by

$$q(p_{I,t}) = C_0 p_{I,t}^2 + C_1 p_{I,t} + C_2 + \frac{C_3}{p_{I,t}} \tag{6.18}$$

Direct substitution verifies that the particular solution to Eq. (6.18) is

---

[41] For $\beta = 2$, the particular solution to Eq. (6.17) is $g(p_{I,t}) = \frac{1}{4c_3\left(r - 2\mu - \sigma^2\right)} p_{I,t}^2 - \frac{q}{2c_3(r-\mu)} p_{I,t} + \frac{q^2}{4c_3 r}$.

$$q = \frac{2p_S pa - p^2 a^2 - p_S^2 - 4p_A pb}{4pb(r+\delta)} \tag{6.19}$$

The expression for q is identical to the q in the deterministic setting (see Chapter 4), and does not involve any of the parameters of the investment cost function. Abel and Eberly (1997) note that q is the present value of expected marginal revenue products, which is exogenous for a competitive firm with constant returns to scale. The q is independent of the specification of the investment cost function, as the path of marginal revenue products is independent of the farm's investment.

The optimal rate of investment I_t is now obtained through substitution of q (which is equal to V_A) back into Eq. (6.11), and for $\beta = 2$ is given by

$$I(p_{I,t}) = \frac{q - p_{I,t}}{2c_3} = \frac{2p_S pa - p^2 a^2 - p_S^2 - 4p_A pb - 4p_{I,t} pb(r+\delta)}{8pb(r+\delta)c_3} \tag{6.20}$$

which differs from the rate of investment in the deterministic setting, in the sense that the rate of investment is dependent on the price of land $p_{I,t}$ at a specific moment in time t. Consequently, the rate of investment fluctuates over time according to the land price process depicted in Eq. (6.7), and gross investment $I(p_{I,t})$ is positive (negative) when the shadow price of land q is greater (smaller) than the purchase price of land $p_{I,t}$. A closed form solution for the expected rate of investment $E(I_t)$ can be derived by rewriting Eq. (6.20), so that

$$E[I_t] = E\left[\frac{q - p_{I,t}}{2c_3}\right] = \frac{q}{2c_3} - \frac{E[p_{I,t}]}{2c_3} \tag{6.21}$$

Given that the land price $p_{I,t}$ evolves according to a geometric Brownian motion, the change in the logarithm of p_I is normally distributed with mean $(\mu - ½\sigma^2)t$ and variance $\sigma^2 t$ over a finite time interval t (Dixit and Pindyck, 1994). The expected value of $p_{I,t}$ is given by

$$E[p_{I,t}] = p_{I,0}e^{\mu t} \tag{6.22}$$

where $p_{I,0}$ is the land price in $t = 0$, and where μ is the drift in land prices. Note that the expected land price increases (decreases) in an exponential fashion towards infinity (zero) over time in the case that $\mu > 0$ ($\mu < 0$). Substitution of Eq. (6.22) back into Eq. (6.21) yields the closed form solution for the expected rate of investment $E(I_t)$, which is given by

$$E[I_t] = \frac{q}{2c_3} - \frac{p_{I,0}e^{\mu t}}{2c_3} \tag{6.23}$$

The behavior of Eq. (6.23) with respect to μ and σ can be determined, given the expected positive signs of the parameters (only $b < 0$). Considering the drift in land prices μ, it can be verified that the expected rate of investment is continuous, concave and decreasing in μ for $t > 0$. When considering the standard deviation in land prices σ, we see that the expected rate of investment does not depend on the standard deviation in land prices σ for all t. Note that the expected rate of investment becomes negative for $\mu > \ln(q/p_{I,0})/t$.

Comparison of the deterministic model with constant land prices (see Chapter 4) and the presented stochastic model with quadratic investment costs shows that the expected rate of investment in the stochastic case is greater (smaller) than the rate of investment in the deterministic case for $\mu < 0$ ($\mu > 0$). Finally, the expected rate of investment in the stochastic case is identical to the rate of investment in the deterministic case when $\mu = 0$.

As in Chapter 5, the equation of motion for land given in Eq. (6.7) can be used to determine the stochastic land stock path A_t, which is given by

$$A(p_{I,t}) = e^{-\delta t}\left(C + \int I(p_{I,t})e^{\delta t}dt\right) \tag{6.24}$$

where C is an arbitrary constant that can be obtained by using the initial condition A_0. Again, a higher rate of investment I_t leads to a larger land stock A_t. The stochastic cattle stock S_t, beef production Q_t and stocking rate SR_t paths can be determined by using Eq. (6.12) and (6.5), respectively.

6.3.2 The stochastic model with uncertainty in land prices and exponential investment costs

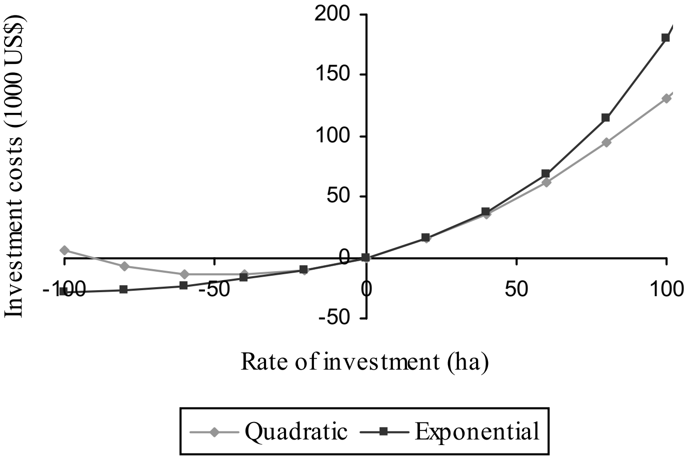
The previous section shows that when investment costs are quadratic (and thus symmetric) in the rate of investment, the expected rate of investment is independent of the standard deviation in land prices σ. This section will show that when investment costs are exponential (and thus non-symmetric) in the rate of investment, the expected rate of investment will be dependent on the standard deviation in land prices σ.

Assume that the cattle rancher undertakes gross investment I_t, while facing exponential increasing investment costs $C(I_t, p_{I,t})$. The form of the investment cost function $C(I_t, p_{I,t})$ in Eq. (6.6) is taken to be

$$C(I_t, p_{I,t}) = \frac{p_{I,t}}{\beta}\left(e^{\beta I_t} - 1\right) \tag{6.6'}$$

where $p_{I,t}$ is the price of land, β is the land sales scale parameter, and where $p_{I,t}/\beta$ represents the maximum return that can be obtained from the sale of land. In Figure 6.5, the quadratic and the exponential investment cost functions are shown. For $\beta = 0.02$, the difference between the quadratic and the exponential investment costs is less than 5% for $0 < I_t < 45$ ha, while the difference becomes increasingly large for $I_t > 45$ ha. The difference between the quadratic and the exponential investment cost function is, however, largest for $I_t < 0$. The quadratic investment cost function first decreases and then increases (and even becomes positive!) as $I_t \to -\infty$ (*i.e.* land sales become very large), while the exponential investment costs function decreases towards the asymptotic value $-p_{I,t}/\beta$ in the case that $I_t \to -\infty$.

Figure 6.5 **Quadratic and exponential investment costs**



Using Eq. (6.6'), maximization of Eq. (6.10) with respect to I_t and S_t yields the *f.o.c.*'s

$$V_A = p_{I,t}e^{\beta I_t} \quad \text{or} \quad I_t = \ln\left(\frac{V_A}{p_{I,t}}\right)\Big/\beta \tag{6.11'}$$

$$p_S = p\left(a + 2bS_tA_t^{-1}\right) \quad \text{or} \quad S_t = \frac{(p_S - pa)A_t}{2pb} \tag{6.12}$$

Subsequent substitution of Eq. (6.11') and (6.12) back into Eq. (6.10) yields

$$rV\left(A_t, p_{I,t}\right) = (h - \delta V_A)A_t + \frac{p_{I,t}}{\beta} - \frac{V_A}{\beta} + \frac{V_A\ln\left(V_A/p_{I,t}\right)}{\beta} + \mu p_{I,t}V_{p_I} + \tfrac{1}{2}\sigma^2 p_{I,t}^2 V_{p_I p_I} \tag{6.13'}$$

where $$h = \frac{2p_S pa - p^2a^2 - p_S^2 - 4p_A pb}{4pb}$$

To find an analytical solution of Eq. (6.13'), again, we take $V(A_t)$ to be a linear function of the land stock A_t (see Eq. 6.14). Substitution of Eq. (6.14) into Eq. (6.13') yields

$$rqA_t + rg = (h-\delta q)A_t + \frac{p_{I,t}}{\beta} - \frac{q}{\beta} + \frac{q\ln\left(q/p_{I,t}\right)}{\beta} \qquad (6.15')$$
$$+ \mu p_{I,t} q_{p_I} A_t + \mu p_{I,t} g_{p_I} + \tfrac{1}{2}\sigma^2 p_{I,t}^2 q_{p_I p_I} A_t + \tfrac{1}{2}\sigma^2 p_{I,t}^2 g_{p_I p_I}$$

which should hold for all values of A_t. As before, the term multiplying A_t on the *l.h.s.* must equal the sum of terms multiplying A_t on the *r.h.s.*, while the term not involving A_t on the *l.h.s.* must equal the sum of terms not involving A_t on the *r.h.s.*. This yields

$$q_{p_I p_I} + \frac{2\mu\sigma^{-2}}{p_{I,t}} q_{p_I} - \frac{2(r+\delta)\sigma^{-2}}{p_{I,t}^2} q = \frac{\tfrac{1}{2} p^{-1} b^{-1} \sigma^{-2}\left(-2p_S pa + p^2 a^2 + p_S^2 + 4p_A pb\right)}{p_{I,t}^2} \qquad (6.16)$$

$$g_{p_I p_I} + \frac{2\mu\sigma^{-2}}{p_{I,t}} g_{p_I} - \frac{2r\sigma^{-2}}{p_{I,t}^2} g = -2\beta^{-1}\sigma^{-2}\left(\frac{1}{\beta p_{I,t}} - \frac{q}{\beta p_{I,t}^2} + \frac{q\ln\left(q/p_{I,t}\right)}{\beta p_{I,t}^2}\right) \qquad (6.17')$$

Differential Eq. (6.16) remains unchanged, which implies that the corresponding expression for q is identical to the q in the setting with quadratic investment costs (see Eq. 6.19). This is not surprising, as the shadow value of land q is independent of the specification of the investment cost function. The intercept term $g(p_{I,t})$, however, cannot be derived analytically and, consequently, an analytical expression for the value of the farm $V(A_t, p_{I,t})$ cannot be determined.

The optimal rate of investment I_t is obtained through substitution of q (which is equal to V_A) back into Eq. (6.11'), and is now given by

$$I_t = \ln\left(\frac{q}{p_{I,t}}\right)\Big/\beta = \ln\left(\frac{2p_S pa - p^2a^2 - p_S^2 - 4p_A pb}{4pb(r+\delta)p_{I,t}}\right)\Big/\beta \qquad (6.20')$$

As in the case with quadratic investment costs, the rate of investment I_t fluctuates over time according to the land price process depicted in Eq. (6.7), and is positive (negative) when the shadow price of land q is greater (smaller) than the purchase price of land $p_{I,t}$. A closed form solution for the expected rate of investment $E(I_t)$ can be derived by rewriting Eq. (6.20'), so that

$$E[I_t] = E\left[\ln\left(\frac{q}{p_{I,t}}\right)\Big/\beta\right] = E\left[\frac{\ln q - \ln p_{I,t}}{\beta}\right] = \frac{\ln q}{\beta} - \frac{E\left[\ln p_{I,t}\right]}{\beta} \qquad (6.21')$$

As $\ln p_{I,t}$ is normally distributed with mean $(\mu - ½\sigma^2)t$ and variance $\sigma^2 t$, the expected value of $\ln p_{I,t}$ is given by

$$E\left[\ln p_{I,t}\right] = \ln p_{I,0} + (\mu - \tfrac{1}{2}\sigma^2)t \tag{6.22'}$$

where $p_{I,0}$, μ and σ are as before. Substitution of Eq. (6.22’) into Eq. (6.21’) yields the closed form solution for the expected rate of investment $E(I_t)$, which is given by

$$E(I_t) = \frac{\ln q}{\beta} - \frac{\ln p_{I,0} + (\mu - \tfrac{1}{2}\sigma^2)t}{\beta} \tag{6.23'}$$

Like before, the behavior of Eq. (6.23’) with respect to μ and σ can be determined. Considering the drift in land prices μ, it can be verified that the expected rate of investment is continuous, linear and decreasing in μ for $t > 0$. Similarly, when considering the standard deviation in land prices σ, the expected rate of investment turns out to be continuous, convex and increasing in σ for $t > 0$. Note that the expected rate of investment becomes negative for $(\mu - \tfrac{1}{2}\sigma^2) > -\ln(q/p_{I,0})/t$.

Comparison of the deterministic model with constant land prices (see Chapter 4) and the presented stochastic model with exponential investment costs, shows that the expected rate of investment in the stochastic case is greater (smaller) than the rate of investment in the deterministic case for $\mu < 0$ ($\mu > 0$). Similarly, it can be verified that the expected rate of investment in the stochastic case exceeds the rate of investment in the deterministic case for $\sigma > 0$. Finally, the expected rate of investment in the stochastic case is identical to the rate of investment in the deterministic case when $\mu = \sigma = 0$.

Similar to the previous section, Eq. (6.7), (6.12) and (6.5) can be used to determine the stochastic land stock A_t, cattle stock S_t, beef production Q_t and stocking rate SR_t paths, respectively.

6.4 Model results

This section provides a numerical application of the model with uncertainty in land prices and exponential investment costs (see Section 6.3.2) to the case of Costa Rica, for the reference year 1995.[42] A comparative static sensitivity analysis is performed, to analyze the effect of various drifts μ and fluctuations σ in land prices on optimal investment decisions by an average beef cattle rancher in the AZ of Costa Rica. In both cases, results are generated for the situation with and without the livestock interest rate subsidy.

Results are based on 1995 data. The price of beef (p = 1.41 US\$ kg^{-1}), cattle purchase and maintenance (p_S = 213.2 US\$ AU^{-1}) and pasture maintenance (p_A = 55.0 US\$ ha^{-1}) are obtained from the PASTOR system, which is calibrated for the AZ of Costa Rica for the year 1995 (Bouman *et al.*, 1998). The base price of land with road access, poor soil drainage and no further facilities for an average beef cattle farm in the AZ (p_I = 630.0 US\$ ha^{-1}) is obtained from the *Dirección de Tributación Directa* of the Ministry of

---

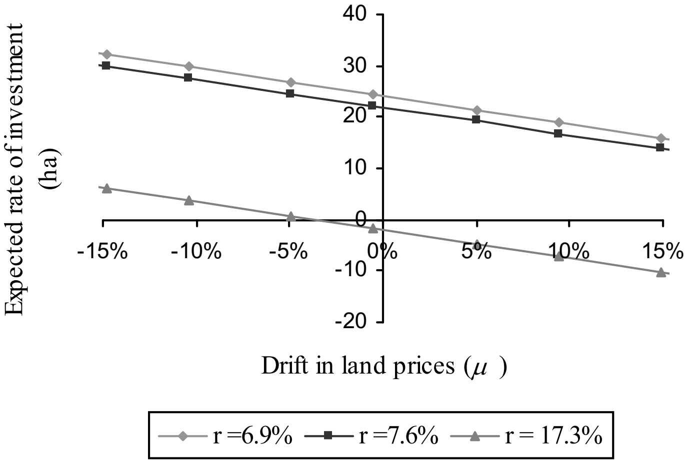
[42] Use is made of the stochastic model with exponential investment costs, as it provides an analytical solution of the expected rate of investment in which the standard deviation in land prices is explicit.

Housing. Drift and standard deviation in real land prices over the period 1984 to 1991 that are corrected for fluctuations in real interest rates are determined in Section 6.2.3 ($\mu = 0.1389$ and $\sigma = 0.4457$). The constant rate of land depreciation is set at $\delta = 0.10$, in line with Faminow (1998) and Bulte *et al.* (2000) who state that pasture-land is abandoned or needs to be recuperated 7 to 12 years after pasture establishment. Exponential land investment costs are determined on the basis of the maximum annual returns that can be obtained from the sale of land ($\beta = 0.02$, see Section 6.3.2). The time discount rate ($r = 6.9\%$ yr^{-1}) is obtained from the World Development Indicators (World Bank, 1999), and calculated as the geometric mean of the real interest rates over the period 1984 to 1997. The official 1995 exchange rate (179.73 Colones US\$$^{-1}$) is, also, obtained from the World Development Indicators (World Bank, 1999). Production function parameter estimates for pasture-based beef production on poorly drained soil types in the AZ of Costa Rica are determined on the basis of input-output coefficients generated by the PASTOR system ($a = 354.3$ and $b = -70.9$).

6.4.1 Drifts in land prices

When evaluating the effect of various drifts in land prices μ and the abolition of the livestock interest rate subsidy on the optimal rate of investment of an average beef cattle ranch in the AZ of Costa Rica, the standard deviation in land prices σ is held constant at 44.6% yr^{-1}. Figure 6.6 shows the optimal rate of investment for various levels of μ and r. Drifts in land prices range from –15% yr^{-1} to +15% yr^{-1}, and abolition of the livestock interest rate subsidy leads to an increase in the interest rate from 6.9% yr^{-1} to 7.6% yr^{-1}.

Figure 6.6 Expected rate of investment for various drifts in land prices μ and interest rates r



The expected rate of investment is negatively related to the drift in land prices and the interest rate. The relation between the expected rate of investment and the drift in land prices is negative because the expected land price $E[\ln p_{l,t}]$ increases with the drift in land prices μ (see Eq. 6.22'), while Eq. (6.23') reveals that the expected rate of investment $E[I_t]$is decreasing in the expected land price $E[\ln p_{l,t}]$. The relation between the expected rate of investment and the interest rate is negative because the shadow value of land q decreases with the interest rate r (see Eq. 6.19), while Eq. (6.23') makes clear that the expected rate of investment increases with the shadow value of land q.

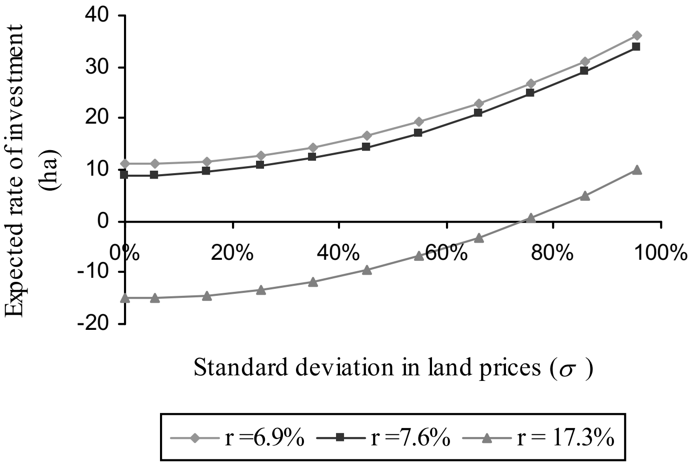
The numerical example in Figure 6.6 shows that the expected rate of investment is about 30% overestimated in the case that land prices are assumed constant instead of increasing with 13.9% yr^{-1}. Furthermore, Figure 6.6 shows that the abolition of the interest rate subsidy (*i.e.* from r = 6.9% yr^{-1} to r = 7.6% yr^{-1}), leads to a 13% decrease in the expected rate of investment for μ = 13.9% yr^{-1}. Finally, note that the expected rate of investment becomes negative for large values of μ and/or r.

A number of conclusions can be drawn from these results. First, the expected rate of investment is overestimated (underestimated) if land prices are assumed constant over time, when they actually tend to increase (decrease) over time. Second, the expected rate of investment can become negative if land prices are expected to increase sufficiently rapidly over time and when interest rates are sufficiently high, as (replacement) investment costs of land exceed the (present) marginal production value of land. Finally, the expected rate of investment can be positive even when land prices are expected to increase over time because current and near future investment costs are sufficiently low to purchase land for beef production.

6.4.2 Fluctuations in land prices

When evaluating the effect of various fluctuations in land prices σ and the abolition of the livestock interest rate subsidy on the optimal rate of investment of an average beef cattle ranch in the AZ of Costa Rica, the drift in land prices μ is held constant at 13.9% yr^{-1}. Figure 6.7 shows the optimal rate of investment for various levels of σ and r. Standard deviations in land prices range from 0% yr^{-1} to 100% yr^{-1}, and abolition of the livestock interest rate subsidy leads to a 0.7% increase in the interest rate to 7.6% yr^{-1}.

Figure 6.7 **Expected rate of investment for various standard deviations in land prices σ and interest rates r**



The expected rate of investment is positively related to the standard deviation in land prices and, like before, negatively related to the interest rate. The relation between the expected rate of investment and the standard deviation in land prices is negative because the expected land price $E[\ln p_{l,t}]$ decreases with the standard deviation in land prices σ (see Eq. 6.22'), while Eq. (6.23') shows that the expected rate of investment $E[I_t]$ is decreasing in the expected land price $E[\ln p_{l,t}]$.

The numerical example in Figure 6.7 shows that the expected rate of investment is about 50% underestimated if land prices are taken constant over time instead of fluctuating with 44.6% yr^{-1}. Like before, Figure 6.7 shows that the abolition of the interest rate subsidy leads to a 13% decrease in the expected rate of investment for $\sigma = 44.6\%\ yr^{-1}$. Finally, note that the expected rate of investment becomes negative for large values of r.

A number of conclusions can be drawn from these results. First, the expected rate of investment is underestimated if land prices are assumed constant over time, while they actually tend to fluctuate over time. Second, the expected rate of investment can become negative when fluctuations in land prices are sufficiently small and interest rates sufficiently high, as speculative and (present value) marginal returns from land do not exceed (replacement) investment costs of land. Finally, the expected rate of investment can be positive even at relatively high interest rates, as fluctuations in land prices provide sufficient speculative returns for purchase land for beef production.

6.5 Conclusions

In this chapter, we have developed a stochastic reversible investment model with adjustment costs, in which land prices are modeled as a geometric Brownian motion. This model sheds new light on the discussion whether rising land prices and land speculation lead to inflated levels of investment in land and eventually to deforestation. Real land price data for the Atlantic Zone (AZ) of Costa Rica indicate that there is evidence for Kaimowitz's (1996) statement that land prices in Central America have risen considerably over the past decades. In the AZ, the drift in land prices (corrected for fluctuations in interest rates) was no less than 13.9% yr^{-1} with a standard deviation of 44.6% yr^{-1} over the period 1984 to 1991. This result is in contrast with Faminow (1998), who found that real land prices in the Brazilian Amazon did not rise during the past decades, although fluctuations in land prices were large. Unlike in Central America, however, the limits of the agrarian frontier in the Brazilian Amazon are not yet in sight. Interest rate data for Costa Rica confirm that interest rate subsidies have been supplied to agricultural credit in general, and to livestock credit in particular. Over the period 1984 to 1996, interest rates charged on agricultural and livestock credit were, respectively, 0.3% and 0.7% below the national average.

The analytical results indicate that the expected rate of investment is determined by the comparison of the marginal production value of land and the expected marginal investment costs (or returns) of land. Critical in this comparison is the form of the investment cost function. If investment costs are assumed quadratic in the rate of investment, expected marginal investment costs (or returns) are determined by the level and the drift in land prices. If investment costs are assumed exponential in the rate of investment, expected marginal investment costs (or returns) are not only determined by the level and the drift in land prices but also by the standard deviation in land prices. The expected rate of investment decreases with the drift in land prices and increases with the standard deviation in land prices, due to larger replacement investment costs and larger speculative returns from land, respectively.

The numerical results for an average cattle rancher in the AZ of Costa Rica indicate that the expected rate of investment is underestimated (overestimated) if land prices are assumed constant over time, while they actually tend to decrease (increase) or fluctuate over time. Furthermore, the expected rate of investment can be positive even when interest rates are relatively high and land prices are expected to increase over time, as sufficiently large fluctuations in land prices provide the economic incentive (*i.e.* speculative returns form land) to develop cattle ranching activities. Finally, livestock interest rate subsidies lead to inflated levels of investment by cattle ranchers. This effect is, however, relatively small compared to the inflated levels of investment that are triggered by fluctuations in land prices.

This Chapter has shown that rising land prices can lead to deflated levels of investments in land, as it becomes increasingly expensive to replace depreciated pasture-land, while the marginal production value of land remains constant. Furthermore, uncertainty in land prices turns out to be a sufficient condition for land speculation, as it gives rise to speculative returns from land in the form of rents accruing to the adjustment technology. Larger fluctuations in land prices lead to an increase in the speculative returns from land, and, consequently, an increase in the expected rate of investment. Put differently, variability in land prices alone is a sufficient condition for land speculation and inflated levels of investments in land, with subsequent consequences for deforestation of agrarian frontier areas. This process is further promoted by subsidized livestock credit. While the role of subsidized livestock credit in deforestation has been widely acknowledged (*e.g.* Solera-Ruíz, 1981; Ledec, 1992; Fearnside, 1989), the role of land speculation has, so far, only be related to deforestation in cases for which it was proven that land prices tended to rise over time (*e.g.* Hecht *et al.*, 1988; Kaimowitz, 1996; Smith *et al.*, 1997; Faminow, 1998).

Future research needs to address a number of limitations not covered by this study (see also Chapter 4). First, the presented approach is of a partial equilibrium nature. Second, it might be interesting to model real land prices as a mixed geometric Brownian and Poisson jump process, given the occurrence of a jump in real land prices in the AZ of Costa Rica around the year 1978. Third, resource degradation is modeled in an artificial way (see Chapter 7). Fourth, externalities related to deforestation have not been taken into account. Finally, the challenge remains to solve the value function for the stochastic model with exponential investment costs.

7 Fertilizer price subsidies, land price appreciation and sustainable cattle ranching

7.1 Introduction

As discussed in Chapter 2, cattle ranching in the humid tropics of Latin America is often linked to deforestation and resource degradation (Downing *et al.*, 1992; Kaimowitz, 1996; Faminow, 1998). Deforestation has important social environmental effects (externalities), such as loss of biodiversity and increased emission of the trace and greenhouse gases CO_2, N_2O and NO (*e.g.* Ledec, 1992; Veldkamp, 1994; Plant, 1999; Van Kooten and Bulte, 2000). Resource degradation, on the other hand, has important private economic environmental effects, such as soil erosion and loss of soil nutrients (*e.g.* Haynes and Williams, 1993; Myers and Robbins, 1991; Williams and Charters, 1991).

Soil nutrient availability is one of the most important factors determining pasture productivity in Latin America (Hernández *et al.*, 1995; Faminow, 1998). Consequently, soil nutrient depletion will (eventually) lead to pasture degradation and declining pasture productivity (Myers and Robbins, 1991; Williams and Chartres, 1991). With progressive pasture degradation, cattle ranching becomes less and less profitable. Used (infertile) pasture-land will be abandoned, and cattle ranchers start buying forested areas to take advantage of their initially high fertility levels (Haynes and Williams, 1993; Kaimowitz, 1996).

Economic farm models concerning the trade-off between current soil degradation and future productivity invariably assume a fixed farm size (see for example McConnell, 1983; Barbier, 1990; Barret, 1991; Bulte and Van Soest, 1999; Bulte *et al.*, 2000). This assumption is, however, not applicable to cattle ranching in Latin America. First of all, land is an investment object for cattle ranchers (see Chapters 2 and 6). Secondly, it is suggested that forested (fertile) land is an important source of fertility for cattle ranchers operating at the agrarian frontier (Kaimowitz, 1996).

In this chapter, we will extend the basic economic models for soil nutrient stocks by relaxing the assumption of a fixed farm size to analyze the effect of fertilizer price subsidies and land price appreciation on optimal resource use and investment decisions by cattle ranchers in Latin America. Fertilizer application is considered a standard mechanism that leads to land use intensification and reduced resource degradation, as fertility is imported from outside the agro-ecosystem (*e.g.* Barret, 1991; Faminow, 1998). Land price appreciation is expected to lead to extensification, deforestation and resource degradation, as land ownership is considered a long-term investment that is more important than present and future returns from livestock production (*e.g.* Van Hijfte, 1989; Jones, 1990; Kaimowitz, 1996).

Based on the model presented in Chapter 4, a deterministic reversible investment model for cattle ranchers is developed in which soil nitrogen dynamics as well as land dynamics are specifically taken into account. This chapter covers the analytical derivation of steady-state reduced form equations and conditions for global optimality as well as a numerical example of the model for an average beef cattle rancher in the

Atlantic Zone (AZ) of Costa Rica, on the basis of 1995 data. Model simulations are performed for varying levels of fertilizer price subsidy and land sales price increase.

The chapter is organized as follows. Section 7.2 starts with a discussion on the major components of the nitrogen cycle in pasture-based beef production, followed by the empirical estimation of a stocking rate and nitrogen dependent production function for pasture-based beef production in the AZ of Costa Rica. Section 7.3 treats the development of the deterministic reversible investment model for cattle ranchers in which land as well as nitrogen are considered stock variables. Section 7.4 provides a numerical application of the model for the case of an average cattle ranch in Costa Rica. First, we will consider the steady-state solution of the model with variable farm size, and compare it to the steady-state solution of the model in which the farm size is assumed fixed. Second, a comparative static sensitivity analysis is performed with respect to a fertilizer price subsidy, a general land price increase and a land sales price increase. Section 7.5 contains concluding remarks and observations.

7.2 Soil nutrient depletion and pasture-based beef production

7.2.1 Soil nutrient dynamics

Many currently practiced livestock production systems in Latin America result in rapid resource degradation (Ibrahim, 1994; Kaimowitz, 1996; Bouman *et al*, 1999a, 1999b) and externalities in the form of nitrogen leaching and emission of trace and greenhouse gases (Veldkamp, 1994; Bouman *et al*, 1999b; Plant and Bouman, 1999). Economic consequences of resource degradation are especially felt at the farm level through pasture degradation, and the subsequent effects on the future production potential (Haynes and Williams, 1993; Myers and Robbins, 1991; Williams and Charters, 1991).

Pasture degradation is the result of socio-economic as well as environmental factors (Kaimowitz, 1996). Social factors that have contributed to reduced pasture management and, subsequently, pasture degradation in Latin America include decreasing real beef prices, increasing labor costs, reduced access to credit for cattle ranching, import taxes on agricultural inputs, and physical insecurity due to military conflicts and banditry.

Environmental factors that determine pasture degradation include weed invasion, soil compaction, soil erosion, and nutrient depletion (Myers and Robbins, 1991; Hernández *et al.*, 1995; Kaimowitz, 1996; Faminow, 1998). Weed invasion takes place by annual and perennial weed types (Filho, 1990). The annual weed type produces a lot of seeds, develops rapidly, and quickly competes for water, nutrients, space and light, while the perennial weed type grows more slowly, but lasts for years. Soil compaction occurs due to the pasture preparation process and subsequent stamping by cattle (Ibrahim, 1994; Bouman *et al.*, 1998). Compaction negatively affects pasture root development, and increases soil moisture levels, thereby reducing the capacity of the soil to absorb rainfall. Soil erosion is, according to the universal soil loss equation (USLE), determined by rainfall erosivity, soil erodibility, length and degree of slope, vegetative cover and conservation practices (Faminow, 1998). Erosion negatively affects pasture production, due to the loss of the fertile topsoil and the occurrence of landslides. Finally, nutrient depletion takes place when the loss of nutrients from the system (Haynes and Williams, 1993) through leaching, denitrification, volatilization and animal (by-) products (*e.g.* manure and beef) exceeds the gain of nutrients from rain, fixation and external sources (*e.g.* fertilizer and supplements).

Nitrogen availability is considered the most important factor determining pasture productivity in the AZ of Costa Rica (Hernández *et al.*, 1995). Myers and Robbins (1991) as well as Williams and Chartres (1991) demonstrate that nitrogen depletion (in the long run) leads to a decline in pasture productivity and weed invasion. As nitrogen depletion advances and, consequently, pasture productivity declines over time, eventually cattle ranching will no longer be profitable and the land will be abandoned (Uhl *et al.*, 1988; Haynes and Williams, 1993; Faminow, 1998).

Thomas *et al.* (1992) developed a full model of the major pools and processes of the nitrogen cycle in pasture-based beef production. Thomas identified eight sources of nitrogen input and seven sources of nitrogen output. Nitrogen is lost from the organic and inorganic soil nitrogen pool through pasture uptake, animal grazing, the sale of animal products and lost excreta, as well as through denitrification and volatilization, immobilization, and leaching. Nitrogen is added or returned to the organic and inorganic soil nitrogen pool through pasture litter, supplementary feeding, feces and urine, as well as through fertilizer application, deposition, mineralization and fixation.

Soil organic matter plays an important role in the nitrogen cycle, as soil-borne microorganisms convert soil organic matter into inorganic nitrogen (mineralization). In this form, nitrogen is suitable for uptake by the pasture. In terms of the nitrogen cycle outlined above, soil microorganisms are responsible for nitrogen fixation, as well as conversion of feces and pasture litter into inorganic nitrogen. On the other hand, soil micro-organisms are responsible for denitrification and volatilization of nitrogen from soil organic matter, as well as immobilization of inorganic nitrogen from the soil nitrogen stock (Thomas *et al.*, 1992).

In this chapter, a simplified model of soil nitrogen dynamics is used, in which, in line with Bulte *et al.* (2000), inorganic and soil organic matter nitrogen are lumped into one single soil nitrogen pool. On the farm level, the following sources of nitrogen input and output are identified. Nitrogen is lost from the total soil nitrogen stock through leaching, denitrification, volatilization and pasture litter conversion (ϕF_t), cattle grazing ($\gamma SR_t A_t$) and sold land of average fertility ($(F_t/A_t)\, NA_t^{sell}$). Nitrogen is added or returned to the total soil nitrogen stock through rain and fixation (δA_t), fertilizer application (κNF_t) and purchased forested and fertile land ($f^{ini}\, NA_t^{buy}$).[43] The equation of motion for nitrogen used in the model presented in Section 7.3 is given by

$$\dot{F}_t = \delta A_t + \kappa NF_t + f^{ini} NA_t^{buy} - \phi F_t - \gamma SR_t A_t - \frac{F_t}{A_t} NA_t^{sell} \qquad (7.1)$$

---

[43] Nutrient gains through supplements are not considered in this model, as cattle ranchers in Latin America save on labor and external input requirements by tending to operate distant and large pasture areas (Squirres and Vera, 1992).

Here, δ is the nitrogen gain from rain and fixation, κ is the fraction of nitrogen fertilizer that does not leach, f^{ini} is the initial nitrogen stock of forested land, ϕ is the proportional loss of nitrogen through leaching, denitrification, volatilization and litter from unconsumed pasture, γ is the nitrogen loss from grazing, F_t/A_t is the average fertility rate of used pasture-land, and a dot over a variable denotes the derivative of that variable with respect to t.

7.2.2 Nutrient-dependent pasture-based beef production

In this study, we directly model beef production per hectare as a function of stocking rate and net fertility rate.[44] Beef production per hectare Q_A is considered quadratic in the stocking rate SR as well as in the net fertility rate FR, for a number of reasons (see also Chapter 4, Section 4.2.1). First, beef production per hectare is concave in the stocking rate with $dQ_A/dSR \geq 0$ and $dQ_A/dSR^2 \leq 0$. Second, beef production per hectare is concave in the fertility rate with $dQ_A/dFR \geq 0$ and $dQ_A/dFR^2 \leq 0$ (Holmes, 1974; Morrison, 1987; Bulte *et al.*, 2000). Finally, analytical derivation and computability of the model is greatly simplified when using a production function that is quadratic in SR and FR. Total beef production per hectare Q_A is given by

$$Q_A(SR,FR) = \left(a'SR + b'SR^2\right)\left(c'FR + d'FR^2\right) = aSRFR + bSRFR^2 + cSR^2FR + dSR^2FR^2 \qquad (7.2)$$

with $a = a'c'$, $b = a'd'$, $c = b'c'$ and $d = b'd'$

and where a, b, c and d are equation parameters, with a and d positive, and b and c negative. The first term in brackets on the *r.h.s.* in Eq. (7.2) is just the stocking-rate-dependent beef production function as presented in Chapter 4, which determines the attainable level of beef production for different stocking rates, given a certain fertility rate. The second term in brackets on the *r.h.s.* in Eq. (7.2) determines the effect of net soil nitrogen availability on the level of beef production at a certain stocking rate.

The production function for natural-pasture-based beef production is estimated for the three soil types identified in the AZ of Costa Rica (see Chapter 4). Use is made of input-output data generated by the PASTOR system (Bouman *et al.*, 1998), thereby simulating for 26 stocking rates (0.0 to 5.0 AU ha^{-1}) and 13 net fertility rates (0 to 1200 kg N ha^{-1}). As outlined before, beef production per hectare Q_A (*i.e.* total weight of all animal units at the end of the year in kg ha^{-1}) is quadratic in the stocking rate SR (in AU ha^{-1}) and the net fertility rate FR (in kg N ha^{-1}). The functional form of the Quadratic production function was given in Eq. (7.2), where a, b, c and d are regression coefficients. Table 7.1 shows estimation results for the stocking rate and nitrogen dependent natural-pasture-based beef production function per soil type.

---

[44] The net fertility rate FR refers to the total amount of nitrogen in the soil that is available for uptake by the pasture.

Table 7.1 Stocking rate and nitrogen dependent production function estimates per soil type for natural-pasture-based beef production in the AZ of Costa Rica[1]

	Soil type[2]	
	SFW	SFP/SIW
Explanatory variables[3]		
Coefficient *a*	0.8516 ***	0.7665 ***
Coefficient *b*	-0.0005 ***	-0.0004 ***
Coefficient *c*	-0.1706 ***	-0.1536 ***
Coefficient *d*	0.0001 ***	0.0001 ***
Performance indicators		
Adjusted R^2	0.9742	0.9744
White test (prob.)	0.0000	0.0000
Number of observations	338	338

Notes: [1] Dependent variable is total weight of animals in kg ha^{-1}.

[2] SFW = soil fertile well drained; SFP = soil fertile poorly drained; SIW = soil infertile well drained.

[3] Significant at the at the 10% level (*), the 5% level (**), and the 1% level (***).

According to the *t*-test, all parameter coefficients of the production function are significantly different from zero at the 1% level. Beef production is lower on the SIW and SFP compared to the SFW, due to acidity and drainage problems, respectively (Bouman *et al.*, 1998). Adjusted R^2 levels are high, indicating that the regression is strong in explaining the variation of the dependent variable in the sample. Any problems with heteroskedasticity are solved by using White's heteroskedasticity-consistent standard errors and covariance.

7.3 The deterministic model with soil nitrogen depletion

Based on the deterministic model presented in Chapter 4, a deterministic reversible investment model for cattle ranchers is developed in which beef production is determined by the stocking rate as well as net soil nitrogen availability. The model involves two stock variables (land and nitrogen) and four control variables (buy land, sell land, buy fertilizer and adjust stocking rate). Steady state reduced form equations and conditions for global optimality are derived analytically.

The cattle rancher is engaged in pasture-based beef production, thereby using cattle S_t, soil nitrogen fertility F_t and pasture-land A_t. As shown in Section 7.2, beef production per hectare $Q_A(SR_t, FR_t)$ is quadratic in the stocking rate SR_t (= S_t/A_t) and the fertility rate FR_t (= F_t/A_t), while assuming constant returns to scale when determining total beef production $Q(SR_t, F_t, A_t)$. The rancher can buy forested (and fertile) land NA_t^{buy} and sell used pasture-land NA_t^{sell}, while facing convex investment costs $C(NA_t)$ related to labor requirements for land purchase and land sale (see Chapter 4). Similarly, the rancher can invest in nitrogen fertility NF_t, while facing convex investment costs $C(NF_t)$ related to labor requirements for fertilizer purchase and application. The annual net income stream π_t is

$$\pi(SR_t, F_t, A_t, NF_t, NA_t) = pQ(SR_t, F_t, A_t) - p_S SR_t A_t - p_A A_t - C(NA_t) - C(NF_t) \quad (7.3)$$

with $$Q(SR_t, F_t, A_t) = A_t Q_A(SR_t, FR_t) = aSR_t F_t + bSR_t \frac{F_t^2}{A_t} + cSR_t^2 F_t + dSR_t^2 \frac{F_t^2}{A_t} \quad (7.4)$$

$$C(NA_t) = p_{NA}^{buy} NA_t^{buy} - p_{NA}^{sell} NA_t^{sell} + c_{NA}\left((NA_t^{buy})^{\beta} + (NA_t^{sell})^{\beta}\right) \quad (7.5)$$

$$C(NF_t) = p_{NF} NF_t + c_{NF} NF_t^{\beta} \quad (7.6)$$

where $$FR_t = \frac{F_t}{A_t}$$

$\beta = n/(n\text{-}1)$ and $n \in \{2, 4, 6, \ldots\}$

Here, p represents the beef price, p_S is the price of cattle purchase and maintenance, p_A is the price of pasture maintenance, p_{NA}^{buy} is the price of bought land, p_{NA}^{sell} is the price of sold land, p_{NF} is the price of nitrogen fertilizer, c_{NA} is the adjustment cost scale parameter for land trade, c_{NF} is the adjustment cost scale parameter for nitrogen fertilizer purchase, and β is the adjustment cost elasticity. Note that the investment cost function for land (Eq. 7.5) is equivalent to the investment cost function presented in Chapter 4 (Eq. 4.7), apart from the fact that the purchase and sale of land are made explicit in the present model. The farm maximizes the present value of net income streams over time, subject to the equation of motion for land and the equation of motion for nitrogen fertility. The optimization problem is formulated as follows

Maximize $$V(F_0, A_0) = \max_{NA_t, NF_t, SR_t} E_t\left\{\int_0^{\infty} [\pi_t] e^{-rt} dt\right\} \quad (7.7)$$

subject to $$\dot{A}_t = NA_t^{buy} - NA_t^{sell} \quad \text{(eq. of motion for } A_t\text{)}$$

$$\dot{F}_t = \delta A_t + \kappa NF_t + f^{ini} NA_t^{buy} - \phi F_t - \gamma SR_t A_t - \frac{F_t}{A_t} NA_t^{sell} \quad \text{(eq. of motion for } F_t\text{)}$$

and $A_0 > 0$, $SR_0 > 0$, $F_0 > 0$, $NA_0 > 0$ and $NF_0 > 0$ (initial conditions)

$A_t \geq 0$, $SR_t \geq 0$, $F_t \geq 0$, $NA_t \geq 0$ and $NF_t \geq 0$

where r is the time discount rate, and where δ, κ, f^{ini}, ϕ, γ and F_t/A_t are as before. The equation of motion for land is given by the amount of land bought (NA_t^{buy}) net of the amount of land sold (NA_t^{sell}). The equation of motion for nitrogen fertility has already been described in Section 7.2.1. The value function (Eq. 7.7) satisfies the Hamilton-Jacobi-Bellman equation

$$rV(F_t,A_t)=\max_{NA_t,NF_t,SR_t}\left[\begin{array}{l} pQ(SR_t,F_t,A_t)-p_S SR_t A_t-p_A A_t-C(NA_t)-C(NF_t) \\ +\left(NA_t^{buy}-NA_t^{sell}\right)V_A \\ +\left(\delta A_t+\kappa NF_t+f^{ini}NA_t^{buy}-\phi F_t-\gamma SR_t A_t-\dfrac{F_t}{A_t}NA_t^{sell}\right)V_F \end{array}\right] \tag{7.8}$$

where $V_F=\partial V/\partial F$ and $V_A=\partial V/\partial A$. By using Eq. (7.4) to (7.6), maximization of Eq. (7.8) with respect to NA_t, NF_t and SR_t, respectively, yields the *f.o.c.*'s

$$V_A+f^{ini}V_F=p_{NA}^{buy}+c_{NA3}\beta(NA_t^{buy})^{\beta-1} \quad \text{or} \quad NA_t^{buy}=\left(\frac{V_A+f^{ini}V_F-p_{NA}^{buy}}{c_{NA3}\beta}\right)^{1/(\beta-1)} \tag{7.9}$$

$$V_A+\frac{F_t}{A_t}V_F=p_{NA}^{sell}-c_{NA3}\beta(NA_t^{sell})^{\beta-1} \quad \text{or} \quad NA_t^{sell}=\left(\frac{p_{NA}^{sell}-V_A-\dfrac{F_t}{A_t}V_F}{c_{NA3}\beta}\right)^{1/(\beta-1)} \tag{7.10}$$

$$\kappa V_F=p_{NF}+c_{NF3}\beta NF_t^{\beta-1} \quad \text{or} \quad NF_t=\left(\frac{\kappa V_F-p_{NF}}{c_{NF3}\beta}\right)^{1/(\beta-1)} \tag{7.11}$$

$$p\left((a+2cSR_t)F_t+(b+2dSR_t)\frac{F_t^2}{A_t}\right)=(p_S+\gamma V_F)A_t$$

$$\text{or} \quad SR_t=\frac{(p_S+\gamma V_F)A_t^2-apF_tA_t-bpF_t^2}{2pF_t(cA_t+dF_t)} \tag{7.12}$$

Eq. (7.9) states that the marginal production value of bought (forested and fertile) land V_A plus the marginal production value of its initial nitrogen stock $f^{ini}V_F$, should be equal to the current market purchase price of this unit of land p_{NA}^{buy} plus the costs that are required to take it in production. Similarly, Eq. (7.10) states that the marginal production value of sold (deforested and degraded) land V_A plus the marginal production value of its average nitrogen stock $(F_t/A_t)V_F$, should be equal to the current market sales price of this unit of land p_{NA}^{sell} minus the costs that are required to market it. As a result, land is bought if $p_{NA}^{buy} < V_A + f^{ini}V_F$, and sold if $p_{NA}^{sell} > V_A + (F_t/A_t)V_F$.

Eq. (7.11) is the familiar optimality condition, according to which the marginal production value of nitrogen from fertilizer that is retained in the soil κV_F should be equal to the current market purchase price of nitrogen fertilizer p_{NF} plus the costs that are required to purchase, transport and apply it. Note that nitrogen fertilizer is applied if $p_{NF} < \kappa V_F$.

Finally, optimality condition (7.12) states that the marginal production value of a change in the stocking rate (*l.h.s.*), should be equal to the marginal costs resulting from this change in the stocking rate (*r.h.s.*). The latter includes costs related to cattle purchase and maintenance $p_S A_t$, as well as costs related to (future) changes in pasture productivity due to soil nitrogen depletion resulting from cattle grazing $\gamma V_F A_t$.

Assuming the presence of a unique steady state for the land stock A_t and the nitrogen stock F_t, implies that the following conditions should hold simultaneously:

$$\dot{A}_t = 0 \rightarrow NA_t^{buy} = NA_t^{sell} \tag{7.13}$$

$$\dot{F}_t = 0 \rightarrow \delta A_t + \kappa NF_t + f^{ini} NA_t^{buy} = \phi F_t + \gamma SR_t A_t + \frac{F_t}{A_t} NA_t^{sell} \tag{7.14}$$

From Eq. (7.13) it is clear that, in the steady state, the amount of land bought equals the amount of land sold. Similarly, Eq. (7.14) states that, in the steady state, the nitrogen gains from rain and fixation, fertilizer application and bought (forested and fertile) land should be equal to the nitrogen losses from leaching, denitrification, volatilization, litter from unconsumed pastures, grazing and the sale of (deforested and degraded) land.

7.4 Model results

We now apply the theoretical model presented in Section 7.3 to the case of an average beef cattle ranch in the AZ of Costa Rica. First, we will consider the steady-state solution of the model with variable farm size, and compare it to the steady-state solution of the model in which the farm size is assumed fixed. Next, a comparative static sensitivity analysis is performed to analyze the effect of a fertilizer price subsidy, a general land price increase and a land sales price increase, on the long-term (steady state) production and investment decisions by the cattle rancher. Model results are obtained using GAMS (Brooke *et al.*, 1998). The GAMS code for this model is given in Appendix 7A.

Base run results are obtained with 1995 data. The price of beef (p = 1.41 US\$ kg^{-1}), cattle purchase and maintenance (p_S = 213.2 US\$ AU^{-1}), pasture maintenance (p_A = 55.0 US\$ ha^{-1}), and fertilizer (p_{NF} = 1.0 US\$ kg^{-1}) are obtained from the PASTOR system (Bouman *et al.*, 1998). The base purchase price of land with road access, poor soil drainage and no further facilities for an average beef cattle farm in the AZ ($p_{NA}^{buy} = p_{NA}^{sell}$ = 630.0 US\$ ha^{-1}) is obtained from the *Dirección de Tributación Directa* of the Ministry of Housing. Quadratic adjustment costs related to investments in land are determined on the basis of secondary data regarding labor supply, costs and requirements (see Chapter 4), thereby assuming that 25% of all beef cattle farms invest simultaneously (c_{NA3} = 6.864 and β = 2). Quadratic adjustment costs related to the application of fertilizer are determined in the same way (c_{NF3} = 4.516*10^{-5} and β = 2). The time discount rate (r = 6.9% yr^{-1}) and the official 1995 exchange rate (179.73 Colones US\$$^{-1}$) are taken from the World Development Indicators (World Bank, 1999). Production function parameter estimates for stocking rate and nitrogen dependent pasture-based beef production on poorly drained soil types in the AZ of Costa Rica are established on the basis of input-output data simulated by the PASTOR system (see Section 7.2.2: $a = 0.852$, $b = -0.490*10^{-3}$, $c = -0.171$, and $d = 9.820*10^{-5}$). Parameters in the equation of motion for nitrogen are obtained from secondary data (Stoorvogel, 1995: $\delta = 16.0$ kg N ha^{-1} yr^{-1}; Bouman *et al.*, 1999b: $\kappa = 60.0$ % yr^{-1}; Hengsdijk *et al.*, 1998: $\phi = 0.105$ % yr^{-1}; Bouman *et al.*, 1998: $\gamma = 37.2$ kg N AU^{-1} yr^{-1}; Bulte *et al.*, 2000: $f^{ini} = 1200$ kg N).

7.4.1 The steady-state solution

To analyze the difference between an economic soil nutrient stock model with variable and fixed farm size, we determine the steady-state solution for both situations (see Table 7.2). Indicators include the value of the farm, resource stock, rate of investment, fertilizer use, fertility rate and the stocking rate.

Table 7.2 Steady-state solutions for an average beef cattle ranch in the AZ of Costa Rica, for variable as well as fixed farm size

	Unit	Variable farm size	Fixed farm size
Value of the farm	US$	74,131.8	45,672.6
Resource stock			
Land	ha yr^{-1}	152.0	152.0
Cattle	AU yr^{-1}	184.9	0.0
Nitrogen	kg N yr^{-1}	90,801.7	23,328.6
Rate of investment[1]	ha yr^{-1}	23.2	0.0
Fertilizer use	kg N ha^{-1} yr^{-1}	0.0	0.0
Resource intensity			
Fertility rate	kg N ha^{-1}	597.3	153.5
Stocking rate	AU ha^{-1}	1.22	0.00

Notes: [1] The rate of investment refers the amount of land bought or sold.

The steady-state solution for the model in which the farm size is variable (see Section 7.3) indicates that an average beef cattle ranch encompasses about 152 ha of pasture-land and 185 AU of beef cattle, which implies a stocking rate of 1.22 AU ha^{-1}. Each year, the cattle rancher buys 23.2 ha of forested (fertile) land and sells 23.2 ha of deforested (degraded) land, in order to maintain the fertility rate at its optimal level of about 597 kg N ha^{-1}. This implies that pasture-land is abandoned in about 7 years after pasture establishment, and that the soil's nitrogen stock is mined at a rate of about 85 kg ha^{-1}yr^{-1}. This result is in line with tropical pasture studies by Thomas *et al.* (1992), Cadisch *et al.* (1994) and Bouman *et al.* (1999b), which report annual rates of soil N depletion of between 60 and 99 kg ha^{-1}. Finally, note that no fertilizer is applied to enhance present and future pasture productivity, and that the value of the farm is about 74.1*10^{3} US$.

The model in which a fixed farm size is assumed (*i.e.* where $NA_t^{buy} = NA_t^{sell} = 0$ and $A_t = 152.0$ ha) indicates that beef production is no longer profitable (and thus no longer practiced) after about 14 years of cattle ranching. Consequently, the soil's N stock is mined at a rate of about 75 kg ha^{-1}yr^{-1}. Note, however, that the soil's N is not completely depleted. In the steady state, the soil's N stock is still about 153 kg N ha^{-1}. Finally, the value of the farm is about $45.7*10^3$ US$.

7.4.2 Simulations

Fertilizer price subsidies are likely to result in land use intensification and reduced resource degradation, as soil fertility can, to a large extent, be substituted by fertilizer (Barret, 1991; Faminow, 1998). In cattle ranching, however, current relative prices do not provide the economic incentive to apply fertilizer on natural pastures (Bouman *et al.*, 1999b). Land prices in Latin America are, generally, expected to increase due to deforestation, infra-structure development and urbanization (Fearnside, 1990; Diegues, 1992; Ledec, 1992; Kaimowitz, 1996). In cattle ranching, however, increases in land prices are considered to lead to extensification and resource degradation, as land ownership is considered a long-term investment which is more important than returns from livestock production (Van Hijfte, 1989; Jones, 1990; Kaimowitz, 1996).

Table 7.3 **Price elasticities for an average beef cattle ranch in the AZ of Costa Rica, for a fertilizer price subsidy, a general land price increase and a land sales price increase**[1]

	Fertilizer price subsidy (50%)	General land price increase (10%)	Land sales price increase (10%)
Value of the farm	0.02	–0.94	1.69
Resource stock			
Land	0.11	–0.77	0.60
Cattle	0.12	–0.68	0.63
Nitrogen	0.13	–0.64	0.67
Rate of investment[2]	0.01	–0.51	0.74
Fertilizer use	∞ [3]	0.00	0.00
Resource intensity			
Fertility rate	0.01	0.14	0.07
Stocking rate	0.00	0.10	0.03

Notes: [1] Price elasticities are given for a one per cent change in price, and are calculated as the quotient of the percentage change in indicator value (*e.g.* land stock) and the percentage change in price (Sadoulet and De Janvry, 1995)

[2] The rate of investment refers the amount of land bought or sold.

[3] Fertilizer use increases from 0 kg ha^{-1} yr^{-1} to 9.6 kg ha^{-1} yr^{-1} for a 50% fertilizer price subsidy.

This section takes a look at the effects of fertilizer price subsidies, general land price increases and land sales price increases on the long term (steady state) value of the farm, resource stock, rate of investment, and resource use intensity. Table 7.3 shows price elasticities of an average beef cattle ranch in the AZ of Costa Rica, for a 50% fertilizer price subsidy, a 10% increase in the general land price (*i.e.* the purchase and sales price of land) and a 10% increase in the land sales price. Results are generated on the basis of the model with variable farm size (see Section 7.3), and price elasticities are given for a one percent change in price.

Fertilizer price subsidy

Results for the fertilizer price subsidy are presented in Table 7.3 and indicate that the use of fertilizer is increasing in the fertilizer price subsidy. Eq. (7.11) reveals that fertilizer use NF_t is decreasing in the fertilizer price p_{NF}, or, put differently, increasing in the fertilizer price subsidy. A larger use of fertilizer, in turn, leads to an increase in the nitrogen stock as well as the fertility rate. This point is clarified when solving the steady-state condition (7.14) for F_t and F_t/A_t, respectively

$$F_t = \frac{\delta A_t + \kappa NF_t + f^{ini} NA_t^{buy} - \gamma SR_t A_t - \frac{F_t}{A_t} NA_t^{sell}}{\phi} \tag{7.15}$$

$$\frac{F_t}{A_t} = \frac{\delta A_t + \kappa NF_t + f^{ini} NA_t^{buy} - \phi F_t - \gamma SR_t A_t}{NA_t^{sell}} \tag{7.16}$$

Eq. (7.15) and (7.16), respectively, show that the steady state nitrogen stock F_t and fertility rate F_t/A_t are linearly increasing in the use of fertilizer.[45]

Given the production function that is concave in the fertility rate (see Eq. 7.2), an increase in the fertility rate implies a decrease in the marginal production value of nitrogen V_F. The marginal production value of land V_A, however, increases due to an increase in the fertility rate.[46] The decrease in V_F discourages the use of fertilizer, and dampens the increase in fertilizer use as triggered by the fertilizer price subsidy (see Eq. 7.11). The increase in V_A and F_t (despite the decrease in V_F) provides the incentive to increase the farm size, which can be clarified by substituting optimality conditions (7.9) and (7.10) into the steady-state condition (7.13) and solving for A_t, so that

$$A_t = \frac{F_t V_F}{p_{NA}^{buy} + p_{NA}^{sell} - 2V_A - f^{ini} V_F} \tag{7.17}$$

Eq. (7.17) indicates that the optimal land stock is increasing in the shadow value of land V_A and the nitrogen stock F_t. The optimal rate of investment and the optimal stocking rate are the net resultant of these processes in V_F, F_t and A_t (see Eq. 7.9, 7.10 and 7.12, respectively).

The numerical example in Table 7.3 shows that the fertilizer price subsidy leads to positive and inelastic response reactions, despite the relatively large subsidy of 50% for which the price elasticities have been calculated. However, no response reactions are obtained for fertilizer subsidies below 50% as the cost of nitrogen obtained from forested land (630 US$ ha^{-1} / 1200 kg N ha^{-1} = 0.52 US$ kg^{-1} N) is about half the cost

---

[45] Note that only the fraction κ of the applied fertilizer is retained in the soil.

[46] Analysis of the marginal values for the equation of motion of land and nitrogen in the GAMS output confirms that the shadow value of land V_A and nitrogen V_F are, respectively, increasing and decreasing in the fertilizer price subsidy.

of nitrogen obtained from fertilizer (p_{NF} = 1.0 US\$ kg^{-1}). Consequently, the suggested 50% fertilizer subsidy is big enough to promote the use of fertilizer by cattle ranchers in Costa Rica. The land, cattle and nitrogen stock grow with just over 0.1%, while the increase in the value of the farm and resource use intensity are negligible.

General land price increase

Results for the increase in the general land price (*i.e.* purchase and sales price of land) presented in Table 7.3 indicate that the rate of investment is decreasing in the general land price p_{NA}. Eq. (7.9) says that the amount of purchased land NA_t^{buy} is decreasing in the land price p_{NA}. The steady-state condition (7.13) indicates that the amount of land purchased NA_t^{buy} is equal to the amount of land sold NA_t^{sell}, which can only be the case when the fertility rate F_t/A_t is increased (see Eq. 7.10).

A lower rate of investment leads to a decrease in the nitrogen stock. It follows from Eq. (7.15) that the optimal nitrogen stock F_t decreases as the rate of investment NA_t decreases, as land is purchased at initial fertility f^{ini} and sold at average fertility F_t/A_t. Moreover, the average fertility at which the land is sold is increasing in the general land price.

As in the fertilizer subsidy case, an increase in the fertility rate implies a decrease in the marginal production value of nitrogen V_F and an increase in the marginal production value of land V_A.[47] The decrease in V_F discourages the use of fertilizer even further (Eq. 7.11), while the decrease in V_F and F_t (despite the increase in V_A) provides the incentive to decrease the farm size (Eq. 7.17). Finally, the increase in the optimal stocking rate is the net resultant of the above described processes in V_F, F_t and A_t (see Eq. 7.12).

The example in Table 7.3 shows that the general land price increase leads to negative and relatively inelastic response reactions. The value of the farm is almost 1% lower in the case that the land purchase and sales price increase simultaneously. The resource stock is 0.6% to 0.8% smaller, while the rate of investment (*i.e.* the amount of land purchased or sold) is about 0.5% lower. Finally, the fertility rate and stocking rate are just over 0.1% larger, as compared to the situation before the general land price increase.

Land sales price increase

Results for the land sales price increases presented in Table 7.3 indicate that the rate of investment is increasing in the land sales price p_{NA}^{sell}. Eq. (7.10) states that the amount of land sold NA_t^{sell} is increasing in the land sales price p_{NA}^{sell}, while the steady-state condition (7.13) reveals that the amount of land sold NA_t^{sell} is equal to the amount of land purchased NA_t^{buy}. Put differently, the larger the turnover rate of land, the larger the difference between the land purchase price p_{NA}^{buy} and the land sales price p_{NA}^{sell}.

A larger turnover rate of land, in turn, leads to an increase in nitrogen stock as well as in fertility rate. Eq. (7.15) shows that the optimal nitrogen stock F_t is linearly increasing in the rate of investment, as land is

---

[47] Analysis of the marginal values for the equation of motion of land and nitrogen in the GAMS output confirms that the shadow value of land V_A and nitrogen V_F are, respectively, increasing and decreasing in the general land price.

purchased at initial fertility f^{ini} and sold at average fertility F_t/A_t. Similarly, from Eq. (7.16), it is clear that the optimal fertility rate grows proportionally with the rate of investment.

Similar to the fertilizer subsidy case, an increase in the fertility rate implies a decrease in the marginal production value of nitrogen V_F and an increase in the marginal production value of land V_A.[48] The decrease in V_F discourages the use of fertilizer even further (Eq. 7.11), while the increase in V_A and F_t (despite the decrease in V_F) provides the incentive to increase the farm size (Eq. 7.17). The optimal stocking rate is the net resultant of the here described processes in V_F, F_t and A_t (see Eq. 7.12).

The numerical example in Table 7.3 shows that the value of the farm increases with almost 1.7%, if the land sales price is above (instead of equal to) the land purchase price. The resource stock is 0.6% to 0.7% larger, while the turnover rate of land is almost 0.8% higher. Finally, resource use intensity is less than 0.1% larger, as compared to the situation where the land purchase price equals the land sales price.

7.5 Conclusions

The model developed in this chapter – in which soil nutrient dynamics as well as land dynamics are specifically taken into account – differs from the basic soil nutrient stock models (*e.g.* McConnell, 1983; Barbier, 1990; Barret, 1991; Bulte and Van Soest, 1999; Bulte *et al.*, 2000) in two respects. First, the farm size is not assumed fixed. Second, the purchase (sale) of land implies a nutrient inflow (outflow). Consequently, this model not only enables the determination of the optimal level of the nutrient stock in the long run (as in the basic soil nutrient stock models), but also of the optimal farm size and rate of investment.

Analysis of the steady-state solution for the model with variable farm size indicates that soil nitrogen depletion is economically efficient for an average cattle rancher in the Atlantic Zone (AZ) of Costa Rica. Soils are, however, not completely depleted, as forested (fertile) land is continuously purchased and used (degraded) land is continuously sold in order to maintain the fertility rate at its optimal level. Consequently, used pasture-land is abandoned before it has been completely mined. This result is in contrast with the model that assumes a fixed farm size and with Bulte *et al.* (2000) who indicate that soil nitrogen mining should optimally take place 'up to the level where agricultural production can no longer be supported and pastures have to be abandoned.' This conclusion is, however, governed by the assumption of a fixed farm size. This assumption is, however, not justified in the case of cattle ranchers in Latin America because land is an investment object as well as an important source of fertility.

Simulations were carried out for a fertilizer price subsidy, an increase in the general land price (*i.e.* purchase and sales price of land), and a land sales price increase. Results indicate, in line with Bouman *et al.* (1999b), that current relative prices do not provide the economic incentive to apply fertilizer on natural pastures. In fact, the cost of nitrogen obtained from forested land is about half the cost of nitrogen obtained from fertilizer. However, if the fertilizer subsidy is sufficiently large, fertilizer application leads to a small

---

[48] Analysis of the marginal values for the equation of motion of land and nitrogen in the GAMS output confirms that the shadow value of land V_A and nitrogen V_F are, respectively, increasing and decreasing in the land sales price.

increase in the optimal farm size (as the marginal production value of land increases) and, to a minor extent, to an increase in the rate of investment and the fertility rate (due to the substitution of soil nitrogen for nitrogen fertilizer). This finding is consistent with Barret (1991) and Faminow (1998), who state that fertilizer application leads to land use intensification and reduced resource degradation.

Furthermore, the simulation results indicate that an increase in the general land price leads to a decrease in the optimal farm size and the rate of investment (due to larger replacement investment costs) and to an increase in the fertility rate (in order to raise the marginal production value of land). On the other hand, an increase in the sales price of land results in an increase in the optimal farm size and the rate of investment (as land trade becomes more profitable) and, to a minor extent, in an increase in the fertility rate (due to the higher turnover rate of land). Consequently, the notion of Van Hijfte (1989), Jones (1990) and Kaimowitz (1996) that land price appreciation leads to extensification and deforestation is only correct when the land sales price increases relative to the land purchase price at a specific moment in time. If the land purchase and the land sales prices increase simultaneously, the opposite occurs. Moreover, my results do not support their claim that increases in land prices lead to resource degradation.

Finally, I would like to mention a number of limitations of this study (see also Chapter 4). First, the presented approach is of a partial equilibrium nature. Second, a simplified version of the nitrogen cycle is applied, in which soil organic matter and inorganic nitrogen pools are lumped into one single soil nitrogen pool. Third, a simplified stocking rate and nitrogen dependent beef production function is applied, in which cattle and nitrogen are (to a certain extent) substitutable. Finally, externalities related to deforestation have not been taken into account.

Appendix 7A GAMS code of the model

```
$ONEMPTY
***************************************************************************************************************************
*** HACIENDA MODEL Ch7_05
*** 1995 PRICES
***************************************************************************************************************************
*** DEFINITION OF SETS ****************************************************************************************************
***************************************************************************************************************************
SETS
  T    year
;

SETS
  T    / 0 * 100 /
;
***************************************************************************************************************************
*** DEFINITION OF PARAMETERS **********************************************************************************************
***************************************************************************************************************************
PARAMETERS

  A       constant #1 in the Quadratic production function (SR  *FR)
  B       constant #2 in the Quadratic production function (SR  *FR^2)
  C       constant #3 in the Quadratic production function (SR^2*FR)
  D       constant #4 in the Quadratic production function (SR^2*FR^2)

  ER      exchange rate in C per US$
  R       discount rate in percentage per year
  DF(T)   Discount factor per year

  P       price of output in US$ per unit output
  PS      price of variable inputs in Dollars per AU cattle
  PA      price of variable inputs in Dollars per ha land
  PF      price of variable inputs in Dollars per kg fertility
  PNA     price of new land in US$ per ha
  PNF     price of new fert in US$ per kg

  CNA2    constant #2 in the Land Investment cost function (purchase costs)
  CNA3    constant #3 (eta) in the Land Investment cost function (adjustment costs)
  CNF2    constant #2 in the Fert Investment cost function (purchase costs)
  CNF3    constant #3 (eta) in the Fert Investment cost function (adjustment costs)
  BETA    power in the Investment cost function (adjustment costs)

  NDR     nitrogen loss through leaching & denitrification & volatilization & litter conversion in % of total N per yr
  NER     nitrogen efficiency rate in % of applied nitrogen per yr
  DELTA1  nitrogen input from rain and fixation in kg per ha per yr
  DELTA2  nitrogen loss through grazing in kg per AU per yr
  NINI    initial nitrogen availability in kg N per ha
;
* Quadr. p.f. Q(SR,FR)
A      =    0.851608624545;
B      =   -0.000490105252665;
C      =   -0.170629425197;
D      =    9.81981336706e-05;

ER     =  179.6300 ;
R      =    0.0691 ;
DF(T)  = 1/((1+R)**ORD(T));
P      =    1.4100 ;
PS     = (136.3676316*P)+((87833.4/38/ER)+((34.26/38)*1600/ER)) ;
PA     = (((3734+3599)/ER)+(1.59*1600/ER)) ;
PF     =    0.0000 ;
PNA    =  629.8208 ;
PNF    =  (180/ER) ;
```

```
CNA2   =    1.0000 ;
CNA3   =    6.8640 ;
CNF2   =    1.0000 ;
CNF3   =   (((CNA3/(9.1*8))*3)/626.4047)*0.1 ;
BETA   =    2.0000 ;

NDR    =   (0.1000 + 0.0050) ;
NER    =    0.6000 ;
DELTA1 =   16.0000 ;
DELTA2 =   37.2000 ;
NINI   = 1200.0000 ;

*************************************************************************************************************************
*** DEFINITION OF VARIABLES *********************************************************************************************
*************************************************************************************************************************
VARIABLES
  vPI(T)         annual profit flow in US$ per yr
  vV             discounted sum of annual profit flows in US$
;
POSITIVE VARIABLES
  vNF(T)         gross annual investments in fert in kg per year (yr)
  vNAB(T)        gross annual investments in land in ha per year (yr)
  vNAS(T)        gross annual dis-investments in land in ha per year (yr)
  vA(T)          annual land use in hectare (ha) per yr
  vF(T)          annual fert use in kilogram (kg) per yr
  vFSR           fixed stocking rate in AU per ha per yr
  vSR(T)         annual stocking rate in AU per ha per yr
  vFR(T)         annual fert rate in kg per ha per yr
  vS(T)          annual cattle use in animal units (AU) per yr
;
*************************************************************************************************************************
*** DEFINITION OF EQUATIONS *********************************************************************************************
*************************************************************************************************************************
EQUATIONS
  eSR(T)         equation defining annual stocking rate in AU per ha per yr
  eMA(T)         equation of motion for land in ha
  eMF(T)         equation of motion for fert in kg
  ePI(T)         equation defining annual profit flow in US$ per yr
  eV             equation defining objective function in US$
;
*** DEFINITION OF LOWER/UPPER LEVELS AND STARTING VALUES *****************************************************************
*************************************************************************************************************************
  vV.L        =  89185.184 ;

  vPI.LO(T)    = -2.0E+6 ;

  vA.LO(T)     =    1.0000 ;
  vA.UP(T)     = 1500.0000 * 1.0000 ;
  vA.L(T)      =  179.5070 * 1.0000 ;
  vA.FX("0")   =    1.0000 ;

  vNAB.LO(T)   =    0.0001 ;
  vNAB.L(T)    =   24.6910 ;
  vNAS.LO(T)   =    0.0001 ;
  vNAS.L(T)    =   24.6910 ;

  vF.LO(T)     =    1.0000 * 1.0000 ;
  vF.UP(T)     = 1500.0000 * NINI ;
  vF.L(T)      =  179.5070 * 593.125 ;
  vF.FX("0")   =    1.0000 * NINI ;

  vNF.LO(T)    =    0.0001 ;
  vNF.UP(T)    =  179.5070 * 593.125 * 4.0000 ;
  vNF.L(T)     =    0.0002 ;
```

```
*** EQUATIONS ***********************************************************************************************************
*************************************************************************************************************************
  eSR(T)..       vSR(T)  =E= vFSR ;

  eMA(T+1)..     vA(T+1) =E= vA(T) + vNAB(T) - vNAS(T) ;

  eMF(T+1)..     vF(T+1) =E= (1-NDR)*vF(T) + DELTA1*vA(T) + NER*vNF(T) + NINI*vNAB(T)
                           - (vF(T)/vA(T))*vNAS(T) - DELTA2*vFSR*vA(T) ;

  ePI(T)..       vPI(T)  =E=  P*(  ((A*(vFSR)+C*(vFSR**2))*((vF(T)   )      ))
                                 + ((B*(vFSR)+D*(vFSR**2))*((vF(T)**2)/vA(T))) )
                            - PS*vFSR*vA(T) - PA*vA(T) - PF*vF(T)
                            - CNA2*PNA*vNAB(T) - CNA3*(vNAB(T)**BETA)
                            + CNA2*PNA*vNAS(T) - CNA3*(vNAS(T)**BETA)
                            - CNF2*PNF*vNF(T)  - CNF3*(vNF(T)**BETA) ;

  eV..           vV      =E= SUM(T, DF(T)* vPI(T)) ;

*************************************************************************************************************************
*** MODEL, OPTIONS AND SOLVE STATEMENTS *********************************************************************************
*************************************************************************************************************************

MODEL Ch7_05 / ALL /
;
OPTION
  NLP     = CONOPT2
  LIMCOL  = 1
  LIMROW  = 1
  ITERLIM = 100000
  RESLIM  = 2500
;
SOLVE Ch7_05 USING NLP MAXIMIZING vV
;
```

8 Discussion and conclusions

The main purpose of this study is to obtain a better understanding of the economic rational underlying the investment and resource use decisions of cattle ranchers in Latin America. To this effect, we develop an analytical framework that enables the analysis of these decisions and assess the factors that are considered to have contributed to the expansion of cattle ranching over the last decades. This chapter deals with the implications of the study and is structured as follows. Section 8.1 presents the main results and relates them to the research objectives as defined in Chapter 1. In Section 8.2, the main policy implications of these findings are discussed. Section 8.3 summarizes the most important limitations of this study and provides suggestions for future research.

8.1 Expansion of cattle ranching

8.1.1 Causes of expansion

The factors underlying the expansion of cattle ranching in Latin America since the 1960's have been – and still are – highly discussed in the so-called "cattle ranching debate" in the literature. The first objective of this research is to recapitulate the different economic factors that the literature mentions as the causes of the expansion of cattle ranching. Analysis shows that the expansion is generally attributed to (see Chapter 2):

- the characteristics of cattle ranching, which facilitates the development of relatively large pasture establishments in agrarian frontier forest areas where markets do not yet exist or are distant;
- the increased Latin American demand for beef products in general, and the increased local demand for beef products in particular;
- government policies, like subsidized livestock credit, infrastructure development, land titling and migration programs, which provide cattle ranchers the incentive to expand their cattle ranching activities;
- land speculation, as cattle ranchers hold more land for beef production than what would be optimal from a productive point of view, due to the fact that land ownership provides economic returns from beef production as well as from speculation with land;
- resource degradation, as forest areas are an important source of fertility and because more land is required to maintain beef production.

We recognize, however, that the cattle ranching debate is mostly qualitative and also incomplete in a number or respects. It remains unclear why beef production increased despite the considerable decrease and variability in real beef prices since the mid-1970's. Furthermore, the role of land speculation as a contributor to deforestation is highly debated and it largely comes down to whether or not land prices tend to rise over time. Finally, the literature deals only sparsely, and then mostly qualitatively, with the effect of resource degradation on the expansion of cattle ranching.

8.1.2 Analytical framework

A greater understanding of the economic rationale of cattle ranchers in Latin America may help to shed new light on the cattle ranching debate. Consequently, the second objective of this research is to develop an analytical framework that enables the investigation of investment and resource use decisions of cattle ranchers in Latin America.

Existing cattle ranching models are not considered adequate for analyzing resource use and investment decisions of cattle ranchers in Latin America. Though benefit-cost approaches appear to be a flexible tool in dealing with complex bio-economic relations, they do not take the optimizing behavior of the cattle rancher into account (*e.g.* Browder, 1988; Hecht *et al*., 1988; Smith *et al*., 1997). Dynamic optimization approaches do pay attention to the cattle rancher's optimizing behavior, but are more restrictive in dealing with complex bio-economic relations (*e.g.* Standiford and Howitt, 1992; Nicholson *et al*., 1994; Costanza and Neuman, 1997; Bulte *et al*., 2000). These approaches invariably assume a fixed farm size (*i.e.* land is not considered an investment option) and ignore uncertainty or resource degradation, despite the fact that these aspects are fundamental to cattle ranching in Latin American (Squirres and Vera, 1992; Downing *et al*., 1992; Kaimowitz, 1996; Faminow, 1998).

On the basis of the dynamic Neoclassical investment theory with adjustment costs (Eisner and Strotz, 1963; Gould, 1968; Treadway, 1969; Mussa, 1977; Abel, 1990), we develop a relatively simple farm-economic model for cattle ranchers in Latin America. The cattle rancher is considered a profit maximizer, who sees land as a productive resource (pasture based beef production) as well as an investment object (see Chapter 4). This approach holds a number of advantages compared to the earlier mentioned dynamic cattle ranching and livestock models. First, it is relatively simple because the complex relation between agro-ecological conditions, pastures and cattle is summarized in a production function for pasture-based beef production that directly relates stocking rate to beef production. Second, the derived reduced form equations unambiguously relate resource use and investment decisions to price and production parameters. Third, it does not consider farm size as fixed and, consequently, treats land not only as a productive resource but also as an investment object. Finally, the model allows for the inclusion of stochastic processes (see Chapters 5 and 6) and soil nutrient dynamics (Chapter 7).

Model indicators include the value of the farm, rate of investment, farm size, cattle stock, stocking rate and beef production. We use farm size and rate of investment as proxies for the pressure on and deforestation of agrarian frontier forest areas: first, farm size because cattle ranchers generally operate at agrarian frontier forest areas (see Chapter 2) and second, the rate of investment because a larger rate of investment implies a larger farm size (see Chapters 4 to 7) and because the rate of investment is indicative for the speed at which cattle ranchers move into the forest to maintain soil fertility at the desired level (see Chapter 7). Numerical applications of the different versions of the cattle ranching model developed in this study are given for the Atlantic Zone (AZ) of Costa Rica.

8.1.3 Explaining the expansion

In the first step of this research, we found that the economic factors behind the expansion of cattle ranching in Latin America, currently put forward in the cattle ranching debate, are in some cases qualitative and incomplete. Therefore, the final objective of this research is to assess the effects of those economic factors. In particular, we assess the effect of decreasing and fluctuating beef prices, resource degradation, and land speculation on the investment and resource use decisions of cattle ranchers.

Beef prices

Latin American beef production increased considerably over the last decades, despite the general decrease and relatively large fluctuations in real beef prices since the mid 1970's (see Chapter 2) and the sensitivity of cattle ranchers to decreases in beef prices (see Chapter 4). Within the demand (beef price) debate, the increase in beef production has been attributed to the increased Latin American demand for beef products in general (Seré and Jarvis, 1992; Kaimowitz, 1996; Faminow, 1998) and the increased local demand for beef products in particular (Faminow, 1997). So far, nobody has emphasized the importance of speculative returns from beef production, while in practice cattle ranchers can obtain short-term gains by adjusting the level of beef production in response to changing beef prices.

We explicitly relate investment decisions of cattle ranchers to expected drifts and fluctuations in beef prices, through the development of a stochastic version of the cattle ranching model in which beef prices are modeled as a geometric Brownian motion (see Chapter 5). It turns out that the expected rate of investment is increasing in the drift and standard deviation in beef prices, as the marginal production value of land is increasing in the drift and standard deviation in beef prices due to larger future and speculative returns from beef production, respectively.

The numerical example for the AZ of Costa Rica reveals that the expected rate of investment may be positive even when deterministic economic analysis (which assumes all prices constant over time) indicates that beef prices are too low to purchase land for beef production. This is a particularly interesting result because numerous deterministic economic studies have stressed that cattle ranching in Latin America is only profitable in the presence of speculative returns from land and/or government subsidies (see for example Edelman, 1985; Hecht *et al.*, 1988; Jarquín, 1990; Van der Kamp, 1990; Mattos and Uhl, 1994). Furthermore, the numerical example indicates that the rate of investment can be positive even when beef prices are expected to decrease over time. With respect to this latter point, it is worth noting that real beef prices in Costa Rica were relatively high and stable till the mid-1970's, while they showed a general decrease and far larger fluctuations as of the mid 1970's (FAO, 2002). Despite this decrease in beef prices, cattle ranchers increased the rate of investment in response to the more strongly fluctuating beef prices, to gain speculative returns from beef production. Consequently, the increase in the total pasture area and beef production in Costa Rican was and is, amongst others, triggered by the speculative returns from beef production.

Summarizing, it is shown that the expected rate of investment and farm size are deflated due to expected decreases in beef prices but inflated due to expected fluctuations in beef prices. For the case of Costa Rica, the inflationary effect resulting from fluctuations in beef prices outweighs the deflationary effect resulting from expected decreases in beef prices, with subsequent consequences for deforestation. In contrast, Jarvis (1986) states that beef price instability reduces the attractiveness of beef production in most Latin American countries. Although this may be true for risk-aversive cattle ranchers, this study demonstrates that beef price instability increases the attractiveness of beef production for risk-neutral cattle ranchers.

Resource degradation

Soil nutrient depletion is considered the principal cause of pasture degradation and subsequent declining pasture productivity in tropical Latin America (Myers and Robbins, 1991; Williams and Chartres, 1991). With progressive pasture degradation, cattle ranching will become less profitable, used infertile pastureland will be abandoned, and new fertile forested land will be bought (Haynes and Williams, 1993; Kaimowitz, 1996).

Existing economic farm models that consider the trade-off between current soil degradation and future productivity invariably assume a fixed farm size (see for example McConnell, 1983; Barbier, 1990; Barret, 1991; Bulte and Van Soest, 1999; Bulte *et al.*, 2000). However, this assumption is not applicable to cattle ranching in Latin America, where land is seen both as a productive resource and as an investment object (see Chapters 2, 4 and 6) and where cattle ranchers operating at the agrarian frontier consider forested land an important source of fertility (Kaimowitz, 1996). For that reason, we develop a deterministic reversible investment model, which specifically takes soil nitrogen dynamics as well as land dynamics into account (see Chapter 7). This model enables the determination of the optimal size of the soil nutrient stock (like the basic nutrient stock models) as well as the optimal farm size and rate of investment.

The illustrative example for the AZ of Costa Rica indicates that soil nitrogen depletion is economically efficient from the cattle rancher's perspective. Contrary to the model version with fixed farm size and the findings of Bulte *et al.* (2000), however, the soil is not completely mined and cattle ranching is not abandoned. Instead, forested (fertile) land is continuously purchased and used (degraded) land is continuously sold as this maintains the ranch's soil fertility at its optimal level. Current relative prices do not provide the economic incentive to apply fertilizer, as nitrogen availability for uptake and nitrogen efficiency by natural pastures is relatively low (Bouman *et al.*, 1999b). Sufficiently large fertilizer price subsidies do lead to the application of fertilizer and, in line with Barret (1991) and Faminow (1998), result in some land use intensification and reduced resource degradation. However, fertilizer price subsidies lead to an increase in optimal farm size and rate of investment, and thereby catalyze deforestation.

In sum, it is shown that resource degradation provides cattle ranchers with an incentive to continuously convert forest into pasture, as forest areas form an important source of fertility for cattle ranchers operating at the agrarian frontier (Kaimowitz, 1996). Fertilizer does not form an economically viable alternative for soil fertility, as current fertilizer prices and application costs per kilogram are far higher than the cost per kilogram of soil fertility obtained through deforestation.

Land speculation

Within the cattle ranching debate, land speculation is often considered the most important source of expansion of cattle ranching in Latin America. Cattle ranching, supposedly, not only provides recurrent returns from beef production, but is also viewed as the easiest vehicle to secure the land while waiting for land prices to rise

(Hecht, 1992; Kaimowitz, 1996; Faminow, 1998). For that reason, cattle ranchers hold more land for beef production than what would be optimal from a productive point of view (Kaimowitz, 1996; Jansen *et al*, 1997; Smith *et al*, 1997). Proof for the hypothesis that land speculation leads to inflated levels of investment in land is, however, invariably related to the question whether land prices tend to rise over time and, thus, addressed in a deterministic context (see for example Fearnside, 1990; Diegues, 1992; Hecht *et al.*, 1988; Kaimowitz, 1996; Smith *et al.*, 1997; Faminow, 1998). We note, however, that speculation refers to the situation in which an economic agent responds to rapidly changing prices (Pass *et al.*, 2000). Consequently, we specifically differentiate between the effect of increasing land prices and the effect of fluctuating land prices on investment and resource use decisions of cattle ranchers.

To this end, we develop a stochastic cattle ranching model in which land prices are modeled as a geometric Brownian motion (see Chapter 6). It is shown that the expected rate of investment is decreasing in the drift in land prices and increasing in the standard deviation in land prices, due to larger replacement investment costs and larger speculative returns from land, respectively.

The numerical example for Costa Rica reveals that the expected rate of investment can be positive even when land prices are expected to increase over time, as sufficiently large fluctuations in land prices provide the economic incentive (*i.e.* speculative returns form land) to develop cattle ranching activities. Our results do not sustain the often mentioned notion that increasing land prices lead to inflated levels of investment in land (Hecht *et al.*, 1988; Fearnside, 1990; Diegues, 1992; Hecht, 1992; Kaimowitz, 1996; Smith *et al.*, 1997; Faminow, 1998). If depreciation of pastureland is taken into account, increasing land prices lead to larger replacement investment costs and, consequently, to deflated levels of investment in land. An increase in the land sales price relative to the land purchase price (at a specific moment in time) leads to inflated levels of investment in land as investment costs decrease due to the increased land sales returns (see Chapter 7). Furthermore, the numerical example shows that livestock interest rate subsidies lead to inflated levels of investments in land, although this effect is relatively small compared to the inflated levels of investment that are triggered by fluctuations in land prices (Chapter 4; Solera-Ruíz, 1981; Ledec, 1992; Fearnside, 1989).

Consequently, it can be concluded that variability in land prices alone is a sufficient condition for land speculation and inflated levels of investment in land, with consequences for deforestation of agrarian frontier areas. Furthermore, we refine the land speculation debate by showing that increasing land prices only lead to inflated levels of investment in land if the land sales price increases relative to the land purchase price. The notion of Van Hijfte (1989), Jones (1990) and Kaimowitz (1996) – that land price appreciation leads to extensification and deforestation – is only correct when the land sales price increases relative to the land purchase price. When both the land purchase and the land sales price increase, the opposite occurs: extensification and deforestation slow down.

8.2 Policy implications

Land prices play an important role in the Latin American cattle ranching debate, as cattle ranchers view land as a productive resource as well as an investment object. As shown, an increase in the general land price (*i.e.*

purchase and sales price of land) leads to a decrease in the optimal farm size and rate of investment (see Chapters 4, 6 and 7), while an increase in the sales price of land (*i.e.* relative to the purchase price of land) leads to an increase in the optimal farm size and rate of investment (see Chapter 7). In agrarian frontier forest areas, land prices tend to rise because the marginal production value of land increases as a result of infrastructure development, forest clearing and population growth (Fearnside, 1990; Diegues, 1992; Kaimowitz, 1996). Note, however, that this does not necessarily imply that the general land price increases. Consequently, government road construction and migration programs in agrarian frontier forest areas boost the land sales prices, and encourage cattle ranchers to move further and faster into the forest. Resource degradation, which results from the conversion of tropical forest to pasture for cattle ranching (see Chapter 7), accelerates this process further. On the other hand, improvement of existing infrastructure leads to reduced transport costs, lower input costs and, consequently, could encourage land use intensification (see Chapters 4 and 7). Whether road construction into agrarian frontier areas should be preferred over improvement of existing infrastructure, depends on the costs, benefits and welfare losses (due to deforestation) of both investment options.

Most of the land that is converted from forest to pasture over the past decades used to be government-owned. Forested land could either be claimed by showing that the land had been used for a number of years (Jones, 1990), or was bought from the government at a price well below its market or marginal production value (Kaimowitz, 1996). Chapter 4 shows that the rate of investment in land is increasing in the difference between the purchase price of land and the marginal production value of land. Consequently, the government policy of supplying land at a price well below the marginal production value of land leads to relatively large cattle ranches. In fact, governments in Latin America might have earned equal (or higher) returns, had they sold forested land at a price closer to the marginal production value of land. This would also have facilitated the enforcement of land taxes and reduced welfare losses related to deforestation.

Furthermore, we have shown that uncertainty in land prices leads to inflated levels of investments in land and deforestation by cattle ranchers, relative to a situation with constant land prices (see Chapter 6). A land price stabilization policy could reduce these effects. However, land prices are somewhat difficult to control as they are, to a large extent, determined on the local land market and, moreover, greatly influenced by erratic infrastructure development. According to the macro-economic theory, however, an increase in (land) prices leads to a decrease in the interest rate, and *vice versa* (*e.g.* Branson, 1989). An interest rate stabilization policy can therefore reduce fluctuations in land prices, which, in turn, leads to reduced levels of deforestation and of subsequent welfare losses. Moreover, interest rate stability is also favorable for other sectors in the economy (*e.g.* Gillis, *et al*., 1987).

Uncertainty in beef prices is somewhat lower than uncertainty in land prices, but in the same way leads to inflated levels of investments in land and deforestation by cattle ranchers (see Chapter 5). Similarly, a beef price stabilization policy could reduce these effects. Beef prices are, however, to a large extent determined on the international beef market (Seré and Jarvis, 1992; Kaimowitz, 1996). Nevertheless, beef prices can be stabilized around a certain level or trend, by, for example, applying an import tax or import quota (export tax or export quota) whenever the international beef price lies below (above) the pre-defined national beef price. Subsequent welfare losses should be compared to the welfare gains that are obtained from the reduction in deforestation.

Government credit schemes and interest rate subsidies have been widely provided to cattle ranchers in Latin America, and helped cattle ranchers to overcome credit constraints, while also making cattle ranching a relatively attractive investment option (Ledec, 1992; Kaimowitz, 1996, Faminow, 1998). Although interest rate subsidies undoubtedly promote the expansion of cattle ranching and thus deforestation, numerous studies (*e.g.* Solera-Ruíz, 1981; Ledec, 1992; Fearnside, 1989) as well as Chapter 4 and 6 of this study show that cattle ranchers are not very responsive to interest rate subsidies. Consequently, one can ask whether an interest rate subsidy is the most effective instrument to promote the development of agrarian frontier areas. Moreover, interest rate subsidies distort investment priorities within as well as outside the agricultural sector, and direct scarce capital away from investment options with higher returns.

Beef production per animal head and per hectare increased with 33% and 120% over the last four decades, and is explained by the almost doubled stocking rate in combination with declining beef prices and the adoption of more productive cattle and pasture species (see Chapter 2). It is, however, unlikely that support for cattle ranching research and extension leads to a reduction in deforestation. Technological change oriented towards the development of more productive pasture varieties and cattle species leads to an increase in the marginal production value of land and, consequently, encourages investments in land and deforestation (Von Amsberg, 1994; Kaimowitz, 1996; Chapter 4). On the other hand, technological change oriented towards reduced fertilizer leaching leads to land use intensification (higher stocking rates), a relatively small increase in the optimal farm size and rate of investment, and will also reduce nutrient depletion (see Chapter 7). Consequently, although technological change will not lead to lower levels of deforestation, it may help to reduce soil nutrient depletion and help to prevent resource degradation.

8.3 Future research

In this study we developed a farm-economic approach at the farm level, to gain insight in the resource use and investment decisions of cattle ranchers in Latin America as well as the consequences of these decisions for deforestation. We summarize the most important limitations of the presented approach, and provide suggestions for future research.

Although the presented approach takes into account that wages rise when aggregate labor demand increases, it is essentially of a partial-equilibrium nature. This implies that secondary price effects resulting from interactions with other economic agents are not considered. Cattle ranchers are, however, expected to have limited influence on the formation of beef, labor and input prices because: 1) beef prices are determined on the international market, 2) cattle ranching is characterized by relatively low labor and input requirements, and 3) cattle ranchers represent a very small minority relative to the total number of farmers (see Chapter 2). On the other hand, cattle ranchers are expected to influence the formation of land prices, which further justifies the use of a convex investment cost function (see below).[49] Consequently, general equilibrium effects that are not already considered in the presented approach are expected to be of limited influence on the presented results. Nevertheless, it would be extremely interesting to consider the aggregate effect of all agricultural producers on regional land use and deforestation. This would require a general-equilibrium or a multi-agent approach. It would enable us to address issues like “How long can deforestation continue?” and “To whom does the cattle rancher sell his land?"

We argued that the investment cost function is convex in the rate of investment, as the installation of pastureland becomes more expensive when done quicker (see Chapter 4). It is reasoned that adjustment costs related to investments in land are considered a function of labor requirements for forest clearing, while taking into account that wages will rise when aggregate labor demand increases. This may seem far-fetched and, also, does not explain why it would be more costly to sell more land at the same time. Another, more compelling, approach is to determine the investment cost function on the basis of the regional own-price elasticity of demand and supply for land. This would, however, also lead to a convex investment cost function, as an increase in aggregate demand for land would lead to a rise in land prices, and *vice versa*. In fact, the exponential investment cost function applied in Chapter 6 could be an appropriate functional form of the investment cost function in this case. Consequently, the assumption of convex investment costs seems reasonable for the case of Latin American cattle ranchers. Ideally, however, the investment cost function should be determined on the basis of the own-price elasticity of demand and supply for land, as well as the installation costs of pastureland.

Furthermore, we assumed that investments in land are reversible, which implies that the cattle rancher can buy and sell land at any moment in time against the prevailing land price. The costs related to the adjustment of the land stock are sunk costs. In some cases, however, the cattle rancher cannot sell his land due to, for example, political instability. Consequently, the model would become irreversible. Abel and Eberly (1997) show that the shadow value of land is unaffected by the irreversibility assumption, and that the only effect of irreversibility on investment behavior is that the rate of investment is set to zero, whereas it would otherwise have been negative. The value of the farm, on the other hand, is reduced as a result of not being able to sell land. Consequently, the assumption of irreversibility will not alter the direction of our results.

We also assumed that cattle is a variable input, which implies that the cattle rancher can adjust his level of beef production in response to (for example) a change in beef prices by adjusting the land and cattle stock, though not by selling the cattle at a lower or higher age. Although data from the Costa Rican National Production Board (CNP) as well as Jarvis (1986) and Kaimowitz (1996) indicate that cattle ranchers mainly adjust their farm size and/or cattle stock in response to changed market conditions, the model would provide additional economic insight if it were to allow for the possibility of selling beef cattle at a lower or higher age. Taking into account this so called “endogenous time lag” would lead to a further increase in the profitability

---

[49] Cattle ranchers are the most important buyers of agrarian frontier forest land and the most important suppliers of deforested land (see Chapter2, 6 and 7).

of cattle ranching (see, for example, Brazee and Mendelsohn, 1988). As a result, incorporation of an endogenous time lag may alter the size though not the direction of our results.

The cattle ranchers' optimization problem is characterized by simple profit maximization. This is often considered a too simplified representation of the cattle rancher's objective function, for several reasons. First, it does not take into account the prestige value related to land and cattle ownership (Ledec, 1992; Kaimowitz, 1996). Second, this formulation implies that the cattle rancher is considered a risk-neutral individual, who prefers the alternative with the highest expected monetary returns despite the probability of gains or losses (Robinson *et al*., 1984). The cattle rancher might as well have been modeled as being risk-averse or risk-loving, which would imply that the expected utility from the monetary income is characterized by decreasing or increasing marginal utility, respectively (Hardaker *et al*., 1997). The formulation of a utility function that considers the expected utility from land and cattle ownership as well as the expected utility obtained from profit given a certain risk attitude might therefore have been a more accurate representation of the cattle rancher's objective function. However, given that more land and cattle imply more prestige (Ledec, 1992; Kaimowitz, 1996) and that cattle ranchers are characterized as profit maximizers who do not depend on the income they obtain from cattle ranching (see Chapter 2, Section 2.2), we expect our results to be even underestimated due to the fact that we ignore prestige and risk attitude.

Finally, I would like to mention that the presented model does not address externalities related to deforestation, such as elevated emission levels of trace and greenhouse gases. The calculation of CO_2 emissions – via burning, methane production of cattle, and conversion of tropical forest into pasture – as well as N_2O and NO emissions – via the conversion of tropical forest into pasture – is, however, relatively simple and easily incorporated into the model.[50] Subsequent pricing of CO_2, N_2O and NO emission does not lead to problems in derivation of the model (these costs are linear and increasing in the rate of investment, farm size and cattle stock) and would lead to a reduction in the marginal production value of land. Hence, it can be expected that the imposition of a tax on the emission of CO_2, N_2O or NO, in line with the Kyoto protocol, would lead to lower levels of deforestation caused by cattle ranchers in Latin America and hence to reduced levels of trace and greenhouse gas emission.

---

[50] Johnson and Johnson (1995), for example, provide figures on the emission of methane by cattle, Plant and Keller (1999) and Veldkamp (1994) provide figures on soil organic carbon losses (in the form of CO_2) related to the conversion of tropical forest into pasture, and Keller *et al.* (1993), Keller and Reiners (1994) and Veldkamp *et al.* (1999) provide figures on the emission of N_2O and NO by pastures and tropical forests.

References

Abel, A.B., 1983. Optimal investment under uncertainty. The American Economic Review 73(1): 228-233.

Abel, A.B., 1985. A stochastic model of investment, marginal *q* and the market value of the firm. International Economic Review 26 (2): 305-322.

Abel, A.B., O.J. Blanchard, 1986. The present value of profits and cyclical movements in investment. Econometrica 54(2): 249-273.

Abel, A.B., 1990. Consumption and investment. Pages 726-778 in: Friedman, B. and F. Hahn (Eds) Handbook of monetary economics. Elsevier Science Publishers, New York: North-Holland, USA.

Abel, A.B. and J.C. Eberly, 1994. A unified model of investment under uncertainty. The American Economic Review 84(5): 1369-1384.

Abel, A.B. and J.C. Eberly, 1997. An exact solution for the investment and value of a firm facing uncertainty, adjustment costs, and irreversibility. Journal of Economic Dynamics and Control 21(4-5): 831-852.

Aguilar, I. and M. Solís, 1988. La elite ganadera en Costa Rica. Editorial de la UCR, San José, Costa Rica.

Antle, J. 1983. Infrastructure and aggregate agricultural productivity: International evidence. Economic Development and Cultural Change 31(3): 609-619.

Arnold, G.W. and M.L. Dudzinski, 1967. Studies on the diet of the grazing animal 2: The effect of physiological status in ewes and pasture availability on herbage intake. Australian Journal of Agricultural Research, 18: 349-359.

Baker, R.D., D. Micol and C. Béranger, 1992. Pasture fattening in the humid temperate zone. Pages 271-287 in: Jarrige, R. and C. Béranger (Eds) Beef cattle production. Elsevier Science Publishers, Amsterdam, The Netherlands. 487 pp.

Barbier, E.B., 1990. The farm-level economics of soil conservation: The uplands of Java. Land Economics 66(2): 199-211.

Barbier, E.B., J.C. Burgess and A. Markandya, 1991. The economics of tropical deforestation. Ambio 20(2): 55-58.

Barret, S., 1991. Optimal soil conservation and the reform of agricultural pricing policies. Journal of Development Economics 36(2): 167-187.

Bellman, R., 1957. Dynamic programming. Princeton N.J.: Princeton University Press. 340 pp.

Bennet, D., F.H.W. Morley, K.W. Clark and M.L. Dudzinski, 1970. The effect of grazing cattle and sheep together. Australian Journal of Experimental Agriculture and Animal Husbandry, 10: 694-709.

Binswanger, H.P., K. Deininger and G. Feder, 1995. Power distortians, revolt and reform in agricultural land relations. Pages 2661-2772 in: Behrman, J. and T.N. Srinivasan (Eds) Handbook of development economics: Volume IIIB. Elsevier Science Publishers, New York: North-Holland, USA.

Bishop, A.H. and H.A. Birrel, 1975. Efficiency of grazing/fodder conservation systems. Proceedings of Third World Conference Animal Production: p. 217-223.

Bosworth, D., P. Dawkins and T. Stromback, 1996. The economics of the labor market. Longman, Harlow, UK.

Bouman, B.A.M., A. Nieuwenhuyse and H. Hengsdijk, 1998. PASTOR: a technical coefficient generator for pasture and livestock systems in the humid tropics, version 2.0. Quantitative Approaches in Systems Analysis No.18. AB-DLO/C.T. de Wit Graduate school for Production Ecology. Wageningen, The Netherlands. 59 pp., plus appendices.

Bouman, B.A.M., R.A.J. Plant and A. Nieuwenhuyse, 1999a. Quantifying economic and biophysical sustainability trade-offs in tropical pastures. Ecological Modelling 120(1): 35-50.

Bouman, B.A.M. and A. Nieuwenhuyse, 1999b. Exploring options for sustainable beef cattle ranching in the humid tropics: A case study for the Atlantic Zone of Costa Rica. Agricultural Systems 59(2): 145-161.

Bouman, B.A.M., H.G.P. Jansen, R.A. Schipper, H. Hengsdijk and A. Nieuwenhuyse (Eds), 2000. Tools for land use analysis on differrent scales: With case studies for Costa Rica. Kluwer Academic Publishers, Dordrecht, The Netherlands. 274 pp.

Bourdon, R.M. and J.S. Brinks, 1986. The Colorado State University beef prodcution model. Pages 227-238 in: Spreen, T.H. and D.H. Laughlin (Eds) Simulation of beef cattle production systems and its use in economic analysis. Westview Press, London, UK. 269 pp.

Branson, W.H., 1989. Macroeconomic theory and policy. Harper & Row Publishers, New York, USA. 656 pp.

Brazee, R. and R. Mendelsohn, 1988. Timber harvesting with fluctuating prices, Forest Science 34: 359-372.

Brooke, A., D. Kendrick, A. Meerhaus and R. Raman, 1998. GAMS release 2.5: A user’s guide. GAMS Development Corporation, Washington D.C., USA. 262 pp.

Browder, J.O., 1988. Public policy and deforestation in the Brazilian Amazon. Pages 247-297 in: Repetto, R. and M. Gillis (Eds) Public policies and the misuse of forest resources. Cambridge University Press, Cambridge, UK.

Bulte, E.H. and D.P. van Soest, 1999. A note on soil depth, failing markets and agricultural pricing. Journal of Development Economics 58(1): 245-254.

Bulte, E.H., B.A.M. Bouman, R.A.J. Plant, A. Nieuwenhuyse and H.G.P. Jansen, 2000. The economics of soil nutrient stocks and cattle ranching in the tropics: optimal pasture degradation in humid Costa Rica. European Review of Agricultural Economics 27(2): 207-226.

Byrne, P.F., 1968. An evaluation of different stocking rates of Mereno sheep. Wool economic research report 13, Australian Bureau of Agricultural Economics, Australia. 80 pp.

Cadisch, G., R.M. Schunke and K.E. Giller, 1994. Nitrogen cycling in a pure grass pasture and a grass-legume mixture on a red latosol in Brazil. Tropical Grasslands 28: 43-52.

Carter, M.R. and J. Kalfayan, 1989. A general equilibrium exploration of the agrarian question. Madison, Wisconson, mimeo.

Chiang, A.C., 1992. Elements of dynamic optimization. McGraw-Hill, Singapore. 327 pp.

Chisholm, A.H., 1965. Towards the determination of optimum stocking rates in the high rainfall zone. Review of Marketing and Agricultural Economics 33: 5-31.

Conrad, J.M. and C.W. Clarck, 1987. Natural resource economics: Notes and problems. Cambridge University Press, Cambridge, UK. 231 pp.

Conrad, J.M., 1997. On the option value of old growth forest. Ecological Economics 22(2): 97-102.

Cornia, G.A., 1985. Farm size, land yields and the agricultural production function: An analysis for fifteen developing countries. World Development 13(4): 513-534.

Costanza, V. and C.E. Neuman, 1997. Managing cattle grazing under degraded forests: An optimal control apporach. Ecological Economics 21(2): 123-129.

Crotty, R., 1980. Cattle, economics and development. Farnham Royal: Commonwealth Agricultural Bureau, England. 253 pp.

DGEC [Dirección General de Estadística y Censos], 1987. Censo agropecuario 1984. Ministerio de Economía, Industria y Comercio, San José, Costa Rica.

Diegues, A.C., 1992. The social dynamics of deforestation in the Brazilian Amazon: An overview. Department Publication 36, United Nations research institute for social development, Geneva, Switzerland.

Dixit, A.K. and R.S. Pindyck, 1994. Investment under uncertainty. Princeton, NJ: Princeton University Press, New Jersey, USA. 468 pp.

Donald, A.D., F.H.W. Morley, P.J. Waller, A. Axelsen and J.R. Donnelly, 1978. Availability to grazing sheep of gastro-intestinal nematode infection arising from summer contamination of pastures. Australian Journal of Agricultural Research, 20: 189-204.

Downing, E.T., S.B. Hecht, H.A. Pearson and C. Garcia-Downing, 1992. Development or destruction. The conversion of tropical forest to pasture in Latin America. Westview Press, Boulder, Colorado, USA. 405 pp.

Edelman, M., 1985. Extensive land use and the logic of the latifundio: A case study in Guanacaste province, Costa Rica. Human Ecology 13: 153-185.

Edelman, M., 1992. The logic of latifundio, the large estates of Northwestern Costa Rica since the late nineteenth century. Stanford University Press, Stanford, USA. 478 pp.

Eisner, R. and R.H. Strotz, 1963. Determinants of business investment. In: Commission on money and credit impacts of monetary policy. Engelwood Cliffs: Prentice-Hall, New Jersey, USA.

Eswaran, M. and A. Kotwal, 1986. Access to capital and agrarian production organization. Economic Journal 96: 482-498.

Faminow, M.D., 1997. Spatial economics of local demand for cattle products in Amazon development. Agriculture, Ecosystems and Environment 62(1): 1-11.

Faminow, M.D., 1998. Cattle, deforestation and development in the Amazon: An economic, agronomic and environmental perspective. CAB International, New York, USA. 253 pp.

Faminow, M.D. and S.A. Vosti, 1998. Livestock deforestation links: Policy issues in the Western Brazilian Amazon. Pages 88-103 in: Nell, A.J. (Ed.) Livestock and the environment. Proceedings of the International Conference on Livestock and the Environment, organised by: World Bank, Food and Agricultural Organisation and International Agricultural Centre, Wageningen, The Netherlands.

FAO [Food and Agriculture Organization of the United Nations], 2002. The FAOSTAT databases. http://apps.fao.org/lim500/agri_db.pl or via the FAO homepage: http://www.fao.org/

Fearnside, P.M., 1989. Deforestation and agricultural development in Brazilian Amazonia. Interciencia 14: 291-297.

Fearnside, P.M., 1990. Predominant land uses in Brazilian Amazonia. Pages 233-251 in: Anderson, A.B. (Ed.) Alternatives to deforestation: Steps toward sustainable uses of the Amazon rain forest. Oxford University Press, New York, USA. 281 pp.

Feder, G., 1985. The relation between farm size and farm productivity. The role of family labor, supervision and credit constraints. Journal of Development Economics 18(2-3): 297-313.

Filho, M.B.D., 1990. Plantas invasoras em patagems cultivadas sa Amazonia: Estrategias de manejo e controle. Documentos 52, EMBRAPA-CPATU, Belém, Brazil.

Fisher, I., 1930. Theory of interest. Macmillan and Co, London, UK.

Gillis, M., D.H. Perkins, M. Roemer and D.R. Snodgrass, 1987. Economics of development: Second edition. W.W. Norton & Company Inc., New York, USA. 623 pp.

Gould, J.P., 1968. Adjustment costs in the theory of investment of the firm. Review of Economic Studies 35: 47-55.

Hardaker, J.B., R.B.M. Huirne and J.R. Anderson, 1997. Coping with risk in agriculture. CAB International, Oxon, UK. 274 pp.

Hayami, Y and K. Otsuka, 1993. The economics of contract choice: An agrarian perspective. Clarendon Press, Oxford, UK. 209 pp.

Hayashi, F., 1982. Tobin's marginal *q* and average *q*: A neoclassical interpretation. Econometrica 50 (1): 213-224.

Haynes, R.J. and P.H. Williams, 1993. Nutrient cycling and soil fertility in the grazed pasture ecosystem. Advances in Agronomy 49:119-199.

Heady, E.O. and J.L. Dillon, 1961. Agricultural production functions. Iowa State University Press, USA. 667 pp.

Hecht, S.B., 1985. Environment, development and politics: Capital accumulation and the livestock sector in Eastern Amazonia. World Development 13(6): 663-684.

Hecht, S.B., R.B. Norgaard and G. Possio, 1988. The economics of cattle ranching in Eastern Amazonia. Interciencia 13(5): 233-240.

Hecht, S.B., 1992. Logics of livestock and deforestation: The case of Amazonia. Pages 7-25 in: Downing, T.E., S.B. Hecht, H.A. Pearson and C. Garcia-Downing (Eds) Development or destruction: The conversion of tropical forest to pasture in Latin America. Boulder, CO: Westview, 405 pp.

Hengsdijk, H., A. Nieuwenhuyse and B.A.M. Bouman, 1998. LUCTOR: Land crop technical coefficient generator. A model to quantify cropping systems in the northern Atlantic Zone of Costa Rica. Version 2.0. Quantitative Approaches in Systems Analysis No.17. AB-DLO/C.T. de Wit Graduate School for Production Ecology. Wageningen, The Netherlands. 65 pp., plus appendices.

Hengsdijk, H., B.A.M. Bouman, A. Nieuwenhuyse, R.A. Schipper and J. Bessembinder, 2000. Technical coefficient genrators for quantifying land use systems. Pages 97-114 in: Bouman, B.A.M., H.G.P. Jansen, R.A. Schipper, H. Hengsdijk and A. Nieuwenhuyse (Eds) Tools for land use analysis on differrent scales: With case studies for Costa Rica. Kluwer Academic Publishers, Dordrecht, The Netherlands. 274 pp.

Hernández, M., Argel, P.J., Ibrahim, M.A. and L. 't Mannetje, 1995. Pasture production, diet selection and liveweight gains of cattle grazing *Brachiaria brizantha* with or without *Arachis pintoi* at two stocking rates in the Atlantic Zone of Costa Rica. Tropical Grasslands 29: 134-141.

Hirshleifer, J., 1965. Investment decisions under uncertainty: Choice-theoretic apporaches. The Quarterly Journal of Economics 4: 509-536.

Holmes, W., 1974. The role of nitrogen fertilizer in the production of beef from grass. Pages 57-69 in: Proceedings No.142, The Fertilizer Society, London, UK.

Holmes, W., 1980. Grazing management. Pages 125-174 in: Holmes, W. (Ed.), 1980. Grass, its production and utilization. Blackwell Scientific Publications, UK. 295 pp.

Holmes, W., 1987. Beef production from managed grasslands. Pages 91-100 in: Snaydon, R.W. (Ed.), 1987. Managed grasslands: Analytical studies. Elsevier Science Publishers, Amsterdam, The Netherlands. 285 pp.

Ibrahim, M.A, 1994. Compatibility, persistence and productivity of grass-legume mixtures for sustainable animal production in the Atlantic Zone of Costa Rica. Ph.D. thesis, Wageningen Agricultural University, Wageningen, The Netherlands. 129 pp.

Jansen, H.G.P, M.A. Ibrahim., A. Nieuwenhuyse, L. 't Mannetje, M. Joenje and S. Abarca, 1997. The economics of improved pasture and sylvipastoral technologies in the Atlantic Zone of Costa Rica. Tropical Grasslands 32: 34-44.

Jarquín, J, 1990. Sistema de producción pecuario e intermediación de leche y ganado en Nueva Guinea. Programa de Desarrollo Rural para la Zona de Nueva Guinea, Estudios de Base, Informe No.9. ULA-CDR, San José, Costa Rica.

Jarvis, L.S., 1986. Livestock development in Latin America. The World Bank, Washington, USA. 214 pp.

Johnson, K.A. and D.E. Johnson, 1995. Methane emissions from cattle. Journal of Animal Science 73(8): 2483-2492.

Jones, R.J. and R.L. Sandland, 1974. The relation between animal gain and stocking rate. Journal of Agricultural Science 83: 335-342.

Jones, J.R., 1990. Colonization and environment - land settlement projects in Central America. United Nations University Press, Tokyo, Japan. 155 pp.

Jorgenson, D.W., 1963. Capital theory and investment behaviour. American Economic Review 53: 247-259.

Kaimowitz, D., 1996. Livestock and deforestation in Central America in the 1980s and 1990s: A policy perspective. Center for International Forestry Research, Jakarta, Indonesia. 88 pp.

Kamien, M.I. and N.L. Schwartz, 1991. Dynamic optimization: The calculus of variations and optimal control theory in economics and management. Advanced Textbooks in Economics, North-Holland, Amsterdam, The Netherlands. 380 pp.

Kawagoe, T., Y. Hayami and V. Ruttan, 1985. The intercountry agricultural production function and productivity differences between countries. Journal of Development Economics 17: 113-132.

Keller, M., Veldkamp, E., Weitz, A.M., and Reiners, W.A., 1993. Pasture age effects on soil-atmosphere trace gas exchange in a deforested area of Costa Rica. Nature 365:244-246.

Keller, M. and W.A. Reiners, 1994. Soil-atmosphere exchange of nitruous oxide, nitric oxide, and methane under secundary succession of pasture to forest in the Atlantic Zone of Costa Rica. Global Biogeochemistry Cycles 8: 399-409.

Korver, S. and J.A.M. Arendonk (Eds), 1988. Modelling of livestock production systems. A Seminar in the European Community Programme for the Coordination of Agricultural Research. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Kutcher, G.P. and P.L. Scandizzo, 1981. The agricultural economy of Northeast Brazil. Johns Hopkins University Press, Baltimore, USA. 271 pp.

Langlands, J.P. and I.L. Bennet, 1973. Stocking intensity and pastoral production 3: Wool production, fleece characteristics and the utilization of nutrients for maintenance and wool growth by Mereno sheep grazed at different stocking rates. Journal of Agricultural Science 81: 211-218.

Ledec, G., 1992. The role of bank credit for cattle raising in financing tropical deforestation: An economic case study from Panama. Ph.D. dissertation, University of California, Berkely, USA.

Leonard, D. and N. van Long, 1992. Optimal control theory and static optimization in economics. Cambridge University Press, Cambridge, UK. 353 pp.

Lucas, R.E., 1967. Optimal investment policy and the flexible accelerator. International Economic Review 8: 78-85.

Lucas, R.E. and E.C. Prescot, 1971. Investment under uncertainty. Econometrica 39: 659-682.

Marciano, C., 1999. Integrated bio-economic land use models: An analysis of the possibilities of sustainable natural forest management in the Atlantic Zone of Costa Rica. Report 143, REPOSA (CATIE/MAG/WAU), Turrialba, Costa Rica. 104 pp.

Marsh, R., 1975. Systems of grazing management for beef cattle. Pages 119-128 in: Hodgson, J. and D.K. Jackson (Eds) Pasture utilization by the grazing animal. Occasional symposium No.8, British Grassland Society, Hurley, UK.

Mas-Colell, A., M.D. Whinston and J.R. Green, 1995. Microeconomic theory. Oxford University Press, Oxford, UK. 981 pp.

Mattos, M.N. and C. Uhl, 1994. Economic and ecological perspectives on ranching in the Eastern Amazon. World Development 22(2): 145-158.

May, R.M., 1992. How many species inhabit the earth? Scientific American 267(4): 18-24.

McConnell, K.E., 1983. An economic model of soil conservation. American Journal of Agricultural Economics 64: 83-89.

McMeekan, C.P., 1956. Grazing management and animal production. Pages 146-156 in: Proceedings of the 7th International Grassland Congress.

Morley, F.H.W., A. Axelson, K.G. Pullen and J.B. Nadin, 1978. Growth of cattle on phalaris and lucerne pastures, part 1: Effect of pasture, stocking rate and anthelmintic treatment. Agricultural Systems, 3: 123-145.

Morley, F.H.W., 1981. Management of grazing systems. Pages 379-400 in: Morley, F.H.W. (Ed.) Grazing animals. Elsevier Scientific Publishing Company, Amsterdam, The Netherlands. 411 pp.

Morrison, J., 1987. Effects of nitrogen fertilizer. Pages 61-70 in: Snaydon, R.W. (Ed.) Managed grasslands: Analytical studies. Elsevier Science Publishers, Amsterdam, The Netherlands. 285 pp.

Mussa, M., 1977. External and internal adjustment costs and the theory of aggregate and firm investment. Economica, 47: 163-178.

Myers, N., 1981. The hamburger connection: How Central America’s forests became North America’s hamburgers. Ambio 10: 3-8.

Myers, R.J.K. and G.B. Robbins, 1991. Sustaining productive pastures in the tropics 5: Maintaining productive sown grass pastures. Tropical Grasslands 25: 104-110.

Nicholson, C.F., D.R. Lee and R.N. Boisvert, 1994. An optimization model of the dual-purpose cattle production system in the humid lowlands of Venezuela. Agricultural Systems 46: 311-334.

Nickell, S.J., 1978. The investment decision of firms. Cambridge University Press, Oxford, UK. 326 pp.

Nieuwenhuyse, A., B.A.M. Bouman, H.G.P. Jansen, R.A. Schipper and R. Alfaro, 2000. The physical and socio-economic setting: The northern Atlantic Zone of Costa Rica. Pages 9-34 in: Bouman, B.A.M., H.G.P. Jansen, R.A. Schipper, H. Hengsdijk and A. Nieuwenhuyse (Eds) Tools for land use analysis on differrent scales: With case studies for Costa Rica. Kluwer Academic Publishers, Dordrecht, The Netherlands. 274 pp.

Noy-Meir, I., 1975. Stability of grazing systems: An application of predator-prey graphs. Journal of Ecology 63: 459-484.

Pass, C., B. Lowes and L. Davies, 2000. Collins dictionary of economics. HarperCollins Publishers, Glasgow, UK. 558 pp.

Pindyck, R.S., 1991. Irreversibility, uncertainty, and investment. Journal of Economic Literature 29: 1110-1152.

Plant, R.A.J., 1999. Effects of land use on regional nitrous oxide emissions in the humid tropics of Costa Rica. Ph.D. thesis, Wageningen Agricultural University, Wageningen, The Netherlands. 129 pp.

Plant, R.A.J. and M. Keller, 1999. Modeling changes in soil nitrogen cycling induced by conversion of tropical forest to pasture. Pages 25-38 in: Plant, R.A.J. (Ed.). Effects of land use on regional nitrous oxide emissions in the humid tropics of Costa Rica. Ph.D. thesis, Wageningen Agricultural University, Wageningen, The Netherlands. 129 pp.

Plant, R.A.J. and B.A.M. Bouman, 1999. Modeling nitrogen oxide emissions from current and alternative pastures in Costa Rica. Journal of Environmental Quality 28(3): 866-872.

Ridder, N., H. van Keulen, N.G. Seligman and P.J.H. Neate (Eds), 1986. Modelling of extensive livestock production systems: Proceedings of the ILCA/CABO Workshop. ILCA, Addis Ababa, Ethiopia. 349 pp.

Riewe, M.E., 1964. An experimental design for grazing trials using the relationship of stocking rate to animal gain. Pages 1507-1510 in: Proceedings of the 9th International Grassland Congress.

Rivas, L., C. Seré, L.R. Sanint and J.L. Cordeu, 1988. La situación de la demanda de carnes en países seleccionados de América Latina y el Caribe. Proyecto Coloborative FAO-RLAC/CIAT.

Robinson, L.J., P.J. Barry, J.B. Kliebenstein and G.F. Patrick, 1984. Risk attitudes: Concepts and measurement approaches. In: Barry, P.J. (Ed.) Risk management in agriculture. Iowa State University Press, Iowa, USA. 282 pp.

Roebeling, P.C., H.G.P. Jansen, A. van Tilburg and R.A. Schipper, 2000. Spatial equilibrium modelling for evaluating inter-regional trade flows, land use and agricultural policy. Pages 65-96 in: Bouman, B.A.M., H.G.P. Jansen, R.A. Schipper, H. Hengsdijk and A. Nieuwenhuyse (Eds) Tools for land use analysis on differrent scales: With case studies for Costa Rica. Kluwer Academic Publishers, Dordrecht, The Netherlands. 274 pp.

Sadoulet, S., and A. De Janvry, 1995. Quantitative development policy analysis. The Johns Hopkins University Press, Baltimore, USA. 397 pp.

Salas, W.U., J.S. León, J. Aguilar and C.V. Barboza, 1983. El sector agropecuario Costaricense: Un analisis dinamico 1950-1980. UCR-Escuela de Economía Agrícola, San José, Costa Rica. 198 pp.

Seré, C. and L.S. Jarvis, 1992. Livestock economy and destruction. Pages 95-113 in: Downing, T.E., S.B. Hecht, H.A. Pearson and C. Garcia-Downing (Eds) Development or destruction: The conversion of tropical forest to pasture in Latin America. Boulder, CO: Westview, 405 pp.

Simpson, J.R., 1988. The economics of livestock systems in developing countires: Farm and project analysis. Westview Press, London, UK. 297 pp.

Smith. J., J.V. Cadavid, A. Rincon and R. Vera, 1997. Land Speculation at the frontier: A seeming paradox in the Colombian savana. Agricultural Systems 54(4), 501-520.

Solera-Ruiz, C.L., 1981. Assessment of the goals and the policies of the national development plan 1979-1982 for beef cattle in Costa Rica. Ph.D. dissertation, Iowa State University, USA.

Spreen, T.H. and D.H. Laughlin (Eds), 1986. Simulation of beef cattle production systems and its use in economic analysis. Westview Press, London, UK. 269 pp.

Squirres, V.R. and R.R. Vera, 1992. Commercial beef ranching in tropical and semi-arid zones. Pages 437-454 in: Jarrige, R. and C. Beranger (Eds.) Beef cattle production. Elsevier, Amsterdam, The Netherlands, 487 pp.

Srinivasan, T.N. 1972. Farm size and productivity: Implications of choice under uncertainty. The Indian Journal of Statistics 34(B): 409-420.

Standiford, R.B. and R.E. Howitt, 1992. Solving empirical bioeconomic models: A rangeland management application. American Journal of Agricultural Economics 74(2): 421-433.

Stefanou, S.E., 1992. Economics of adjustment: Deterministic and stochastic analysis (draft). Pennsylvania State University, USA.

Stoorvogel, J.J. 1995. Geographical information systems as a tool to explore land characteristics and land use with reference to Costa Rica. Ph.D. thesis, Wageningen Agricultural University, Wageningen, The Netherlands. 151 pp.

Swanson, T.M., 1992. Economics of biodiversity convention. Ambio 21(3): 250-257.

Thomas, R.J., C.E. Lascano, J.I. Sanz, M.A. Ara, J.M. Spain, R.R. Vera and M.J. Fisher, 1992. The role of pastures in production systems, Pages 121-144 in: Pastures for the tropical lowlands: CIAT's contribution. Publication 211, Centro Internacional de Agricultura Tropical (CIAT), Cali, Colombia.

Tobin, J., 1969. A general equilibrium approach to monetary theory. Journal of Money and Credit Banking 1: 15-29.

Torell, L.A. K.S. Lyon and E.B. Godfrey, 1991. Long-run versus short-run planning horizons and the rangeland stocking rate decision. American Journal of Agricultural Economics 73(3): 795-807.

Treadway, A.B., 1969. On rational entrepreneurial behavior and the demand for investment. Review of Economic Studies, 36: 227-239.

Trueblood, M.A., 1989. Agricultural production function estimates from aggregate intercountry observations: A selected survey. Canadian Journal of Agricultural Economics 37: 1045-1060.

Uhl. C., Buschbacher, R. and E.A.S. Serrão, 1988. Abandoned pastures in Eastern Amazonia I: Patterns of plant succession. Journal of Ecology 76: 663-681.

Van der Kamp, E.J., 1990. Aspectos económicos de la ganadería en pequena escala y de la ganadería de la carne en la Zona Atlantica de Costa Rica. Report No.51, Phase 1, Atlantic Zone Program (CATIE/MAG/WAU), Turrialba, Costa Rica.

Van Hijfte, P.A., 1989. La ganadería de carne en el Norte de la Zona Atlántica de Costa Rica. Report No.31, Phase 1, Atlantic Zone Program (CATIE/MAG/WAU), CATIE, Turrialba, Costa Rica. 52 pp., plus appendices.

Van Kooten, G.C. and E.H. Bulte, 2000. The economics of nature: Managing biological assests. Blackwell Publishers, Oxford, UK. 512 pp.

Van Leeuwen, A.C.J. and A.M. Hofstede, 1995. Forests, trees and farming in the Atlantic Zone of Costa Rica: An evaluation of the current and future integration of trees and forests in farming systems in the Atlantic Zone of Costa Rica. Serie Técnica, Informe Técnico No.257, CATIE, Turrialba, Costa Rica. 55 pp., plus appendices.

Van Loon, M., 1997. Characterization of beef cattle farming in the Atlantic Zone of Costa Rica. Report 127, REPOSA (CATIE/MAG/WAU), CATIE, Turrialba, Costa Rica. 46 pp.

Varian, H.R., 1992. Microeconomic analysis. W.W. Norton & Company Inc., New York, USA, 506 pp., plus appendices.

Veldkamp, E., 1994. Organic carbon turnover in the three tropical soils under pasture after deforestation. Soil Science Society of America Journal 58: 175-180.

Veldkamp, E., E. Davidson, H. Erickson, M. Keller and A. Weitz, 1999. Soil nitrogen cycling and nitrogen oxide emissions along a pasture chronosequence in the humid tropics of Costa Rica. Soil Biology and Biochemistry 31(3): 387-394.

Von Amsberg, J., 1994. Economic parameters of deforestation. Policy Research Working Papers WPS 1350, World Bank, Washington D.C., USA.

Watkins, T., 2003. Introduction to cost benefit analysis. San José University, San José, California, USA. 6 pp. http://www.sjsu.edu/faculty/watkins/cba.htm.

White, H., 1980. A Heteroskedasticity-Consistent Covariance Matrix and a Direct Test for Heteroskedasticity. Econometrica 48: 817–838.

White, D.H., B.J. McConchie, B.C. Curnow and A.H. Ternouth, 1980. A comparison of levels of production and profit from Mereno ewes and wethers grazed at various stocking rates in northern Victoria. Australian Journal of Experimental Agriculture and Animal Husbandry, 20: 296-307.

White, D.H., 1987. Stocking rate. Pages 227-238 in: Snaydon, R.W. (Ed.) Managed grasslands: Analytical studies. Elsevier Science Publishers, Amsterdam, The Netherlands. 285 pp.

Wielemaker, W.G. and A.W. Vogel, 1993. Un sistema de información de suelos y tierras para la Zona Atlántica de Costa Rica. Report 22, REPOSA (CATIE/MAG/WAU), CATIE, Turrialba, Costa Rica. 82 pp.

Williams, R., 1986. Export agriculture and the crisis in Central America. University of North Carolina Press, Chapel Hill, USA. 257 pp.

Williams, J. and C.J. Chartres, 1991. Sustaining productive pastures in the tropics 1: Managing the soil resource. Tropical Grasslands 25: 73-84.

Willoughby, W.M., 1959. Limitations on animal production imposed by seasonal fluctuations in pasture and by management procedures. Australian Journal of Agricultural Research 10: 248-268.

World Bank, 1999. World development indicators. CD-ROM.

Zerbe, R.O. and D.D. Dively, 1994. Benefit-cost analysis in theory and practice. Harper Collins College Publishers, New York, USA. 557 pp.

Summary

It is generally acknowledged that cattle ranching in Latin America occupies the major part of the agricultural area, that pasture expansion in favor of cattle ranching is the principal cause of deforestation, and that the conversion of forest into pasture has important environmental consequences. Although the expansion of cattle ranching has been widely discussed in literature, the debate concerning the sources of expansion is mostly qualitative and incomplete. Consequently, the objective of this study is to obtain an improved understanding of investment and resource use decisions of cattle ranchers in Latin America, through the development of an analytical framework that enables the quantitative appraisal of factors that are considered to have contributed to the expansion of cattle ranching since the 1960's. The results that follow from this research are based on a farm-economic model for cattle ranchers in Latin America, where farm size and the rate of investment are used as proxies for the pressure on and deforestation of agrarian frontier forest areas. Farm size, because cattle ranchers mostly operate at agrarian frontier forest areas (see Chapter 2). The rate of investment, because a larger rate of investment implies a larger farm size (see Chapters 4 to 7) and because the rate of investment is indicative for the speed with which cattle ranchers move into the forest (see Chapter 7).

Chapter 2 provides an overview of the historical development of cattle ranching in Latin America, the debate regarding its sources of expansion, and the subsequent environmental consequences. It is recognized that cattle ranchers play a dominant role in Latin American agriculture, as they own the major part of the agricultural area and cattle stock. FAO figures over the period 1961 to 1999 indicate that permanent pastures accounted for no less than 80% of the agricultural area, while the share of permanent pastures in the total area increased from about 25% in 1961 to 30% in 1999. The expansion of the pasture area is largely facilitated by deforestation of tropical forest and woodland areas, and has important environmental consequences. It leads to a loss in species diversity, to an increase in the emission of trace and greenhouse gasses, and to resource degradation as a result of soil erosion and nutrient depletion.

Within this so called 'cattle ranching debate', the expansion of cattle ranching in Latin America is generally attributed to: 1) the characteristics of cattle ranching, which facilitates the development of relatively large establishments in remote areas, 2) the increased Latin American demand for beef products in general and the increased local demand for beef products in particular, 3) government policies, like interest rate subsidies, that provide cattle ranchers the incentive to expand their cattle ranching activities, 4) land speculation, as cattle ranchers hold more land for beef production than what would be optimal from a productive point of view due to the fact that land ownership provides economic returns from beef production as well as from speculation with land, and 5) resource degradation, as forest areas are an important source of fertility and because more land is required to maintain beef production. We recognize, however, that the debate concerning the sources of expansion of cattle ranching in Latin America is mostly qualitative and incomplete in a number or respects. It remains unclear why beef production increased despite the considerable decrease and variability in real beef prices as of the mid 1970's. Also, the role of land speculation as a contributor to deforestation is highly debated, and largely comes down to whether or not land prices tend to rise over time. Finally, the role of resource degradation on the expansion of cattle ranching is sparsely and mostly qualitatively dealt with in literature.

An overview of the most important investment theories to date and the mathematical tools that are used in the development of these theories is given in Chapter 3. Benefit-cost analysis (*BCA*) in general, and the net present value approach in particular, proves to be a flexible tool when dealing with relatively complex investment projects. Major disadvantages of *BCA* are, however, that it does not take into account the optimizing behavior of the decisionmaker, that the investment timing is fixed, and, consequently, that it does not lead to the determination of the optimal investment path over time. In response to these shortcomings, the Neoclassical and Tobin's *q*-theory of investment have been developed. On the basis of a specific objective function, the decisionmaker continues to invest in the fixed capital input up to the point where marginal costs of the investment are equal to marginal returns of this investment. Major disadvantage of the Neoclassical and Tobin's *q*-theory of investment is that it assumes that the investment is reversible. The option approach recognizes that an investment can also be irreversible, and that it may be profitable to delay an irreversible investment option as new information is obtained by waiting. This opportunity cost of investing forms part of the total investment costs, and is taken into account by the option approach.

Two mathematical tools prove to be useful in solving investment problems. First, we discuss the dynamic optimization techniques *calculus of variations*, *optimal control* and *dynamic programming*, which provide the opportunity to determine the optimal investment path that maximizes the discounted sum of annual profit streams over time. Second, we discuss the stochastic Wiener, Ito and Poisson processes, which provide the opportunity to characterize the development of uncertain variables over time that affect the decision to invest. Given the limited size of the time series data and the focus on the analytical tractability of the model, we model beef prices (Chapter 5) and land prices (Chapter 6) as an Ito process.

In Chapter 4 we develop a relatively simple farm-economic model for cattle ranchers in Latin America, on the basis of the dynamic Neoclassical investment theory with adjustment costs. This approach holds a number of advantages relative to earlier dynamic cattle ranching and livestock models. First, the farm size is not considered fixed and, thus, land is not only a productive resource (pasture based beef production) but also an investment object. Second, it is relatively simple because the complex relation between agro-ecological conditions, pastures and cattle is summarized in a stocking rate dependent production function for pasture based beef production. Third, the derived reduced form equations unambiguously relate resource use and investment decisions to price and production parameters. Finally, the model allows for the inclusion of stochastic processes (see Chapters 5 and 6) and soil nutrient dynamics (Chapter 7).

The numerical example for an average cattle rancher in the Atlantic Zone (AZ) of Costa Rica indicates that cattle ranchers are especially sensitive to changes in beef and land prices. An increase in the beef price leads to a larger optimal farm size and rate of investment, as the marginal production value of land increases. An increase in the land price leads to a reduction in the optimal farm size and the rate of investment, due to larger replacement investment costs. Although these results may not seem particularly surprising, they are important for two reasons. First, it gives rise to question why cattle ranching expanded so rapidly over the last decades, while real beef prices declined and real land prices increased (see Chapter 2). Second, it gives rise to the question whether and under what conditions rising land prices do lead to extensification and deforestation, which is frequently claimed in literature. We deal with these issues in Chapters 5 through 7.

A stochastic reversible investment model, in which beef prices are modeled as a geometric Brownian motion, is developed in Chapter 5. Although this model is a relatively simple application of the Neoclassical investment theory with uncertainty, it is the first cattle ranching model in which investment decisions by cattle ranchers are explicitly related to expected trends and fluctuations in beef prices. This is a particularly important issue, given the considerable increase in beef production despite the general decrease in real Latin American beef prices as of the mid 1970's (see Chapter 2) and the sensitivity of cattle ranchers to decreases in beef prices (see Chapter 4). So far within the demand (beef price) debate, this increase has been attributed to the increased Latin American and local demand for beef products in general.

The analytically derived investment rule indicates that cattle ranchers base their investment decisions not only on the level of beef prices, but also on the expected drift and fluctuation in beef prices. The expected rate of investment is increasing in the drift and standard deviation in beef prices, as the marginal production value of land is increasing in the drift and standard deviation in beef prices due to larger future and speculative returns from beef production, respectively. The numerical example for the AZ of Costa Rica shows that the expected rate of investment is underestimated (overestimated) in case beef prices are assumed constant while they actually tend to increase (decrease) or fluctuate over time. Furthermore, the expected rate of investment may be positive even when deterministic economic analysis (which assumes all prices constant over time) indicates that beef prices are too low to purchase land for beef production. Finally, it is shown that the rate of investment can be positive even when beef prices are expected to decrease over time. Consequently, it is concluded that the expansion of cattle ranching and deforestation is, amongst others, triggered by the speculative returns from beef production.

In Chapter 6 we develop a stochastic reversible investment model in which land prices are modeled as a geometric Brownian motion and where investment costs are either quadratic or exponential in the rate of investment. This model forms an extension to the existing Neoclassical investment theory with uncertainty, as the analytically derived investment rules indicate that the expected rate of investment is (not) determined by the standard deviation in land prices in case investment costs are exponential (quadratic) in the rate of investment. Within the cattle ranching debate, this approach sheds new light on the discussion whether increasing land prices and land speculation lead to inflated levels of investment in land and, consequently, deforestation. Proof for the hypothesis that land speculation leads to inflated levels of investment has, so far, only been related to the question whether land prices tend to rise over time.

It is proven analytically that the expected rate of investment is decreasing in the drift in land prices and increasing in the standard deviation in land prices, due to higher replacement investment costs and higher speculative returns from land, respectively. The numerical example for Costa Rica indicates that the expected rate of investment is underestimated (overestimated) in case land prices are assumed constant while they actually tend to decrease (increase) or fluctuate over time. Furthermore, and not surprisingly, it is shown that livestock interest rate subsidies lead to inflated levels of investments in land. Consequently, it is concluded that variability in land prices alone is a sufficient condition for land speculation and inflated levels of investments in land, with subsequent consequences for deforestation of agrarian frontier areas.

A deterministic reversible investment model, in which soil nitrogen dynamics as well as land dynamics are specifically taken into account, is developed in Chapter 7. This time, the production function for pasture based beef production directly relates the stocking rate as well as soil nitrogen availability to beef production. The model forms an extension to the existing models for soil nutrient stocks, as it relaxes the assumption of a fixed farm size and because it recognizes that the purchase (sale) of land implies a nutrient inflow (outflow). Given that cattle ranchers consider land as a productive resource as well as an investment object (see Chapter 2 and 6) and that forested land is an important source of fertility, it does not seem reasonable to assume a fixed farm size when considering cattle ranching in Latin America. Consequently, the presented model enables the determination of the optimal soil nutrient stock (like basic nutrient stock models) as well as the optimal farm size and rate of investment.

The numerical example for the AZ of Costa Rica indicates that soil nitrogen depletion is economically efficient from the cattle rancher's perspective. Contrary to the model versions with fixed farm size the soil is not completely mined and cattle ranching is not abandoned, as forested (fertile) land is continuously purchased and used (degraded) land is continuously sold in order to maintain soil fertility at its optimal level. Simulation results indicate that current relative prices do not provide the economic incentive to apply fertilizer on natural pastures, as the cost of nitrogen obtained from forested land is about half the cost of nitrogen obtained from fertilizer. A sufficiently large fertilizer price subsidy does, however, lead to the application of fertilizer, although the effect on land use intensification and reduced resource degradation is relatively small. Furthermore, simulation results indicate that an increase in the general land price (*i.e.* purchase and sales price of land) leads to a decrease in the optimal farm size and the rate of investment (in line with Chapter 4 and 6) and to an increase in soil fertility. On the other hand, an increase in the sales price of land leads to an increase in the optimal farm size and the rate of investment and, to a minor extent, to an increase in soil fertility. Consequently, it is concluded that land price appreciation only leads to extensification and deforestation, when the land sales price increases relative to the land purchase price.

Finally, in Chapter 8 the most important findings are presented and related to the specific objectives of this research, the major policy implications of these findings are presented, and, finally, the limitations of the applied approach are discussed and suggestions for future research are provided. In this research a comprehensive and flexible analytical framework is developed, which provides the opportunity to obtain an improved understanding of the economic rational underlying the investment and resource use decisions of cattle ranchers in Latin America. It is shown, from a farm-economic perspective, that resource degradation, land speculation, interest rate subsidies and speculative returns from beef production lead to inflated levels of investment in land and, subsequently, deforestation of agrarian frontier forest areas. Price stabilization policies and eradication of targeted interest rate subsidies are expected to yield the largest welfare gains.

Samenvatting (Summary in Dutch)

Het is algemeen bekend dat het grootste gedeelte van het landbouwareaal in Latijns Amerika bestaat uit grasland voor extensieve veehouderij, dat extensieve veehouderij de belangrijkste oorzaak van ontbossing is, en dat de transformatie van bos naar grasland belangrijke consequenties heeft voor het milieu. Hoewel de groei van de extensieve veehouderij uitgebreid besproken is in de literatuur, zijn de genoemde oorzaken die deze groei verklaren over het algemeen weinig kwantitatief onderbouwd en incompleet van aard. Het doel van dit onderzoek is, derhalve, om een beter inzicht te krijgen in de beslissingen van veeboeren in Latijns Amerika ten aanzien van investeringen (*t.w.* aankopen van land) en het gebruik van (natuurlijke) hulpbronnen. Met behulp van een analytische benadering worden, op kwantitatieve wijze, de factoren geëvalueerd die hebben bijgedragen aan de groei van de extensieve veehouderij sinds 1960. De resultaten van dit onderzoek zijn gebaseerd op een bedrijfseconomisch model voor veeboeren in Latijns Amerika, waarin bedrijfsomvang en investeringsniveau worden gebruikt als indicatoren voor de druk op en ontbossing van het (beboste) agrarisch grensgebied. Bedrijfsomvang wordt gehanteerd omdat veeboeren zich met name in het agrarisch grensgebied bevinden (zie Hoofdstuk 2), terwijl investeringsniveau wordt gebruikt omdat een hoger investeringsniveau een grotere bedrijfsomvang impliceert (zie Hoofdstuk 4 t/m 7) en indicatief is voor de snelheid waarmee veeboeren het bos intrekken (zie Hoofdstuk 7).

Hoofdstuk 2 geeft een overzicht van de historische ontwikkeling van de extensieve veehouderij in Latijns Amerika, het debat omtrent de oorzaken van zijn groei en de hieruit volgende consequenties voor het milieu. Veeboeren spelen een belangrijke rol in de agrarische sector van Latijns Amerika, aangezien ze het grootste deel van het landbouwareaal en de (rund-) veestapel bezitten. Data van de FAO over de periode 1961 tot 1999 tonen aan dat (permanent) grasland meer dan 80% van het landbouwareaal beslaat, terwijl het aandeel van grasland in het totale grondoppervlak is gestegen van 25% in 1961 tot 30% in 1999. De toename van het grasland areaal is met name mogelijk gemaakt door ontbossing van (tropische) bosgebieden, hetgeen belangrijke consequenties heeft voor het milieu. Het leidt tot een verlies aan biodiversiteit, tot een toename van de uitstoot van broeikasgassen, en tot degradatie van natuurlijke hulpbronnen vanwege bodemerosie en een afname van de beschikbaarheid van bodemnutriënten.

In het zogeheten 'veehouderij debat' wordt de groei van de extensieve veehouderij in Latijns Amerika met name toegeschreven aan: 1) de karakteristieken van de extensieve veehouderij, die de ontwikkeling van relatief grote bedrijven in afgelegen gebieden mogelijk maakt, 2) de toegenomen vraag naar (rund-) vlees in het algemeen en de toegenomen lokale vraag naar vlees in het bijzonder, 3) overheidsbeleid, zoals rente-subsidies, die veeboeren aansporen hun veehouderij activiteiten verder te vergroten, 4) landspeculatie, waardoor veeboeren meer land aanhouden dan de hoeveelheid die optimaal zou zijn vanuit een productietechnisch oogpunt omdat landbezit niet alleen opbrengsten oplevert uit vleesproductie maar ook uit speculatie met land, en 5) degradatie van natuurlijke hulpbronnen, omdat bos een belangrijke bron van bodemvruchtbaarheid is en omdat meer land nodig is om de vleesproductie te handhaven. Het is echter opvallend dat de oorzaken genoemd in het veehouderij debat over het algemeen weinig kwantitatief onderbouwd en incompleet van aard zijn. Zo blijft het onduidelijk waarom de vleesproductie toenam ondanks de aanzienlijke daling van de reële vleesprijzen sinds het midden van de jaren zeventig. Tevens is de rol van landspeculatie in het ontbossingproces onderwerp van discussie, en wordt over het algemeen verklaard aan de hand van het al dan niet stijgen van landprijzen. Tot slot, de rol die degradatie van natuurlijke hupbronnen speelt in de groei van de extensieve veehouderij is in beperkte mate en weinig kwantitatief onderbouwd in de literatuur.

Een overzicht van de belangrijkste investeringstheorieën en de wiskundige instrumenten die worden gebruikt in de ontwikkeling van deze theorieën, wordt gegeven in Hoofdstuk 3. Kosten baten analyse (*KBA*) in het algemeen, en de net contante waarde benadering in het bijzonder, is een flexibele methode voor het evalueren van relatief complexe investeringsprojecten. Belangrijkste nadelen van *KBA* zijn dat het optimalseringsgedrag van de economische agent niet in beschouwing wordt genomen, dat het tijdstip van investering vast staat en dat, daarom, niet het optimale tijdpad van investeringen wordt bepaald. In antwoord op deze tekortkomingen zijn de Neoklassieke en Tobin's *q* investeringstheorie ontwikkeld. Geleid door een specifieke doelstelling, zal de economische agent doorgaan met investeren in het vaste kapitaalgoed totdat de marginale kosten van de investering gelijk zijn aan de marginale opbrengsten van deze investering. Belangrijkste nadeel van de Neoklassieke en Tobin's *q* investeringstheorie is dat er vanuit wordt gegaan dat investeringen omkeerbaar zijn. De optiebenadering onderkent dat investeringen onomkeerbaar kunnen zijn en dat het winstgevend kan zijn om een onomkeerbare investeringsmogelijkheid uit te stellen, aangezien nieuwe informatie wordt verkregen door wachten. Deze schaduwkosten maken deel uit van de totale investeringskosten en worden expliciet meegenomen in de optiebenadering.

Een tweetal wiskundige instrumenten is zeer geschikt voor het oplossen van investeringsproblemen. Ten eerste bespreken we de dynamische optimaliseringstechnieken *calculus of variations*, *optimal control* en *dynamic programming*, die het mogelijk maken om het optimale tijdpad van investeringen te bepalen. Ten tweede bespreken we de stochastische Wiener, Ito en Poisson processen, die het mogelijk maken de ontwikkeling van onzekere variabelen over de tijd te karakteriseren. Gegeven de beperkte omvang van de tijdsserie data en de aandacht voor de analytische navolgbaarheid van het model, modeleren we vleesprijzen (Hoofdstuk 5) en landprijzen (Hoofdstuk 6) als een Ito proces.

In Hoofdstuk 4 ontwikkelen we een relatief eenvoudig bedrijfseconomisch model voor veeboeren in Latijns Amerika, op basis van de Neoklassieke investeringstheorie met aanpassingskosten. Deze benadering heeft enkele voordele ten opzichte van reeds bestaande dynamische veehouderijmodellen. Ten eerste, de bedrijfsomvang wordt niet constant verondersteld, hetgeen impliceert dat land niet alleen een productiegoed is (grasland rundvleesproductie) maar ook een investeringsobject. Ten tweede, het model is relatief eenvoudig omdat de complexe relatie tussen agro-ecologische omstandigheden, grasland en vee is samengevat in een veedichtheid afhankelijke productiefunctie voor grasland (rund-) vleesproductie. Ten derde, de vastgestelde afgeleide vormen verschaffen een ondubbelzinnige relatie tussen investeringen en het gebruik van (natuurlijke) hulpbronnen aan de ene kant, en prijs- en productiegegevens aan de andere kant. Tot slot, het model kan op relatief eenvoudige wijze worden uitgebreid met stochastische processen (zie Hoofdstuk 5 en 6) en bodemnutriëntendynamica (Hoofdstuk 7).

Het numerieke voorbeeld van een gemiddelde veeboer in de Atlantische Zone (AZ) van Costa Rica, laat zien dat veeboeren vooral gevoelig reageren op veranderingen van vlees- en landprijzen. Een stijging van de vleesprijs leidt tot een grotere optimale bedrijfsomvang en investeringen, omdat de marginale productiewaarde van land toeneemt. Een stijging van de landprijs leidt tot een kleinere optimale bedrijfsomvang, als gevolg van de hogere vervangingsinvesteringskosten van land. Hoewel deze resultaten op het eerste gezicht niet verrassend lijken, zijn ze belangrijk om twee redenen. In de eerste plaats roept het de vraag op waarom extensieve veehouderij zo sterk is gegroeid over de afgelopen decennia, terwijl de reële vleesprijzen zijn gedaald en de reële landprijzen zijn gestegen (zie Hoofdstuk 2). In de tweede plaats rijst de vraag onder welke omstandigheden een stijging van de landprijzen leidt tot extensivering en ontbossing, zoals vaak wordt beweerd in de literatuur. Deze onderwerpen worden behandeld in Hoofdstuk 5 t/m 7.

Een stochastisch omkeerbaar investeringsmodel waarin vleesprijzen worden gemodelleerd als een geometrisch Brownse beweging, wordt ontwikkeld in Hoofdstuk 5. Hoewel het model een relatief eenvoudig toepassing is van de Neoklassieke investeringstheorie met onzekerheid, is dit het eerste veehouderijmodel waarin investeringsbeslissingen van veeboeren worden gerelateerd aan verwachte trends en fluctuaties in vleesprijzen. Dit is een belangrijke kwestie, gegeven de toename van de vleesproductie ondanks de daling van de reële vleesprijzen in Latijns Amerika sinds het midden van de jaren zeventig (zie Hoofdstuk 2) en de gevoeligheid waarmee veeboeren reageren op een daling van de vleesprijzen (zie Hoofdstuk 4). Tot nu toe wordt, binnen dit vraag (vleesprijs) debat, de stijging van de vleesproductie toegeschreven aan de toegenomen Latijns Amerikaanse en lokale vraag naar vleesproducten.

De investeringsvergelijking geeft aan dat veeboeren hun investeringsbeslissingen niet alleen nemen op basis van de huidige vleesprijzen, maar ook op basis van de verwachte trend en fluctuatie in vleesprijzen. Het verwachte investeringsniveau stijgt met een toename van de trend en standaardafwijking in vleesprijzen, omdat de marginale productiewaarde van land stijgt als gevolg van, respectievelijk, hogere toekomstige en speculatieve opbrengsten. Het numerieke voorbeeld voor de AZ van Costa Rica toont aan dat het verwachte investeringsniveau onderschat (overschat) wordt als vleesprijzen constant zijn verondersteld, terwijl ze in werkelijkheid stijgen (dalen) of fluctueren over de tijd. Bovendien kan het zelfs zo zijn dat het verwachte investeringsniveau positief is, ondanks dat deterministisch economische analyse (die prijzen constant veronderstelt) aantoont dat vleesprijzen te laag zijn om land te kopen voor vleesproductie. Tenslotte wordt aangetoond dat het investeringsniveau positief kan zijn, zelfs als verwacht wordt dat vleesprijzen zullen dalen. Derhalve kan worden geconcludeerd dat de groei van de extensieve veehouderij en de hieruit volgende ontbossing, onder andere, wordt verklaard door speculatieve opbrengsten verkregen uit vleesproductie.

In Hoofdstuk 6 ontwikkelen we een stochastisch omkeerbaar investeringsmodel, waarin landprijzen worden gemodelleerd als een geometrisch Brownse beweging en waarin investeringskosten kwadratisch of exponentieel stijgen met een toename van het investeringsniveau. Dit model vormt een aanvulling op de Neoklassieke investeringstheorie met onzekerheid, aangezien de afgeleide investeringsvergelijking aantoont dat het verwachte investeringsniveau (niet) wordt bepaald door de standaardafwijking in landprijzen als de investeringskosten exponentieel (kwadratisch) stijgen in het investeringsniveau. Binnen het veehouderij debat geeft deze benadering nieuw inzicht in de discussie of stijgende landprijzen en landspeculatie leiden tot een verhoogd investeringsniveau in land en, dus, ontbossing. Bewijs voor de hypothese dat landspeculatie leidt tot een verhoogd investeringsniveau is, tot nu toe, uitsluitend gebaseerd op het al dan niet stijgen van landprijzen.

Het wordt analytisch aangetoond dat het verwachte investeringsniveau daalt met een toename van de trend in landprijzen en stijgt met een toename van de standaardafwijking in landprijzen. Dit is een gevolg van, respectievelijk, toegenomen vervangingsinvesteringskosten en hogere speculatieve opbrengsten uit land. Het Costa Rica voorbeeld laat zien dat het verwachte investeringsniveau onderschat (overschat) wordt als landprijzen constant zijn verondersteld, terwijl ze in werkelijkheid dalen (stijgen) of fluctueren over de tijd. Verder is aangetoond dat rentesubsidies leiden tot een hoger investeringsniveau in land. Derhalve kan worden geconcludeerd dat variabiliteit in landprijzen voldoende voorwaarde schept voor landspeculatie en leidt tot een verhoogd investeringsniveau in land en, dus, ontbossing van het agrarisch grensgebied.

Een deterministisch omkeerbaar investeringsmodel waarin bodemstikstof- en landdynamica worden meegenomen, wordt ontwikkeld in Hoofdstuk 7. In dit geval is de productiefunctie voor grasland vleesproductie niet alleen afhankelijk van de veedichtheid maar ook van de beschikbaarheid van stikstof in de bodem. Dit model vormt een aanvulling op bestaande bodemnutriëntenmodellen, aangezien het afziet van de aanname van een vaste bedrijfsomvang en omdat het model onderkent dat de aankoop (verkoop) van land een instroom (uitstroom) van bodemnutriënten impliceert. Gegeven dat veeboeren land niet alleen beschouwen als een productiegoed maar ook als een investeringsobject (zie Hoofdstuk 2 en 6) en dat bosgebied een belangrijke bron van bodemvruchtbaarheid is, lijkt het niet redelijk een vaste bedrijfsomvang te veronderstellen als de extensieve veehouderij in Latijns Amerika wordt beschouwd. Het model biedt niet alleen de mogelijkheid de optimale bodemnutriëntenvoorraad te bepalen (zoals in bestaande bodemnutriëntenmodellen), maar ook de optimale bedrijfsomvang en het optimale investeringsniveau.

Het numerieke voorbeeld voor de AZ van Costa Rica toont aan dat het ontrekken van nutriënten aan de bodem economisch efficiënt is vanuit het oogpunt van de veeboer. In tegenstelling tot bodemnutriëntenmodellen die een vaste bedrijfsomvang veronderstellen wordt de bodem in dit model niet volledig uitgeput, omdat bebost (vruchtbaar) land voortdurend wordt gekocht en gebruikt (gedegradeerd) land voortdurend wordt verkocht teneinde het optimale niveau van bodemvruchtbaarheid te handhaven. Simulatieresultaten tonen aan dat de huidige relatieve prijzen niet de economische prikkel verschaffen om kunstmest op natuurlijk grasland te gebruiken, aangezien de kosten van stikstof uit kunstmest ongeveer tweemaal zo hoog zijn als die van stikstof verkregen door ontbossing. Een voldoende grote kunstmestsubsidie leidt, niettemin, tot het gebruik van kunstmest, ofschoon het effect op intensivering van het landgebruik en bodemconservering relatief klein is. Verder wordt aangetoond dat een stijging van de algemene landprijs (*t.w.* de aan- en verkoopprijs van land) leidt tot een reductie van de optimale bedrijfsomvang en investeringsniveau (in overeenstemming met Hoofdstuk 4 en 6), en tot toename van de bodemvruchtbaarheid. Een stijging van de verkoopprijs van land, daarentegen, leidt tot een toename van de optimale bedrijfsomvang en investeringsniveau benevens een geringe toename van de bodemvruchtbaarheid. Derhalve kan worden geconcludeerd dat een stijging van de landprijzen alleen leidt tot extensivering en ontbossing als de verkoopprijs van land stijgt ten opzichte van de aankoopprijs van land.

In Hoofdstuk 8, tenslotte, worden de belangrijkste resultaten samengevat en in verband gebracht met de specifieke onderzoeksvragen, worden beleidsaanbevelingen gepresenteerd en, tot slot, worden de beperkingen van de gebruikte benadering bediscussieerd en aanbevelingen voor verder onderzoek gegeven. Dit onderzoek heeft geresulteerd in de ontwikkeling van een volwaardig en flexibel model, dat een verhoogd inzicht verschaft in de economische logica die ten grondslag ligt aan de beslissingen van veeboeren in Latijns Amerika ten aanzien van investeringen in land en het gebruik van (natuurlijke) hulpbronnen. Het is bewezen, vanuit een bedrijfseconomisch perspectief, dat bodemdegradatie, land speculatie, rentesubsidies en speculatieve opbrengsten uit vleesproductie allen leiden tot een verhoogd niveau van investeringen in land en, dus, ontbossing van het agrarisch grensgebied. De grootste welvaartstoename kan worden verkregen door prijs stabilisatie beleid en afschaffing van rentesubsidies.

Curriculum Vitae

Peter Cornelis Roebeling was born on January 3, 1969 in Weert, The Netherlands. He studied at Wageningen University (WU) from 1989 till 1995, and obtained his masters (M.Sc.) degree in Rural Development Studies with a major in Development Economics. During his practical period he worked for a development project for the consolidation of agricultural production co-operatives (PROCORAC) in Comayagua, Honduras. In the last phase of his study he also worked as teaching assistant for the course Peasant Economics at the Development Economics Group of Wageningen University.

After his graduation, he performed a brief consultancy at the *Centro Internacional de Agricultura Tropical* (CIAT) in Colombia. In 1996 he started working as a research assistant at the Development Economics Group of WU. In August 1996 he was assigned to the bilateral research project on Sustainable Land use and Food Security (DLV) in The Netherlands (WU) and Costa Rica (*Universidad Nacional*), where he was responsible for the development of the research methodology and the training of the local project staff. Subsequently, from January 1998 till February 1999, he worked for the Research Program on Sustainability in Agriculture (REPOSA) of WU, where he developed a Spatial Equilibrium Model (SEM) for the agricultural sector in Costa Rica.

In March 1999, he started his dissertation work at the Development Economics Group of Wageningen University. During his dissertation work, he also worked part-time for the Representative Advisory Council of Wageningen University and the Mansholt Graduate School. Currently, he is working at the Tropical Landscapes Program of the Sustainable Ecosystems Division at the Commonwealth Scientific and Industrial Research Organization (CSIRO) in Australia.

Other publications by the author

Roebeling, P.C., E.M.T. Hendrix and R. Ruben, 2002. Deforestation due to uncertainty in land and capital prices: The case of cattle ranching in the humid tropics of Costa Rica. Paper presented at the 2nd world congress of environmental and resource economists (AERE / EAERE) in June 2002, Monterey CA, USA.

Roebeling, P.C. and E.M.T. Hendrix, 2002. Land speculation as a cause of deforestation: The role of cattle ranching in the humid tropics of Costa Rica. In: Ierland, E.C. van, H.P. Weikhard and J. Wesseler (Eds) Risk and uncertainty in environmental and resource economics (proceedings). Wageningen, The Netherlands.

Roebeling, P.C. and R. Ruben, 2001. Technological progress vs. economic policies as tools to control deforestation: The Atlantic Zone of Costa Rica. Pages 135-152 in: Angelsen, A. and D. Kaimowitz (Eds) Agricultural technologies and tropical deforestation. CAB International, Wallingford, United Kingdom. 422 pp.

Jansen, H.G.P., R.A. Schipper, P.C. Roebeling, E.H. Bulte, H. Hengsdijk, B.A.M. Bouman and A. Nieuwenhuyse, 2001. Alternative approaches to the economics of soil nutrient depletion in Costa Rica: Explorative, predictive and normative bio-economic models. Pages 211-237 in: Heerink, N., H. van Keulen and M. Kuiper (Eds) Economic policy and sustainable land use: Recent advances in quantitative analysis for developing countries. Physica-Verlag, Heidelberg, Germany. 376 pp.

Roebeling, P.C., H.G.P. Jansen, R.A. Schipper, F. Sáenz, E. Castro, R. Ruben, H. Hengsdijk and B.A.M. Bouman, 2000. Farm modelling for policy analysis at the farm and regional level. Pages 171-198 in: Bouman, B.A.M., H.G.P. Jansen, R.A. Schipper, H.Hengsdijk and A.Nieuwenhuyse (Eds) Tools for land use analysis at different scales with case studies for Costa Rica. Kluwer Academic Publishers, Dordrecht, The Netherlands. 274 pp.

Roebeling, P.C., H.G.P. Jansen, A. van Tilburg and R.A. Schipper, 2000. Spatial equilibrium modeling for inter-regional trade flows, land use and agricultural policy analysis. Pages 65-96 in: Bouman, B.A.M., H.G.P. Jansen, R.A. Schipper, H.Hengsdijk and A.Nieuwenhuyse (Eds) Tools for land use analysis at different scales with case studies for Costa Rica. Kluwer Academic Publishers, Dordrecht, The Netherlands. 274 pp.

Roebeling, P.C., H.G.P. Jansen, A. van Tilburg and R.A. Schipper, 1999. Modelando el equilibrio espacial para el análisis de la politica agrícola: Liberalización del comercio en Costa Rica. Pages 73-90 in: Herrera, D. (Ed.) Instrumentos metodológicos de apoyo a la reconversión productiva. Instituto Interamericano para la Cooperación en la Agricultura (IICA), Coronado, Costa Rica.

Roebeling, P.C., F. Saenz, E. Castro and G. Barrantes, 1999. Farm household modelling for agrarian policy analysis and appraisal: A case study in the Atlantic Zone of Costa Rica. Pages 76-102 in: Pelupessy, W. and R. Ruben (Eds) Agrarian Policies in Central America. MacMillen Press, UK. 209 pp.

Roebeling, P.C., R. Ruben, F. Sáenz, E. Castro and G. Barrantes, 1998. Políticas agrarias para la intensificación sostenible del sector ganadero: Una aplicación en la Zona Atlántica de Costa Rica. Pages 156-174 in: Castro, E. and R. Ruben (Eds) Políticas agrarias para el uso sostenible de la tierra y la seguridad alimentaria en Costa Rica. UNA-CINPE / WAU-DLV, Heredia, Costa Rica. 174 pp.

Roebeling, P.C., January 1998. Course on a regional economic and agricultural land use model. Training manual prepared for research staff of the MAG, UCR and UNA, Guápiles, Costa Rica.

Roebeling, P.C., F. Saenz, E. Castro and G. Barrantes, 1997. Farm household market integration in the light of perceived soil degradation: An application in the Atlantic Zone of Costa Rica. Paper presented at the ASERCCA-conference in September 1997, Portsmouth, UK.

Kruseman, G., H. Hengsdijk, R. Ruben, P. Roebeling and J. Bade, 1997. Farm household modelling system for the analysis of sustainable land use and food security: Theoretical and mathematical description. DLO / WAU, DLV Report No.7, Wageningen, The Netherlands. 56 pp.

Bade, J., H. Hengsdijk, G. Kruseman, R. Ruben and P.C. Roebeling, 1997. Farm household modelling in a regional setting: The case of Cercle de Koutiala, Mali. DLO / WAU, DLV Report No.6, Wageningen, The Netherlands. 40 pp.

Roebeling, P.C., February 1997. Course on sustainable land use and food security in the Atlantic Zone of Costa Rica. Training manual prepared for the local research staff at CINPE-UNA, Heredia, Costa Rica.

Roebeling, P.C., E. Castro, G. Barrantes and F. Saenz, 1996. Informe de proyecto politicas agrarias para el uso sostenible del suelo: Aspectos metodologicos sobre la estimacion de los modulos. UNA-CINPE / WAU-DLV, Heredia, Costa Rica. 53 pp.

Ruben, R, and P.C. Roebeling, 1995. Options for consolidation of land reform co-operatives: A contract choice approach. Paper presented at the Agrarian Questions-conference in May 1995, Wageningen, The Netherlands.

Roebeling, P.C., 1995. Mathematical presentation of the Cabuyal multiple goal linear programming model. Centro Internacional de Agricultura Tropical (CIAT), Cali, Colombia. 10 pp.

Roebeling, P.C., 1995. Optimal behaviour in a model of semi-collective rural co-operation. M.Sc.-thesis, Wageningen Agricultural University, Wageningen, The Netherlands. 54 pp.

Roebeling, P.C., 1994. Impacto potencial del refinanciamiento y los pequeños proyectos al desarrollo empresarial. Practical training thesis, Wageningen Agricultural University, Wageningen, The Netherlands. 48 pp.