Natural forest re-growth on abandoned agricultural land in the Swiss mountains

An economic analysis of patterns and causes using spatial statistical models and interviews

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by

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Summary

According to the Swiss land-use statistics, the wooded area in Switzerland increased by 17 000 ha between 1979/85 and 1992/97. A large part of the new wooded area occurred as natural re-growth on former agricultural land in the mountainous areas. The objective of this thesis was to investigate the patterns and causes of natural forest re-growth on agricultural land in the Swiss mountains (Alps and Jura mountains). To investigate 'patterns' means to describe the locations where natural forest re-growth has occurred. To investigate the 'causes' is understood as the investigation of the socio-economic determinants of natural forest re-growth.

The thesis was designed as a cumulative work and consists of four complementary studies. In all studies, multivariate spatial statistical models were used to investigate the patterns of forest re-growth. In these models, natural forest re-growth is explained as a function of geo-physical and socio-economic factors. Land-use change data from two nationwide land-use surveys (carried out by the Swiss Federal Statistical Office over a 12-year period between 1979/85 and 1992/97) and aerial photographs of four mountain municipalities (taken over a 50-year period between 1953 and 2000) provided the basis for the investigation of natural forest re-growth.

The explanatory variables used in the spatial statistical models are proxy variables for the costs and benefits of the cultivation of agricultural land. Explanatory variables were derived from climate station data (i.e. radiation, precipitation, temperature), a digital soil suitability map, a digital elevation model, a digital road network, a digital map of construction zones, Swiss land-use statistics data as well as population, employment and agricultural censuses. In four case study municipalities, interviews with farmers and landowners were conducted. All data were available in geo-referenced form or were brought into a spatially explicit form and stored in a Geographic Information System (GIS).

The first of the four studies investigated the regional-scale pattern of agricultural land abandonment (measured as percentage reforested agricultural land) throughout the entire Swiss mountain area. Selected geo-physical variables (e.g. average steepness, average soil depth, average summer precipitation) and socio-economic variables (e.g. average distance to roads, population change, proportion of commuters, proportion of full-time farms, proportion of employees in the non-agricultural sectors) were used as explanatory variables. Relationships between variables were investigated by means of linear regression models. The second study and third study both investigated the patterns of forest re-growth on a spatially disaggregated scale in the entire Swiss mountain area. The basis of these studies were presence/absence data of forest re-growth and selected geo-physical variables (e.g. steepness, soil depth, soil stoniness, degree days, summer precipitation) and socio-economic variables (e.g. distance to roads, distance to settlements, distance to construction zones, population change, proportion of full-time farms, rate of change of farms, proportion of agricultural employees). Logistic regression models were used to investigate the relationships between variables. The fourth study investigated the patterns and causes of forest re-growth, including individuals' motives to abandon and maintain the cultivation of marginal agricultural land and allow forest re-growth to occur. This study was conducted in four municipalities (Tujetsch, Eggiwil, Soazza and Blitzingen) in the Swiss Alps. In this study, classification trees based on presence/absence data of land abandonment/forest re-growth and selected geo-physical variables (e.g. summer precipitation, steepness, radiation, soil depth) were combined with interviews.

Results of the mountain wide studies show that forest re-growth occurred more frequently on land with steep slopes, stony and shallow soils, and low heat sums. In areas with very steep slopes and stony soils, forest re-growth occurred less frequently than in areas with intermediate steepness and soil stoniness. Forest re-growth occurred more frequently closer to forest edges. New forest areas occurred primarily in the agro-climatically unfavorable areas at high altitudes, but also in the agro-climatically favourable areas in the southern parts of the Swiss mountains (i.e. canton of Ticino). Non-linear relationships between forest re-growth and its geo-physical determinants were found in all models.

Forest re-growth occurred more frequently in regions/municipalities, in which the rate of change of farms was high and the majority of farms were managed on a part-time basis. One model suggests that forest re-growth occurred more frequently in municipalities in which population had increased. No statistically significant relationship was found between emigration and forest re-growth. Nor was one found between the structure of agricultural land parcels, farm size, the distance of the land to settlements and construction zones. Models show different results in regard to the influence of off-farm job opportunities on forest re-growth. On the regional scale, the models suggest that forest re-growth occurred more frequently, where good off-farm job opportunities existed. On the disaggregated spatial scale, models suggest that forest re-growth occurred more frequently where off-farm job opportunities were less favorable. Different results were also obtained in regard to the influence of accessibility on forest re-growth. On the regional scale, models show that regions with an underdeveloped road infrastructure were favored in terms of forest re-growth. On the disaggregated scale, models show that forest re-growth occurred more frequently closer to roads. Interviews in the case study municipalities revealed that land that was directly accessible by roads was less frequently overgrown by trees and bushes than land that was not directly accessible by roads.

In the four case study municipalities, many farms have been abandoned during the last decades. Remaining farms have often increased in size, whereas farm labour decreased or remained stable. Resulting labour shortages caused labour intensive practices and cultivation forms to be abandoned. In particular the abandonment of the labour intensive manual clearance of trees and bushes from pastures (the so called 'Schwenden') has led to forest re-growth. Policy factors such as the prohibition of the reconstruction of old stables for use as summer residences, delayed land consolidations, regulations concerning animal welfare discouraging farmers from investing in new stables and machines and the prohibition of free grazing have enhanced forest re-growth. On the contrary, the cultivation of marginal land has been maintained in many places. This could be explained by the opportunity costs of agricultural labour (e.g. aged farmers who retain traditional farming practices), extensive cultivation forms (e.g. deer and horse pasturing), agricultural requirements (e.g. farmers maintain the cultivation of marginal land in order to not exceed the prescribed number of livestock per hectare), and other cultivation forms (e.g. hobby farming, use of old stables and their surroundings for residential purposes). These factors and cultivation forms reduce management costs, enlarge benefits or describe non-profit oriented behaviour.

It is concluded that decision makers should pay more attention to the non-linearity in the pattern of forest re-growth and local peculiarities that influence it when designing policy measures to prevent or support natural forest re-growth and its consequences for the environment. Local peculiarities are: the geo-physical characteristics of the land (climate, topography, quality of the soils), (ii) structural peculiarities (road infrastructure, proportion of full-time farms, rate of change of farms), (iii) economic peculiarities (off-farm employment opportunities) and (iv) policy factors (e.g. the prohibition of the reconstruction of old stables for use as summer residences, delayed land consolidations, regulations concerning animal welfare, the prohibition of free grazing). Furthermore, if the aim of agricultural, regional and/or environmental politics is to prevent forest re-growth and its consequences for the environment, more financial incentives for the cultivation of alpine pastures should be provided.

Zusammenfassung

Nach Schätzungen der Arealstatistik Schweiz hat die mit Bäumen bestockte Fläche in der Schweiz zwischen 1979/85 und 1992/97 um rund 17 000 ha zugenommen. Ein grosser Teil der neuen bestockten Fläche entstand als natürlicher Aufwuchs auf ehemaligen landwirtschaftlichen Nutzflächen im Berggebiet. Das Ziel der vorliegenden Dissertation war es, die Muster und Ursachen der natürlichen Wiederbewaldung landwirtschaftlicher Nutzflächen im Schweizer Berggebiet (Alpenraum und Jura) zu untersuchen. Die 'Muster' zu untersuchen bedeutet zu beschreiben, wo Landwirtschaftsflächen aufgegeben wurden und sich wiederbewaldet haben. Unter den 'Ursachen' der Wiederbewaldung werden die sozioökonomischen Faktoren verstanden, welche zur Wiederbewaldung geführt haben.

Die Dissertation wurde als kumulative Arbeit angefertigt und setzt sich aus vier sich ergänzenden Teilstudien zusammen. In allen vier Teilstudien wurden multivariate statistische Modelle für die Untersuchung der Muster der Wiederbewaldung verwendet. In den Modellen wurde die Wiederbewaldung als eine Funktion von geophysikalischen und sozioökonomischen Faktoren erklärt. Landnutzungsdaten aus zwei nationalen Erhebungen des Schweizerischen Bundesamtes für Statistik (erhoben über einen Zeitraum von 12 Jahren zwischen 1979/85 und 1992/97) und Luftbilder von vier Berggebietsgemeinden (erhoben über einen Zeitraum von 50 Jahren zwischen 1953 und 2000) bildeten die Grundlage für die Untersuchung der Wiederbewaldung.

Die Variablen, welche in den räumlich statistischen Modellen für die Erklärung der Wiederbewaldung verwendet wurden, sind Proxy-Variablen für den Aufwand und Nutzen der Bewirtschaftung landwirtschaftlicher Flächen. Die Basis für diese Variablen bildeten Klimadaten (Temperaturdaten, Strahlungsdaten und Niederschlagsdaten), eine digitale Bodeneignungskarte, ein digitales Höhenmodell, digitale Strassennetzdaten, eine digitale Karte der Bauzonen, Landnutzungsdaten des Schweizerischen Bundesamtes für Statistik sowie Daten zur Bevölkerungsentwicklung und

Erwerbs- und Agrarstruktur. In den vier Fallstudiengemeinden wurden Interviews mit Landwirten und Flächenbesitzern durchgeführt. Sämtliche in der Dissertation verwendeten Daten lagen in geo-referenzierter Form vor oder wurden im Rahmen der Dissertation geo-referenziert und sind in einem Geographischen Informationssystem (GIS) gespeichert.

In der ersten der vier Teilstudien wurden die regionalen Muster der Landaufgabe (gemessen als Anteil der wiederbewaldeten landwirtschaftlichen Fläche) im gesamten Berggebiet untersucht. Als erklärende Variablen wurden ausgewählte geophysikalische Variablen (z.B. durchschnittliche Hangneigung, durchschnittliche Bodentiefe, durchschnittlicher Niederschlag in der Vegetationsperiode) und sozioökonomische Variablen (z.B. durchschnittlicher Abstand zu Strassen, Bevölkerungsentwicklung, Anteil Pendler, Anteil Haupterwerbsbetriebe, Anteil der Beschäftigten ausserhalb der Landwirtschaft) verwendet. Zusammenhänge zwischen den Variablen wurden mit Hilfe von linearen Regressionsmodellen untersucht. In der zweiten und dritten Teilstudie wurden die Muster der Wiederbewaldung auf räumlich-disaggregierter Ebene im gesamten Berggebiet untersucht. Die Basis dieser Untersuchungen bildeten Präsenz/Absenz Daten der Landaufgabe/Wiederbewaldung, ausgewählte geophysikalische Variablen (z.B. Hangneigung, Bodentiefe, Bodensteingehalt, Temperatur, Niederschlag in der Vegetationsperiode) und sozioökonomische Variablen (z.B. Abstand zu Strassen, Siedlungen und Bauzonen, Bevölkerungsentwicklung, Anteil Haupterwerbsbetriebe, Veränderungsrate der landwirtschaftlichen Betriebe, Anteil der Beschäftigten in der Landwirtschaft). Logistische Regressionsmodelle wurden in diesen beiden Studien für die Untersuchung der Zusammenhänge zwischen den Variablen verwendet. In der vierten Teilstudie wurden die lokalen Muster und Ursachen der Wiederbewaldung, einschliesslich der Motivation der Flächenbesitzer die Bewirtschaftung marginaler Landwirtschaftsflächen aufzugeben oder beizubehalten, untersucht. Die Untersuchungen wurden in vier ausgewählten Gemeinden in den Alpen durchgeführt. In dieser Studie wurden Klassifikationsbäume auf der Basis von Präsenz/Absenz Daten der Landaufgabe/Wiederbewaldung und ausgewählten geophysikalischen Variablen (z.B. Niederschlag, Hangneigung, Strahlung, Bodentiefe) mit Interviews kombiniert.

Die Ergebnisse der Untersuchungen der Muster der Wiederbewaldung im gesamten Berggebiet zeigen, dass Landwirtschaftsflächen primär an steilen Hängen und auf Flächen mit hoher Steinigkeit, geringer Bodentiefe und geringer Temperatur einwachsen. Dort wo die Hänge extrem steil and steinig sind, ist die Wiederbewaldungsdynamik geringer als in Lagen mit mittlerer Steilheit und Steinigkeit. Die neuen Waldflächen entstanden grösstenteils in der Nähe bestehender Waldflächen. Wiederbewaldete Landwirtschaftsflächen konnten primär in den agro-klimatisch ungünstigen höheren Lagen des schweizerischen Berggebietes, aber auch in den agro-klimatisch günstigeren tieferen Lagen des schweizerischen Berggebietes (südlicher Teil des Kantons Tessin) gefunden werden. In allen Modellen wurden nicht-lineare Beziehungen zwischen der Wiederbewaldung und den geophysikalischen Einflussfaktoren gefunden.

Die Wiederbewaldung war signifikant stärker in Gemeinden/Regionen in denen in der Vergangenheit viele Landwirtschaftsbetriebe aufgegeben wurden und die Mehrheit der Landwirtschaftsbetriebe im Nebenerwerb betrieben wurde. Ein Modell zeigt einen positiven Zusammenhang zwischen der Bevölkerungszunahme und der Wiederbewaldung. Kein statistisch signifikanter Zusammenhang wurde zwischen der Bevölkerungsabnahme und der Wiederbewaldung gefunden. Kein statistisch signifikanter Zusammenhang wurde zwischen der Wiederbewaldung und der Parzellierung, der landwirtschaftlichen Betriebsgrösse und dem Abstand der Landwirtschaftsflächen zu Siedlungen und Bauzonen gefunden. Unterschiedliche Ergebnisse zeigten die Modelle in Bezug auf den Einfluss der wirtschaftlichen Stärke auf die Wiederbewaldung. Auf regionaler Ebene wurden vereinzelt Regionen gefunden, in denen ein gutes ausserlandwirtschaftliches Erwerbsangebot zu einer stärkeren Wiederbewaldung geführt hat. Die Ergebnisse der Modelle auf räumlich disaggregierter Ebene zeigen, dass wirtschaftlich schwache Gemeinden stärker von der Wiederbewaldung betroffen waren, als wirtschaftlich starke Gemeinden. Auch in Bezug auf den Einfluss der Erschliessung auf die Wiederbewaldung zeigen die Untersuchungen unterschiedliche Ergebnisse. Auf regionaler Ebene zeigte sich, dass Regionen mit einer geringen Erschliessung stärker von der Wiederbewaldung betroffen waren als Regionen mit einer guten Erschliessung. Auf disaggregierter Ebene zeigte sich, dass viele Landwirtschaftsflächen in relativ geringer Distanz zu Strassen einwachsen. Die Interviews in den Fallstudiengemeinden ergaben, dass direkt mit dem Fahrzeug erreichbare landwirtschaftliche Flächen weniger von der Wiederbewaldung betroffen waren als nicht direkt mit dem Fahrzeug erreichbare Flächen.

In den untersuchten Gemeinden wurden in den letzten Jahrzehnten viele Landwirtschaftsbetriebe aufgegeben. Viele der verbleibenden Betriebe haben ihre Fläche vergrössert, wobei die Anzahl der Arbeitskräfte gleich blieb oder sich verringerte. Der damit verbundene Arbeitskräftemangel führte in vielen der untersuchten Landwirtschaftsbetriebe zu einer Aufgabe von arbeitsintensiven Praktiken und Bewirtschaftungsformen. Besonders die Aufgabe des manuellen Säuberns der Weideflächen von Bäumen und Sträuchern (des sog. 'Schwendens') führte zur Vermehrung der Waldfläche. Politische Faktoren, wie verzögerte Strukturverbesserungsmassnahmen, das Verbot ehemalige Ställe in Ferienhäuser umzuwandeln, Tierschutzregulierungen, welche dazu führten, dass Investitionen in neue Ställe und Maschinen ausblieben und das Verbot der freien Beweidung, verstärkten die Wiederbewaldung. Im Gegensatz dazu wurde vielerorts die Bewirtschaftung marginaler Flächen aufrecht erhalten. Die Aufrechterhaltung der Bewirtschaftung marginaler Flächen konnte mit den Opportunitätskosten der landwirtschaftlichen Arbeit (z.B. ältere Landwirte, welche

marginale Flächen mit Hilfe traditioneller Bewirtschaftungsmethoden bewirtschaften), extensiven Bewirtschaftungsformen (z.B. Beweidung steiler Hänge mit Rotwild und Pferden), betrieblichen Erfordernissen (z.B. marginale Flächen werden bewirtschaftet, um eine bestimmte, vorgeschriebene Anzahl an Vieh halten zu können) und anderen Arten der Bewirtschaftung (z.B. Hobbylandwirtschaft, Nutzung der ehemaligen Landwirtschaftsflächen als Freizeit- und/oder Feriendomizil) erklärt werden. Diese Faktoren und Bewirtschaftungsformem reduzieren die Bewirtschaftungskosten, erhöhen den Nutzen oder beschreiben nicht-profitorientiertes Verhalten.

Die Schlussfolgerung aus den Ergebnissen dieser Arbeit ist, dass Nichtlinearitäten im Muster der Wiederbewaldung und lokale Besonderheiten, welche die Wiederbewaldung beeinflussen, stärker berücksichtigt werden sollten, wenn es darum geht, Massnahmen für oder gegen die Wiederbewaldung und deren Konsequenzen für die Umwelt zu ergreifen. Zu den lokalen Besonderheiten zählen: (i) standörtliche Besonderheiten (Klima, Topographie, Boden), (ii) strukturelle Besonderheiten (Infrastruktur, Anteil Haupterwerbsbetriebe, Stärke des Rückgangs der Landwirtschaftsbetriebe), (iii) wirtschaftliche Besonderheiten (ausserlandwirtschaftliches Arbeitsangebot) und (iv) politische Faktoren (z.B. das Verbot ehemalige Ställe in Ferienhäuser umzuwandeln, verzögerte Strukturverbesserungsmassnahmen, Tierschutzregulierungen, das Verbot der freien Beweidung). Weiterhin, wenn es das Ziel der Landwirtschafts- Regional- und/oder Umweltpolitik ist, die Wiederbewaldung zu verhindern, sollten stärkere finanzielle Anreize für die Bewirtschaftung von Sömmerungsweiden geschaffen werden.

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Zürich, 9th October 2006

Mario Gellrich

Definitions

The following are definitions of the terms *land abandonment*, *natural forest re-growth*, *patterns* and *causes* as used in the title and text of this thesis.

Land abandonment: The notion of abandoned land is complex and often not clearly defined in the literature. For example, in some central and eastern European countries with predominantly intensive forms of agriculture, as in many of the EU's new members[1], rough grassland and scrub managed under extensive grazing regimes are often regarded as a form of *semi-abandoned* (DLG, 2005). In other European regions, such as southern Portugal or central Spain, extensive grazing has been the norm for many years and is often considered no less viable than any other form of cultivation (Baldock et al., 1996). Some authors define abandoned land simply as land which is not used at all by the owner or occupier (DLG, 2005). Walther (1984) defines an area as abandoned if it is not regularly used so that the biomass remains unused. Other authors regard an area as abandoned if it has not been used for agricultural production for two years (DLG, 2005). Plaisance (1959) defines abandoned land as: "*Non cultivated land (usually for more than 3 years) more or less invaded by common weeds (thistle, mullein...). These lands were previously cultivated, at least once*". Girard et al. (1994) provides the following definition for fallow land (which he uses synonymously for abandoned land): "*abandonment of all management, temporal or permanent dominance of grasses; increasing vertical and horizontal stratification of vegetation cover; and physiognomical diversity*". Baldock et al. (1996) define abandonment: "... *as taking place when the neglect of the main productive elements is allowed to decline beyond a point at which recuperation is practical, or economically viable.*". These definitions show the difficulty in finding a clear definition for abandoned land which also raises difficulties in the delineation of abandoned land in the field. In this thesis, following Rudel et al. (2000) and Kobler et al. (2005), agricultural

[1]There are 10 new Member States which acceded to the EU on May 1st 2004: Cyprus, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Malta, Poland, Slovakia and Slovenia.

land was defined as abandoned if natural re-growth of forest had occurred on the land.

Natural forest re-growth: In this thesis, natural forest re-growth is defined as the occurrence of woody plants on formerly cultivated land. This includes scrub vegetation, bushes and trees. *Natural re-growth* means that trees, bushes and scrub grow without human intervention. Planned afforestations are not strictly *natural* and were, therefore, not considered in the analyses. It should be noted that natural forest re-growth as defined in this thesis is not an indicator of the permanent abandonment of agricultural land nor does it allow the assessment of whether recuperation of overgrown land will be practical or economically viable in the future. For example, the Swiss land-use statistics, evaluated over a 12-year period between 1979/85 and 1992/97, revealed that many woodlands were cleared in favour of new agricultural areas (SFSO, 2005). For overgrown agricultural areas that are not within the definition of *forest* as defined by the Swiss Forest Law (WaG, 1991) and the regional adaptations of this definition by the Swiss cantons[2], re-use is generally possible.

Pattern: Studies that aim to predict the pattern of land-use/land-cover changes generally address the question "where have land-use changes taken place?". This question has also been referred to as the "location issue" (Serneels & Lambin, 2001). In this thesis, following the notation of Pontius et al. (2001) and Serneels & Lambin (2001), to investigate 'patterns' is understood as the investigation of the characteristics of the locations of *where* natural forest re-growth has occurred.

Causes: In spatially explicit land-use change studies there is often confusion in regard to the term *causes*. Altitude, steepness, distance to roads and markets and population density, which are commonly used variables in land-use/land-cover change studies, are sometimes referred to as the *causes* or *proximate causes* of land-use/land-cover changes (e.g. Serneels & Lambin, 2001). These variables are not the causes of land-use change because they are static in nature. Causes of land-use change always relate to dynamic socio-economic processes such as changing prices of agricultural products and policies (Baldock et al., 1996; Strijker, 2005). Kaimowitz & Angelsen (1998) use the term *causes* to describe the socio-economic determinants of deforestation in non-industrialised countries. They distinguish between *underlying causes* (e.g. changing technologies and demographic trends) and *intermediate causes* (e.g. changing labour costs or prices). In this thesis, following the notion of Kaimowitz & Angelsen (1998), to investigate the 'causes' of natural forest re-growth is understood as the investigation of the dynamic socio-economic determinants of forest re-growth.

[2]Article 1 of the Swiss Forest Law (WaG, 1991) provides a general definition of *forest* which can be modified by the Swiss Cantons.

Abbreviations

ASCH85	Swiss land-use statistics 1979/85
ASCH97	Swiss land-use statistics 1992/97
AIC	Akaike Information Criterion (a measure to compare statistical models)
AUC	Area under the ROC-curve (a measure of the prediction accuracy of a statistical model)
BEK200	Soil suitability map at 1:200,000
BP-test	Breusch-Pagan test (test on heteroskedasticity)
BSF	Schweizerisches Bundesamt für Statistik
cm	Centimeter
CSD	Swiss climate station data
CT	Classification tree (a non-parametric modelling approach)
DEM	Digital Elevation Model
EEA	European Environmental Agency
e.g.	Example Given
ESRI	Environmental Systems Research Institute, Inc.
GIS	Geographic Information System
ha	Hectare
i.e.	Id est (that is)
IEEP	Institute for European Environmental Policy
i.i.d.	Independent identically distributed
JB	Jarque-Bera-test (test on normality)
km	Kilometer
Logit	Logistic regression
LR	Likelihood Ratio
LULCC	Land-use/Land-cover change

m	Meter
MAUP	Modifiable areal unit problem (for definition see section 4.3.1)
ML	Maximum Likelihood
MLERR	Maximum Likelihood-based spatial error model
MLLAG	Maximum Likelihood-based spatial lag model
mm	Millimeter
Moran's I	Moran's I statistics (a measure of spatial dependence)
N	Number of observations
OLS	Ordinary least square regression
P	Probability
Proxy	From lat. *proximus* = "the next", a variable which represents an unobserved factor of land-use/land-cover change
pseudo R^2	Goodness-of-model fit measure similar to the coefficient of determination
R^2	Coefficient of determination (a measure of goodness-of-model fit)
Response	The variable under investigation in a regression model
RMSE	Root mean square error
ROC	Receiver operating characteristics (plot to measure the prediction accuracy of a model)
SFSO	Swiss Federal Statistical Office
SNFI	Swiss National Forest Inventory
SNSF	Swiss National Science Foundation
WSL	Swiss Federal Institute for Forest, Snow and Landscape Research, Birmensdorf/Switzerland

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Part I: Overview and Summaries

CHAPTER 1

Introduction

1.1 Background

In the Alps, mixed farming has been practised since the beginning of human settlement in the 6th millennium B.C. (Bätzing, 1997). As a result of the human settlement process, pre-existing shrublands and forests were cleared or burned over large areas to increase the availability of wide open grasslands for livestock (Laiolo et al., 2004). In today's area of Switzerland, the first major phase of deforestation was probably associated with the settlement of the Alemanni, around the 5th century (Schuler, 1988). In the 12th and 13th centuries, extensive areas had already been deforested in the lowlands (Hauser, 1964). The Black Death and the ensuing decline in population in the Middle Ages brought deforestation to a halt, and some local natural forest re-growth is likely to have resulted from the abandonment of agricultural areas during this period (Mather & Fairbairn, 2000). The second major phase of deforestation was associated with the rapid population growth in the early industrialisation period in the late 18th century (Schuler, 1988). Population growth has been attributed to the intensification of agricultural production, not at least due to the introduction and widespread adoption of the potato which facilitated people in increasing agricultural productivity. Population growth increased the pressure on forests accordingly. For the early 19th century, it is estimated that the proportion of the national land area which remained under forest cover had fallen to 15%[1] (Mather & Fairbairn, 2000).

Several local forest laws, some of them already established at the beginning of the 19th century

[1]For comparison, in the year 1997, forests (i.e. closed forest, open open forest and bushes) covered 28% of the total area of Switzerland.

(Kempf, 1985), and the establishment of the Swiss Forest Police Law in the year 1876 as well as economic development and the introduction of fossil fuels prevented the decline of the remaining forests and resulted in an increase of the forest area from the middle of the 19th century on (Mather & Fairbairn, 2000)[2]. Conservative estimates are that the nationwide forest area increased by one third during the last 150 years (Brändli, 2000). This increase, however, is only partially the result of planned afforestations; a considerable part of the new forest area can be attributed to natural forest re-growth, mostly on abandoned agricultural land (Surber et al., 1973; Brassel & Brändli, 1999; Mather & Fairbairn, 2000; SFSO, 2005).

Since the middle of the 19th century, Swiss agriculture has been characterised by farm abandonment and farm labour migration. While in the year 1900, 31% of the employees in Switzerland worked in agriculture, in 2001, it was only 4.7% (SFSO, 2001). Farm labour migration peaked in the period after World War II (Baur, 1999). This is approximately the same period in which Swiss people began to value land abandonment and forest re-growth negatively. This negative perception can be illustrated by the 'emotional' titles of scientific articles, reports, and dissertations: "*Das Brachlandproblem in der Schweiz*"[3] (Surber et al., 1973); "*Möglichkeiten zur Sicherstellung der Flächennutzung in landwirtschaftlichen Problemgebieten*"[4] (Brunner, 1977); "*Möglichkeiten für die Verhinderung oder Beseitigung der Brachlegung von landwirtschaftlichen Grenzertragsstandorten*"[5] (Moos & Herot, 1977); "*Land abandonment in the Swiss Alps - a new understanding of a land-use problem*" (Walther, 1986). The negative perception of land abandonment and forest re-growth indicated by these publications also reflects the discontent of mountain farmers in regard to the increasing income differences between the agricultural sector and other sectors in the post Wold War II period (Surber et al., 1973; Bebi & Baur, 2002). From the 1950s on, Swiss agricultural politics have been responsive to the worsening economic situation of mountain farmers and introduced a variety of agricultural support measures (Rieder, 1996).

In the 1990s, agricultural land abandonment was an issue of concern in the Swiss National Science Foundation Programme 22 "*Nutzung des Bodens in der Schweiz*" [6] (Rieder et al., 1990; Bernegger et al., 1990). However, as with the studies in the 1970s and 1980s, exact nationwide statistics about the decrease of the agricultural area and increase of forest area were not available at the beginning of the 1990s, and empirical studies on land abandonment and forest re-growth were solely

[2]It is not clear in which period net deforestation changed into net reforestation, although available data indicate that reforestation was the general trend from the mid 19th century on (Brändli, 2000; Mather & Fairbairn, 2000).

[3]engl.: The fallow land problem in Switzerland.

[4]engl.: Opportunities for the prevention of land abandonment in regions in which agricultural production is problematic.

[5]engl.: Opportunities for the removal of fallow land and the prevention of the abandonment of marginal agricultural land.

[6]engl.: The use of soils in Switzerland

restricted to local case studies (see studies by Surber et al., 1973 and Walther, 1986).

New public interest in land abandonment and natural forest re-growth occurred only recently, as the result of two nationwide land-use/land-cover surveys - the Swiss land-use statistics (ASCH, SFSO, 2001), which was conducted over a 12-year period between 1979/85 and 1992/97, and the Swiss National Forest Inventory (SNFI, Brassel & Brändli, 1999), which was conducted over a 10-year period between 1983/85 and 1992/95. In this thesis, the ASCH was used as the basis to investigate natural forest re-growth.

According to the ASCH, 48 174 ha of agricultural land converted to other land-use/land-cover classes between 1979/85 and 1992/97 (60 592 ha decrease plus 12 418 ha increase). Much of the agricultural land converted to forest, woods and unproductive areas. The latter consist mostly of grass and scrub vegetation (Figure 1.1). During the same period, the wooded area[7] increased by 17 033 ha (29 391 ha increase minus 12 358 ha decrease)[8]. New wooded areas had their origin mostly in alpine pastures and areas with scrub vegetation (Figure 1.2). As estimated by the Swiss land-use statistics, 87% of the new wooded area occurred without human intervention, i.e. as natural re-growth (SFSO, 2001).

Figure 1.3 shows an example of a mountain-side (the Mont Grand in the municipality of Soazza[9]) which was left by farmers to become naturally overgrown by trees and bushes. Similar examples of overgrown agricultural land can be found in many other parts of the Swiss mountain area (see Surber et al., 1973; Giovanoli, 2005; SFSO, 2005).

1.2 Motivation of the research

Natural forest re-growth leads to a variety of consequences for the environment. Positive consequences are the stabilisation of soils (Tasser et al., 2003), carbon sequestration (Houghton et al., 1999) and the temporary increase of biodiversity (Laiolo et al., 2004). Negative consequences are the irreversible loss of traditional cultivation forms such as alpine and mountain pasturing (Ihse, 1995; Petretti, 1996; Sickel et al., 2004), a higher probability of wild-fires (Romero-Calcerrada &

[7]The wooded area includes open and closed forest, bushes and groups of trees (see BFS, 1992).

[8]It should be noted that the Swiss National Forest Inventory estimates 47 612 ha increase of forest area in Switzerland between the 1980s and 1990s (Brassel & Brändli, 1999). However, Swiss land-use statistics (ASCH) data and Swiss National Forest Inventory (SNFI) data are difficult to compare. This is because other definitions of 'forest' and sampling approaches are used. Also the time period under investigation differers, i.e., the SNFI used a 10-year study period, whereas the ASCH used a 12-year study period to estimate forest cover changes between the 1980s and 1990s.

[9]The municipality of Soazza is one of the case study municipalities of this thesis.

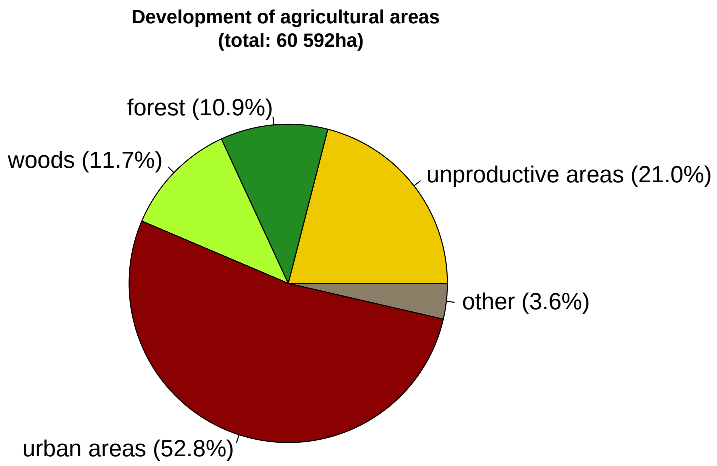


Figure 1.1
Development of agricultural areas between 1979/85 and 1992/97. Figure modified after SFSO (2005).

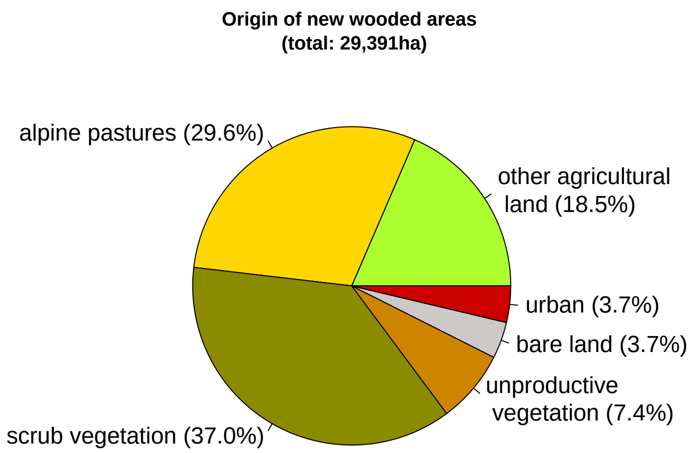


Figure 1.2
Origin of the wooded areas that occurred between 1979/85 and 1992/97. Figure modified after SFSO (2005).

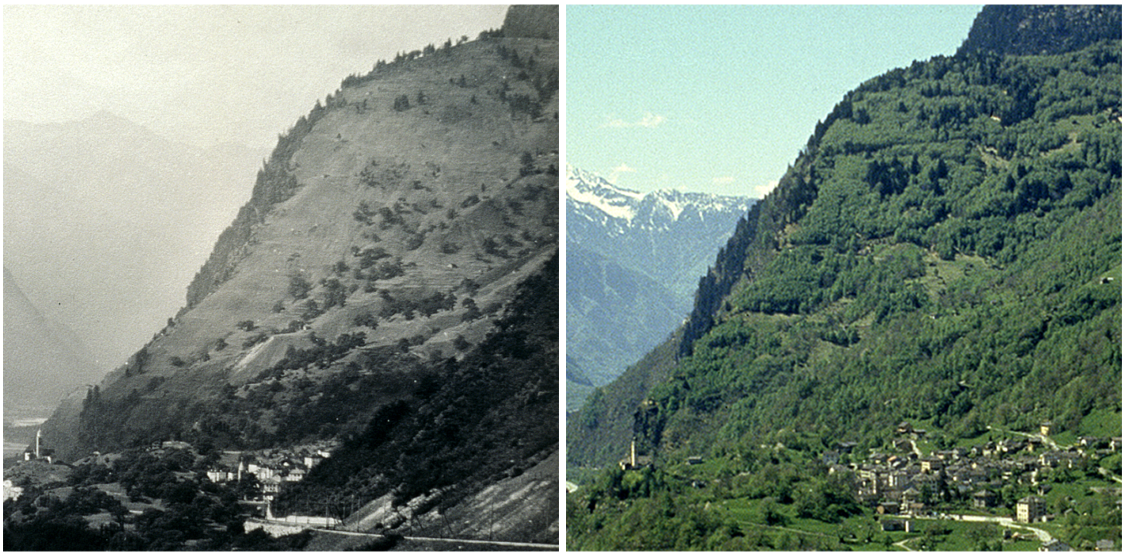


Figure 1.3
Natural forest re-growth on the Mont Grand in Soazza. Left: in the year 1915, the largest part of the hillside was under agricultural cultivation. Right: in the year 2004, almost all land had been abandoned and naturally overgrown by trees and bushes. Source: Chr. Meisser (left) and A. Ciocco (right).

Perry, 2004) and the long-term loss of species-rich habitats (Anthelme et al., 2001; DLG, 2005). In European mountain regions, it is particularly the loss of valuable habitats that is regarded as problematic (Baldock et al., 1996; MacDonald et al., 2000; DLG, 2005). This is because the natural habitat of many species now found in manmade habitats has been destroyed or degraded over centuries of human development and influence (Laiolo et al., 2004). Therefore the survival of these species often depend on the maintenance of manmade habitats such as alpine and mountain pastures (Baldock et al., 1996; MacDonald et al., 2000). In Switzerland, most habitats of high ecological value can be found in low-intensively used areas at high altitudes. As shown in Figure 1.4, it is these areas in particular that are affected by land abandonment and forest re-growth.

In addition to the possible negative effects for the environment, some authors expect negative economic effects from land abandonment and forest re-growth, for example the loss of income from tourism caused by the reduction of the attractiveness of the landscape (Krippendorf, 1984; Hunziker, 1995). Other authors even argue that land abandonment and forest re-growth may have an impact on the economic viability of rural villages (DLG, 2005).

In Switzerland, empirical studies on the geo-physical and socio-economic determinants of land abandonment and natural forest re-growth are rare and exist solely in the form of smaller case studies (Surber et al., 1973; Walther, 1986). As mountain-wide empirical studies are not avail-

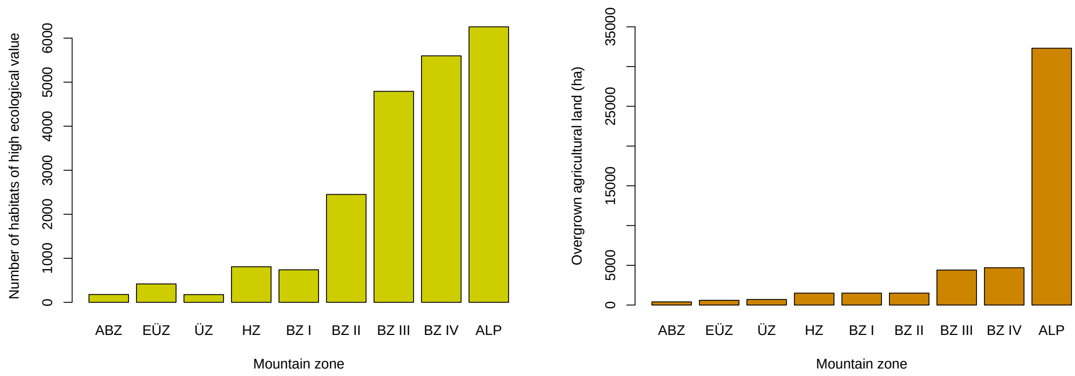


Figure 1.4
Left: number of mapped habitats of high ecological value per mountain zone (source: Dr. Thomas Niklaus Dalang, WSL). Right: agricultural area per mountain zone that became forest between two National Forest Inventories evaluated in 1983/85 and 1993/95 (source: Dr. Urs-Beat Brändli, WSL). Mountain zones are ordered by increasing altitudes starting from left. Figures: author.

able, little is known about the socio-economic determinants of land abandonment and natural forest re-growth in the Swiss mountain area. For example, some authors expect a direct relationship between farm-labour migration and land abandonment and draw the conclusion that land abandonment (and therefore natural forest re-growth) can be prevented by preventing farm-labour migration (Messerli, 1989; Bätzing, 1996; Broggi et al., 1997). However, there is no empirical evidence that the decrease of the number of farms and land abandonment are directly correlated. Naegeli-Oertli (1986), for example, showed for the municipality Grindelwald that, despite the considerable decrease of the number of farms during the last decades, almost no farmland has been abandoned. On the aggregated level, Baur (1999) showed that the rate of change of farms in the Swiss mountain area between 1950 and 1990 was not higher but lower compared to the Swiss Plateau. At the same time, forest re-growth occurred more frequently in the Swiss mountain area than on the Swiss Plateau (Surber et al., 1973; Walther, 1986; SFSO, 2005; Brassel & Brändli, 1999).

With the future liberalisation of the agricultural market, it is expected that the ecological and economic problems related to land abandonment and forest re-growth will increase (Hunziker, 1995; Bätzing, 1996; Broggi et al., 1997). The limited knowledge on the one hand and the relevance in the fields of nature conservation and regional, agricultural and environmental politics on the other hand (see Bloetzer, 2005; Egger, 2005; Geiger, 2005; Kaltenbrunner, 2005; Ragaz, 2005; Rodewald, 2005; Schmid & Bolliger, 2005) make a comprehensive mountain area wide study on the patterns and causes of natural forest re-growth necessary.

1.3 Objectives, research questions and hypotheses

This thesis aimed to investigate the patterns and causes of natural forest re-growth on agricultural land in the Swiss mountains (Alps and Jura mountains). In detail, the three objectives were: 1.) To investigate the regional-scale pattern of agricultural land abandonment (as indicated by natural forest re-growth) in the entire Swiss mountain area. 2.) To investigate the pattern of natural forest re-growth in the entire Swiss mountain area at the disaggregated scale. 3.) To investigate individuals' motives for abandoning and maintaining the cultivation of marginal agricultural land and allowing natural forest re-growth to occur and the causes of natural forest re-growth within selected case study municipalities. From the objectives, three research questions were formulated. The research questions and hypotheses are:

1. *Which mountain area wide pattern of agricultural land abandonment (as indicated by forest re-growth) can be identified at the regional scale*?

   Hypotheses: It is predicted that mountain regions where the topographic conditions were unfavorable for agricultural production, road infrastructure was less developed and off-farm employment was easily possible, i.e. cultivation costs of agricultural land where high and the opportunity costs (i.e. the value of the alternative use) of agricultural labour were high, were favored in terms of land abandonment and natural forest re-growth. Furthermore, it is predicted that mountain regions where the agro-climatic conditions were unfavorable for agricultural production and soils were of poor quality, i.e. benefits of agricultural land were low, were also favored in terms of land abandonment and natural forest re-growth.

2. *Which mountain area wide pattern of natural forest re-growth can be identified at the disaggregated scale*?

   Hypotheses: It is predicted that forest re-growth occurred primarily in agricultural areas where slopes were steep, soils were stony and shallow and land was remote from roads, farmhouses and settlements, i.e. cultivation and accessibility costs were high. It was also predicted that forest re-growth occurred primarily in areas where the climatic conditions were unfavorable for agricultural production and soils were of poor quality, i.e. benefits were low. Furthermore, it was predicted that forest re-growth occurred primarily where off-farm employment was easily possible and land was remote from construction zones, i.e. the opportunity costs of agricultural labour were high and the opportunity costs of land were low.

3. *Which are the underlying causes of natural forest re-growth, and what motivated individuals to abandon or maintain the cultivation of marginal agricultural land and allow forest re-growth to occur*?

Hypotheses: The basic mechanism behind agricultural land-use changes is the economic development and the related relative decrease of agricultural incomes. Decreasing agricultural incomes relative to the incomes possible in jobs outside the agricultural sector means an increase in opportunity costs of agricultural labour (Strijker, 2005). It is predicted that natural forest re-growth can be related to indicators of the increasing opportunity costs of agricultural labour such as farm labour migration and shortages, and the switch over from labour intensive to labour extensive cultivation forms. Furthermore, it is predicted that individuals balanced costs and benefits when they decided to abandon or maintain the cultivation of marginal agricultural land.

1.4 Structure of the thesis

This cumulative thesis consists of two parts. The first part (*Part I: Overview and Summaries*) consists of seven chapters that provide the research background, state of research, theoretical framework, materials and methods, summaries of research studies, a summarised discussion of findings and conclusions and an outlook. In the following, the content of each of the seven chapters is briefly summarised.

- **Chapter 1** provides the research background, motivation of the research, objectives, research questions, hypotheses and structure of the thesis.
- **Chapter 2** includes an overview of existing studies on the patterns, dynamics, causes, consequences and perception and assessment of agricultural land abandonment and natural forest re-growth. Since spatial statistical economic models provide the basis to investigate the patterns and causes of forest re-growth in this thesis, a literature review of such models including commonly used theories, data and modelling approaches is provided.
- **Chapter 3** describes the land rent theories by David Ricardo, and Johann Heinrich von Thünen. The combination of both theories provides the theoretical framework of this thesis, and to explain the pattern of natural forest re-growth in the Swiss mountain area.
- **Chapter 4** provides descriptions of the study areas, data, spatial statistical issues and modelling approaches used in this thesis. The information complements the information given in the research papers.
- **Chapter 5** summarises the objectives, methods, most important findings and main conclusions of the four research studies. The summaries provided in this chapter do not substitute the reading of the full research papers, although they provide a useful overview. Full research papers are provided in the second part of this thesis.

- **Chapter 6** discusses the most important findings of the research studies as well as its practical relevance and the strengths and weaknesses of the approaches. It also provides information about the characteristics of areas in which natural forest re-growth is expected to occur in the future.
- **Chapter 7** comprises conclusions and an outlook.

The second part of the thesis (*Part II - Research papers*) includes four research papers. Research papers include the four single studies which provide the basis of this thesis. The research papers are:

Paper A:

Gellrich, M., Zimmermann, N.E. (2007). Investigating the regional-scale pattern of agricultural land abandonment in the Swiss mountains: a spatial statistical modelling approach. *Landscape and Urban Planning* 79, pp. 65-76.

Paper B:

Gellrich, M., Baur, P., Zimmermann, N.E. (2007). Natural forest re-growth as a proxy variable for agricultural land abandonment in the Swiss mountains: a spatial statistical model based on geo-physical and socio-economic variables. *Environmental Modelling and Assessment* 12, pp. 269-278.

Paper C:

Gellrich, M., Baur, P., Koch, B., Zimmermann, N.E. (2007). Agricultural land abandonment and natural forest re-growth in the Swiss mountains: a spatially explicit economic analysis. *Agriculture, Ecosystems and Environment* 118, pp. 93-108.

Paper D:

Gellrich, M., Baur, P., Robinson, B.H., Bebi, P. (2008). Combining classification tree analyses with interviews to study why sub-alpine grasslands sometimes revert to forest: a case study from the Swiss Alps. *Agricultural Systems* 96, pp. 124-138.

CHAPTER 2

State of research

2.1 Studies on agricultural land abandonment

Agricultural land abandonment is a phenomenon that can be observed worldwide (Baldock et al., 1996; MacDonald et al., 2000; Rudel et al., 2000; Perz & Skole, 2003; DLG, 2005). In western European countries, land abandonment is not new and has been documented for the period after the Black Death in the Middle Ages (Van Hoof et al., in press), for the industrialisation period at the beginning and middle of the 19th century (Mather, 2001) as well as for the post World War II period (Baldock et al., 1996). In the EU12[1], for example, the Utilised Agricultural Area (UAA) decreased by 8% or 11 million ha between 1961/65 and 1983 (Baldock et al., 1996). During the same period, the forest area in the EU12 increased by approximately 15%, much of this taking place before 1977 and thought to be due to natural re-growth rather then planned afforestations (CEC, 1988, cited in Baldock et al., 1996). In many of the EU's new members, such as the Baltic countries, land abandonment has only occurred recently as a result of the economic development in the post-socialist era from the beginning of the 1990s onwards (DLG, 2005).

The Rural Areas & Europe project conducted by the Institute for European Environmental Policy (IEEP) in the 1990s (Baldock et al., 1996; Selby et al., 1996) provides the first comprehensive study on the patterns and processes of agricultural land abandonment in Western Europe. Based on different indicators chosen from a range of databases (including geo-physical and agro-climatic conditions, regional development, economic performance, agricultural structures), and case stud-

[1]The EU12 includes the countries Belgium, Germany, France, Italy, Luxembourg, the Netherlands, Denmark, Ireland, United Kingdom, Greece, Portugal, Spain

ies conducted in parts of Finland, Spain, the Netherlands, Italy and France, the IEEP study identified a clear overall pattern of changing agricultural land-use in Western Europe. It shows an increase of the land-use intensity in the most productive areas, often with an expansion of arable land at the expense of permanent grassland. In marginal regions, arable land and mixed farming systems have been abandoned on a large scale, to be replaced by extensive livestock systems, plantation forestry or natural succession (Baldock et al., 1996). Often, the increase and decrease of land-use intensity took place simultaneously within an area or individual farm.

MacDonald et al. (2000) discuss the environmental consequences of agricultural land abandonment as well as the causes of the abandonment of traditional farming practices in 24 case-study areas in mountain regions in Greece, France, Italy, Spain, Portugal, Sweden, Finland, Austria, Slovenia, Switzerland and Germany. Information about the economic development, agricultural structures and land-use changes were provided by regional authorities. From the 24 regional authorities 21 mentioned the abandonment of farmland as one of the main pressures on the environment. Often farmers ceased to use land associated with high costs and low yield potential due to poor soil quality, steep slopes, difficult access, higher labour requirements or where farmers' age and health prohibited use of land further away from the farmstead. In some regions, off-farm employment and the time required for pluriactivity contributed to farmers abandoning agriculture. In traditional grassland systems (as in the Alps) overgrazing and undergrazing often occurred simultaneously within an area or individual farm and many former meadows were substituted with permanent grasslands. In mixed arable and livestock farming systems, predominant in the Mediterranean areas, changes in management practises generally involved specialisation into monoculture cropping. According to MacDonald et al. (2000), current policy measures in European mountain regions are not entirely successful in preventing the negative environmental effects of land abandonment - a perception that is shared by authorities in alpine regions (see e.g. Broggi et al., 1997).

Recently, the Dutch Ministry for Agriculture, Nature & Food Quality in cooperation with the Latvian Ministry of Agriculture conducted an international seminar to find adequate political instruments to prevent agricultural abandonment and preserve valuable grasslands in the new Member States of the EU[2] (DLG, 2005). In these countries, it is estimated that on average 26% (locally up to 60%) of the semi-natural grasslands have been temporarily or permanently abandoned (DLG, 2005). Land abandonment is of particular concern in the Czech Republic, Estonia, Hungary, Latvia, Lithuania, Poland, Slovakia and Slovenia. The extent of land abandonment in these countries can be attributed to the structural changes in agriculture caused by the breakup of large collective or state farms and the privatisation of land in the post-socialist era. Many farms went

[2]There are 10 new Member States which acceded to the EU on May 1st 2004: Cyprus, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Malta, Poland, Slovakia and Slovenia.

through a process of fragmentation during which management took time to adjust or was temporarily disrupted. Often these processes led to smaller farm units and farmers were faced with problems such as the lack of equipment, limited access to capital, a scarcity of advice and technical support and difficulties with markets. As a result, labour left the agricultural sector on a large scale resulting in considerable rates of land abandonment and forest re-growth.

In addition to the comprehensive studies mentioned above, various small-scale case studies on the patterns and processes of land abandonment have been conducted. Ihse (1995) investigated the pattern of agricultural land-use change in Sweden in the period after World War II using aerial photography analyses. Results of her study show that in the area of plains, grasslands and wetlands have decreased as a result of the intensification of land-use. Many small farms in regions with less favorable production conditions have been abandoned and the former grasslands have become naturally overgrown or have been planted with spruce. As a result, the structure of many semi-natural habitats has become more simple which is related to negative effects on flora and fauna.

Beaufoy (1996) analysed changes in agricultural structures and land-use in Extremadura (central Spain) in the period after World War II based on different census data. In the 1960s and 1970s, the region was characterised by high out-migration, farm labour migration, land abandonment and forest re-growth. Due to the Common Agricultural Policy (CAP) payments for farmers from the mid 1980s onwards, the practise of agriculture experienced a revival. In the 1990s, agricultural land abandonment was not widespread, and much of the former fallow land and woodlands decreased at the expense of permanent pastureland or irrigated arable land.

Petretti (1996) analysed the human driven patterns and causes of agricultural land-use change in an alpine area in Northern Italy (Valle d'Aosta) based on different census data. Although the Valle d'Aosta is one of the richest regions in Italy (due to good transport connections and tourism), the small rural communities in the valleys have not greatly benefited from the region's economic strength. This, according to Petretti (1996), is one of the reasons for the considerable farm labour migration during the last decades. Contrary to the high farm labour migration, the total cattle stock has decreased only slightly. Both intensification of land-use and land abandonment could be observed within the study area. The area of meadows is decreasing annually in the steeper and less favourable areas, mainly due to forest re-growth on previously grazed areas. Often, only a part of the alpine pastures was abandoned, although completely abandoned pastures have also been found. There has been a shift from labour intensive dairy farming to less labour intensive breeding of calves and steers during the last decades. The main reasons for the observed land-use and farm management changes are the diminishing economic viability stemming from both high costs, in particular for the lease of pasturing rights and labour, and relatively low income.

Selby (1996) investigated the processes of agricultural marginalisation in Finland in the period after World War II. In Finland, where forest accounts for 84% and agricultural land less then 8% of the total land surface area, many farms have been abandoned during the last decades. Reasons for farm abandonment mentioned by Selby (1996) are the ageing of farmers, lack of successors, adoption of alternative professions or ”disillusionment with agriculture”. Poorly located or poorly shaped fields, poor soils, stoniness and proneness to frost are the main geo-physical and structural characteristics of fields most likely to be withdrawn from agriculture and afforested. As forestry was and is an important part of the Finnish industry and many farmers have an additional income from privately owned forests, the government supported old field afforestations. The main economic reasons for the afforestation of agricultural land include the poor returns from farming, objections to leaving land fallow and the availability of grant aid for planting trees.

Kristensen et al. (2004) investigated land-use changes in a case study area in Jutland (Denmark) in the 1990s. Interviews with farmers were conducted, and different statistical methods (Multiple Correspondence Analyses, Hierarchical Cluster Analyses) used in order to investigate farm types, farmer characteristics and landscape changes as well as to analyse their relationships. The most common activities were hedgerow removal and planting, conversion of arable land to permanent grassland, planting of woods and small woodlands and abandonment of permanent grassland. Land abandonment is typical for small farms with a small percentage of arable land and no or few animals but has also been found on larger mixed crop-livestock farms. The authors found that land abandonment and reforestation occurred mostly where farms were managed by middle aged and older farmers.

Romero-Calcerrada & Perry (2004) analysed land-use changes in a case study area in central Spain between 1984 and 1999 using satellite image analyses. Results show considerable increases in scrubland and woodland and decreases in cropland and pastureland. The low profitability of agricultural activities, small size of farms, ageing of the agrarian community as well as good off-farm job opportunities (the study area is located 40 km west of Madrid) for the younger parts of the population are identified as the most relevant causes of land abandonment and forest re-growth.

Van Eetvelde & Antrop (2004) investigated structural and functional changes of three traditional landscapes (case study municipalities) in southern France by analysing aerial photographs. Results show that agricultural intensification and land abandonment acted simultaneously with different forms of urbanisation. In one municipality, land abandonment and forest re-growth could be linked to population growth. The authors concluded that for regions outside the investigated municipalities, an assessment of the relationships between land-use change and population growth remained difficult.

Hietel et al. (2005) investigated land-cover changes in the period between 1945 and 1999 in the Lahn-Dill Highlands - a rural region in the middle of Germany. Based on aerial photography interpretation, different types of land-cover changes are differentiated (e.g. arable land to fallow land, arable land to grassland, fallow land to grassland, grassland to fallow land, etc.). By means of redundancy analysis (RDA), the authors analysed the relationships between land-cover changes and environmental factors (e.g. steepness of slopes, elevation, soil type) and socio-economic factors (e.g. commuters, employment in agriculture, population density). Results show that steep land at higher elevation with poor soils in areas where the majority of farms are managed on a part-time basis and sheep pasturing is common is favored in terms of land abandonment. The authors conclude that transitions to fallow land are indicated in particular by environmental variables characterising unfavorable agricultural conditions, together with socio-economic indicators showing unfavorable non-agricultural employment alternatives.

Nikodemus et al. (2005) used historical maps, aerial photographs, different census data and interviews with local farmers to investigate the impact of economic, social and political factors on land-use changes in a case study area in Latvia over a period of 100 years. While at the beginning of the 20th century, land-use pattern was largely determined by soil type, fertility and drainage, political circumstances after World War II (loss of population as result of death during the war, exile and deportations) and during the period of Soviet occupation (establishment of large collective farms) were identified as the most important drivers of land abandonment and forest re-growth. In the period after Soviet occupation from 1991 on, most land was privatised and many farmers were confronted with structural problems (small farm sizes, scattered land parcels); many landowners live outside the regions and have no interest in cultivating their land. Structural changes in agriculture led to considerable land abandonment and forest re-growth from the beginning of the 1990s on.

In Switzerland, empirical studies on land abandonment have been carried out since the 1970s. Two disciplinary perspectives of empirical studies can be distinguished: agricultural economics and social geography. In social geography, land-use change is regarded as the result of the general social and economic development; changes in values (e.g. population change) or preferences (e.g. pasturing instead of mowing) are identified as the relevant driving factors (Wanner, 1983;

Messerli, 1984; Walther, 1984). In agricultural economics land-use change is explained by exogenous factors such as changing labour markets, relative prices and infrastructure developments (Bernegger et al., 1990; Rieder et al., 1990; Pezzatti, 2001).

The first comprehensive studies on land abandonment in Switzerland were conducted by Surber et al. (1973) and Moos & Herot (1977). According to Surber et al. (1973), land abandonment takes place where the geo-physical and agro-climatic conditions are unfavorable for agricultural production, parcels are fragmented due to previous hereditary customs ("Erbteilungen") and farm labour migration is high. In selected mountain municipalities, Surber et al. (1979) investigated the characteristics of abandoned land parcels. Based on the findings of these case studies, predictive maps were generated (raster maps with cell size 3 km) to assess the nationwide vulnerability of agricultural land becoming abandoned in the near future.

Walther (1986) used a perspective from social geography to explain land abandonment. He used census data from 8 mountain municipalities and conducted field surveys on approximately 400 agricultural plots to investigate the patterns and causes of land abandonment between 1950 and 1980. His findings show that land abandonment mostly takes place where parcels are steep and remote from settlements, agricultural land is fragmented, farms are small-scaled and farmers did not invest in their farms in the past. He concludes that land abandonment is the result of a prevented modernisation of agriculture.

Non-spatially explicit economic studies on land-use intensity and land abandonment have been carried out by Bernegger et al. (1990) and Rieder et al. (1990). Bernegger et al. (1990) used simulation models at the village-level to investigate the influence of agricultural structures on the land-use intensity. Results show that the proportion of arable land per mountain village and the accessibility of agricultural land by roads have a decisive influence on the use-intensity. Rieder et al. (1990) used similar models to investigate the influence of subsidies for the cultivation of steep slopes ("Flächenbeiträge") on the cultivation of grasslands. Findings show that subsidies can prevent the abandonment of grasslands close to villages on which mechanised mowing is not possible. Subsidies can also prevent the abandonment of grasslands remote from villages provided that these areas are directly accessible by roads.

A spatially explicit economic study on the influence of road infrastructure developments on the agricultural structures and land use-intensity was carried out by Pezzatti (2001). Based on farm-level data, he found significant relationships between the road infrastructure development and the overall land-use intensity. Analyses on the parcel level revealed that the land use-intensity decreases with increasing distance of the land from roads.

2.2 Studies on forest re-growth

The empirical studies on forest re-growth found in the literature can safely be divided into: (i) studies on forest transitions, (ii) studies on forest re-growth dynamics, (iii) studies on the environmental consequences of forest re-growth, (iv) studies on the perception and assessment of forest re-growth and (v) studies on the socio-economic determinants of forest re-growth.

2.2.1 Studies on forest transitions

Forest transitions, i.e. the changes from net deforestation to net reforestation, were investigated by Rudel (1998), Mather (2001) and Rudel et al. (2005). The focus of these studies is on the relationships between forest cover changes and population changes and economic development on the country-level, over long time periods. Rudel (1998) investigated worldwide forest transitions in the period between 1922 and 1990 based on forest statistics, population censuses and consumption statistics provided by the Food and Agricultural Organization of the United Nations (FAO), World Bank, and other organisations. He found that a significant number of countries experienced a turnaround in forest cover trends changing from deforestation to reforestation as they became more urban and industrial. Results of multivariate regression models show that during the 1948-1963 period, reforestation occurred under two conditions associated with economic development: (i) a slow rate of population growth and (ii) a highly urbanised population.

Mather (2001) investigated the forest transition in Denmark, France and Switzerland in the 19th and 20th century based on country-level data. Relationships between forest cover changes, population growth, economic development and political settings were analysed to better understand the past processes of deforestation and reforestation in these countries and current forest cover changes in non-industrialised countries. Results suggest that population growth and the related pressure on forests contributed to deforestation in the early 19th century. Recourse crises due to wood shortages, technology changes in agriculture (including the introduction of commercial dairy farming), the introduction of new sources of energy (i.e. fossil fuels instead of charcoal and fuel-wood) as well as new forms of employment brought deforestation to a halt and led to reforestation. Mather (2001) conclude that technology changes in agriculture might also influence deforestation in present-day developing countries.

Rudel et al. (2005) investigated worldwide forest transitions based on FAO data. Arguments about forest recovery take two general forms. In one line of argument (referred to as the ’economic-development path') farm workers leave the farms for better paying non-farm jobs. The decrease of farm labour raises the wages of the remaining farm workers and makes more agricultural enterprises unprofitable. Under these circumstances, farmers abandon their more remote, less productive fields and pastures. This trend can be found in many industrialised countries in Europe and North America. In the other line of argument (referred to as the 'forest scarcity path'), the loss of forests during agricultural expansion increases the prices for forest products. The price increases induce landowners to plant trees instead of crop or pasture grasses. The latter trend can mostly be observed in newly industrialised countries such as India or China. Results of the study show evidence for both theories. Furthermore, Rudel et al. (2005) found out that nations with increasing forest cover and nations with decreasing forest cover differ significantly from one another in both per capita income and the extent of forest cover. Another finding from their study is that even when forest became scarce, the forest transition may not occur unless governments can create effective forestation programs.

2.2.2 Studies on forest re-growth dynamics

Staaland et al. (1998) investigated the dynamics of forest re-growth after agricultural abandonment in a case study area in Southern Norway. In order to do so, they compared aerial photographs taken between 1950 and the 1990s. Tree ages were determined in the field by counting annual rings from increment cores. Results show that the quantity of re-growth scrub (mostly gray alder, *Alnus incana*) decreased with increasing distance from forest edges, and that re-growth rates were slower in wet areas compared to moist areas. Tree ages correlated to the length of the period the open grassland had been abandoned. In the less favourable wet areas, a time-lag between land abandonment and tree growth of 10-15 years was found. The authors also found an effect of moose and roe deer browsing on the forest re-growth dynamic.

Didier (2001) combined aerial photo interpretations (photos taken in 1939 and 1990) with field work (measurements within dendroecological plots) to investigate the recolonisation of European larch (*Larix decidua*) and Swiss stone pine (*Pinus cembra*) at the treeline (above 2000 m a.s.l.) in a study area in the northern French Alps. The shift from heath to open forest has been identified as the most common recolonisation type, followed by the transformation of open forest into forest and of meadows into forest. After abandonment of alpine pastures, European larch formed colonisation patches, in particular close to the ancient chalets. Following the invasion of larch, Swiss stone pine regenerated in the young larch woods forming dense seedling patches. Didier (2001) found that soil conditions and relief form are the most relevant factors which determine the forest re-growth dynamic after agricultural abandonment.

Kozak (2003) investigated forest cover changes in a case study area in the Western Carpathians (Poland) over a period of 180 years between 1823 and 2001. Historical topographic maps and contemporary satellite images were overlaid and compared to extract forest-cover and its change over time along different altitudinal gradients. As a result of the abandonment of grasslands, the proportion of forested land has significantly increased. Results show that forest re-growth occurred at lower and higher altitudes compared to the existing forest and that the land-cover change dynamic was particularly high close to forest edges.

Poyatos et al. (2003) investigated the patterns of forest re-growth after agricultural abandonment in a case study area in northeastern Spain based on aerial photo interpretation (photos taken between 1957 and 1996). Results show a significant increase of Scots pine (*Pinus sylvestris*) at the expense of grassland, cropland, and scrub vegetated areas. The expansion of forest area was accompanied by a significant increase in woodland density. Pine colonisation was significantly higher where slopes are steep and at high altitudes and in the inner parts of terraced agricultural areas, compared to the dryer outer parts of terraces.

2.2.3 Studies on the environmental consequences of forest re-growth

Natural forest re-growth is related to both positive and negative consequences for the environment. Positive consequences are the stabilization of soils (Tasser et al., 2003), carbon sequestration (Houghton et al., 1999) and the temporary increase of biodiversity (Laiolo et al., 2004). Negative consequences are the long-term loss of species-rich habitats (Anthelme et al., 2001) and the higher probability of wild-fires (Romero-Calcerrada & Perry, 2004).

Tasser et al. (2003) investigated the risk of soil erosion due to changes in land use within subalpine-alpine study sites in Italy and Austria. Different factors were analysed in eroded and non-eroded areas. The factors included geomorphological, pedological, phytosociological and land-use characters. Data were statistically analysed by means of logistic regression. Results show that, apart from exposition, inclination and soil depth, land use was an important determinant of soil erosion. Erosion risk is high in abandoned agricultural areas and increases with increasing dwarf shrub coverage. Older abandoned areas covered with dwarf shrubs are especially at risk. An increase in total root density reduces the risk of soil erosion.

Houghton et al. (1999) investigated the influence of land-use changes on the carbon budget in the United States. They reconstructed the rates at which lands were cleared for agriculture, abandoned, harvested for wood, and burned. Historical data for the period 1700-1990 were used in a terrestrial carbon model to calculate annual changes in the amount of carbon stored in terrestrial ecosystems, including wood products. As a result of fire suppression and forest growth on abandoned farmlands, in the period after 1945, carbon accumulation was observed. During the 1980s, the net flux of carbon attributable to land management offset 10 to 30% of U.S. fossil fuel emissions.

Laiolo et al. (2004) investigated the consequences of forest re-growth after pastoral abandonment for the structure and diversity of avifauna in the Grand Paradiso National Park (north-western Italian Alps). In order to do so, bird surveys and habitat structure analyses were conducted in the field. Landscape parameters and grazing pressure, which was quantified via interviews with the local people, were correlated to the species diversity. Results show that forest re-growth generally increases the abundance and diversity of birds, but that species that are highly adapted to grasslands are clearly disadvantaged in a landscape where grazing and mowing is abandoned and forest re-growth occurs. Laiolo et al. (2004) conclude that forest re-growth may have positive effects on the abundance of birds but that the large-scale abandonment of semi-natural pastoral habitats and their replacement with trees and scrub is likely to be detrimental in terms of bird conservation objectives.

Anthelme et al. (2001) investigated the consequences of green alder (*Alnus viridis*) expansion on vegetation changes and arthropod community removal in abandoned alpine pastures in the northern French Alps. Data were collected from sample plots in the field. Results show that plant species richness first increases with increasing alder cover to reach a maximum at approximately 50% alder cover and declines significantly above 50% alder coverage. Alder expansion had clear negative effects on the arthropod abundance which were found to be highest in pure grasslands. Anthelme et al. (2001) hold natural forest re-growth in abandoned pastures and the related decrease of the number of arthropods responsible for the significant decrease of endangered species such as the black grouse (*Tetrao tetrix*) during the last decades.

Romero-Calcerrada & Perry (2004) analysed land-use changes in central Spain between 1984 and 1999 using satellite image analyses. Results show a considerable increase in scrubland and woodland at the expense of cropland and pastureland. As a result of natural forest re-growth, fire risk increased in the study area. The authors argue that an increase in fire-prone (flammable) vegetation types, such as scrubland, may increase burned areas and possibly fire frequency and intensity.

2.2.4 Studies on the perception and assessment of forest re-growth

Recently, scholars have begun to investigate the perception and assessment of natural forest re-growth by concerned people. Hunziker (1995) conducted qualitative interviews with locals and tourists to generate hypotheses concerning the landscape aesthetic impacts of natural forest re-growth on abandoned land in a study area in the Swiss mountains. Two hypotheses were generated: (i) based on four dimensions of landscape experience (tradition, nature conservation, profit and emotion), forest re-growth is experienced in an ambivalent way, (ii) a partial ingrowth of forest into a cultural landscape reaches highest preference. Based on his findings Hunziker (1995) proposes an inverted U-shaped relationship between the quantity of forest re-growth and the aesthetic preferences by locals and tourists.

Höchtl et al. (2005) used historical data (letters, land use statistics, old land registers and maps, photographs) and conducted qualitative interviews with locals and tourists to study the impacts of land abandonment and natural forest re-growth on the landscape's structural diversity, richness of plant species, and the perception and assessment of land abandonment and forest re-growth by locals and tourists. The study area was the community of Premosello Chiovenda in the Val Grande National Park - "Italy's largest wilderness area". Results show that many of the previously cultivated areas have been abandoned and are presently in various states of succession. The floristic species richness is decreasing in higher successional stages, and depending on the altitude, the structural diversity of the landscape is changing. Free nature developments and associated changes in the landscape have significant effects both on locals and tourists. Although many rural and cultural landscape characteristics persist, villages and the surrounding landscape are increasingly being viewed as unattractive. Many villagers felt wronged by politicians and are very unhappy with this situation. Tourists judge the consequences of land abandonment differently. While they regard the resulting landscape's wildness positively, they also regret the cultural losses suffered by rural communities. The authors identified a loss of historical experience, cultural knowledge and local identity due to the decreasing usability and accessibility of the landscape.

2.2.5 Studies on the socio-economic determinants of forest re-growth

Studies on the socio-economic causes of natural forest re-growth have been carried out to better understand the underlying processes of natural forest re-growth. Rudel et al. (2000) describe the circumstances of Puerto Rican reforestation between 1950 and 1990 by matching changes in plots of land with social changes and physical characteristics in the surrounding municipalities. In order to do so, they used forest inventory data (systematically sampled plots) and census data (measures of farm size, household income, off-farm employment and the most valuable crop in a municipality). Three types of analyses were carried out with these data. Firstly, census data were used to describe differences between inventory plots classified as reforesting versus agricultural in the characteristics of the communities in which they are located. Secondly, logistic regression was used to predict whether or not particular plots of land would reforest. Thirdly, all data were aggregated to the municipality level and the proportion of plots in a municipality that are reforesting were calculated. Results show that reforestation was concentrated in the upland regions of the island. Reforested plots had steeper slopes than land with other uses, clustered in coffee-growing municipalities in which smallholders predominated and were almost completely in private hands. Most of the reforestation was concentrated in poorer rural municipalities with smaller farms. These municipalities were also characterized by out-migration and off-farm employment of farmers. Rudel et al. (2000) conclude that industrialisation in Puerto Rico played an important role in drawing workers away from labour intensive agricultural operations leading to reforestation.

Perz & Skole (2003) investigated the social determinants of secondary forests in the Brazilian Amazon between the 1980s and 1990s. The study draws on a spatially explicit data set containing satellite-based estimates of secondary forest growth, matched to census-based social indicators for municipalities. Spatial statistical models were used to investigate relationships between secondary forest re-growth and social indicators. Seven key factors were hypothesised to determine secondary forest growth: (1) settlement history, (2) agricultural intensification, (3) non-traditional land-use, (4) crop-productivity, (5) tenure insecurity, (6) fuelwood extraction and (7) rural in-migration. Explanatory variables were selected based on these key indicators. To account for neighbourhood effects, spatial lagged variables were included in the models. In order to obtain a spatial resolution suitable for spatial modelling, all data were aggregated to the municipality level[3]. Results show that models for the three different subregions (remote, frontier, settled) show different relationships between secondary forest growth and its social determinants. In the remote subregion, forest regrowth was more prevalent where there were higher rural native population densities, more fertilizer use, more annual crops, less pasture and higher crop productivity. Contrary to this, in the frontier neither annuals nor pasture show significant positive effects, only rural firewood collection. In the settled subregion, higher density among rural natives reduced the prevalence of forest regrowth. Municipalities with greater fertiliser use and where firewood extraction was more important had more forest re-growth. The authors conclude that longstanding settlement and traditional activities have positive effects on the extent of secondary forests, but that in-migration and non-traditional land use exert growing influences on forest regrowth as well, especially in frontier areas of the Amazon.

[3] According to Perz & Skole (2003), the municipalities in the Brazilian Amazon are similar to US counties.

Kobler et al. (2005) investigated the patterns and socio-economic determinants of spontaneous afforestation in a study area in south-western Slovenia between 1930 and the 1990s. Multivariate regression models were used to investigate relationships between selected bio-physical variables (e.g. slope, elevation, indices of land-cover change, distance to forest edges) and socio-economic variables (e.g. farm type, amount of land holdings, employment, livestock species, distance to settlements). Different indicators of afforestation were used as the response variables in the linear regression models. Explanatory variables were selected based on theoretical considerations. In order to obtain spatially explicit variables covering the entire study area, census data available at the settlement level were spatially extrapolated. Results show that reforestation occurred less frequently where farm areas are large. The proportion of inhabitants aged between 15 and 64 is positively related to afforestation. Model results were used to predict afforestation in the near future (1999-2017). No in-depth discussion of the importance of single socio-economic factors of reforestation is provided by the authors.

In Switzerland, studies on the pattern and causes of natural forest re-growth are rare. In addition to the studies on agricultural land abandonment conducted by Surber et al. (1973) and Walther (1986) (see section 2.1), Schuler (1977) and Kempf (1985) conducted local studies on forest cover changes. Forest statistics, historical land-use/land-cover maps, aerial photographs, and other historical data provided the basis of these studies. Schuler (1977) investigated forest area changes in the *Höhronen* - a region in the Pre-Alps. He found out that the abandonment of the public use of pastures caused natural forest re-growth. Kempf (1985) investigated forest area changes in the *Walliser Rohnetal* (south-eastern Alps). He found locally varying increases of the forest area which he relates to the overall economic development and (probably) climate change.

2.3 Economic models of land-use/land-cover change

According to Irwin & Geoghegan (2001), two types of economic models of land-use/land-cover change (LULCC) can be distinguished: (i) spatially explicit models and (ii) non spatially explicit models. In spatially explicit economic LULCC models, there are x- and y-coordinates associated with the spatial objects under investigation (e.g. roads, houses, trees). This enables the researcher to identify these objects in the field. Alternatively, in non-spatially explicit models, there are no x- and y-coordinates associated with the spatial objects under investigation. This thesis deals with spatially explicit data. The following sections provide a brief overview of commonly used theories, data and modelling approaches used in spatially explicit economic LULCC studies.

2.3.1 Theories

Economic models of land-use/land-cover changes are developed to understand the human behavioral component that underlies these changes (Irwin & Geoghegan, 2001). These models usually begin from the viewpoint of the individual landowner who makes land-use decisions to maximise utility. Economic theory is used to guide the model development, including choice of functional form and explanatory variables.

Economic theories focussing on the land-use decisions made by individuals and households are typically referred to as micro-economic theories (Briassoulis, 2000). Frequently used micro-economic theories are von Thünen's and Ricardo's land rent theories (von Thünen, 1990; Ricardo, 2002). According to these theories, the distance of the land from markets (von Thünian ideas) and its quality of the land in terms of the geo-physical characteristics (Ricardian ideas) determine land-use decisions. Empirical studies based on von Thünen's and Ricardo's land rent theories can be found by Chomitz & Gray (1996), Nelson & Hellerstein (1997), Geoghegan et al. (2001), Nelson & Geoghegan (2002) and Munroe & York (2003). Von Thünen's and Ricardo's land rent theories provide the theoretical basis to explain the pattern of natural forest re-growth in the Swiss mountains, and have been explained in detail in chapter 3.

Two other micro-economic theories often applied in LULCC research are Boserup's induced innovation theory (Boserup, 1965) and Chayanov's theory of the peasant economy (Chayanov, 1986). Ester Boserup (1910-1999) was a Danish economist. In her book *The Conditions of Agricultural Growth* (Boserup, 1965), she presented an analysis embracing all types of 'primitive agriculture' (e.g. shifting cultivation). In her theory, it is only when rising population density restricts the use of fallowing that agricultural land is brought into annual cultivation. Contending with insufficiently fallowed, less fertile plots covered with grass or bushes, mandates expanded efforts in weed control, fertilization, and irrigation. These changes often induce agricultural innovation, but also increase labour costs. As a result, farmers' workloads tend to rise while efficiency drops. This process of raising production at the cost of more work at lower efficiency is what Boserup calls "agricultural intensification". Boserup's induced innovation theory has mostly been used to explain LULCC in non-industrialised countries. An empirical work based on Boserup's theory can be found by Müller & Zeller (2002), who investigated land-use changes in the Highlands of Vietnam.

According to Chayanov (1888-1937), a Soviet agrarian economist, peasantry is a singular type of economy, based on family labour and seeking subsistence rather than profit (Chayanov, 1986). Chayanov's theory is a utility maximisation theory, where there is a trade-off within peasant households between income generation and work-avoidance. The main factors determining the trade-off are the size and composition of peasant households, which determine the available labour, and in turn the volume of economic activity. An empirical study based on Chayanov's theory has been conducted by Maertens et al. (2006), who analysed farmers' land allocation decisions in a study area in Indonesia, taking into account the lowland-upland dichotomy in the agricultural sector.

2.3.2 Data

Land-use/land-cover change modellers often deal with discrete data derived from aerial photographs and/or satellite images (Serneels & Lambin, 2001; Irwin & Geoghegan, 2001; Müller & Zeller, 2002; Munroe & York, 2003; Kobler et al., 2005; Müller & Munroe, 2005). Examples include data with two classes such as the presence/absence of deforestation as used by Geoghegan et al. (2001), and data with more than two classes such as *urban*, *forest* and *agriculture* as used by Munroe & York (2003). In order to verify the classified remote sensing data, image processing is often combined with field work. The latter is also referred to as *ground truthing*. Land-use/land-cover change is investigated by comparing classifications from satellite images and/or aerial photographs from two or more points in time (see Serneels & Lambin, 2001 and Kobler et al., 2005).

In spatially explicit economic LULCC models, land-use/land-cover changes are typically correlated with geo-physical and socio-economic explanatory variables. The selection of explanatory variables is guided by economic theory (see section 2.3.1). Explanatory variables often relate to the agro-climatic conditions (e.g. precipitation, radiation, temperature), topographic conditions (e.g. steepness, topographic position), soil characteristics (e.g soil type, soil texture), distance measures (e.g. distance to roads or settlements) and socio-economic characteristics (e.g. policies, regulations, migration, degree of mechanisation), and are typically used as proxies for cultivations costs and benefits (Chomitz & Gray, 1996; Pfaff, 1999; Walsh et al., 1999; Serneels & Lambin, 2001; Geoghegan et al., 2001; Müller & Zeller, 2002; Kobler et al., 2005).

The explanatory variables used for LULCC research are often 'constructed'. For example, soil and climate data are generally measured at discrete points (e.g. climate stations, soil samples). To obtain area-wide estimates of these data, they must be spatially interpolated. Interpolation is typically done by means of geostatistical interpolation approaches such as inverse distance weighted (IDW) interpolation or kriging (Kaluzny et al., 1998; Haining, 2003). IDW and kriging are often used to interpolate geo-physical data. Other approaches have been developed to interpolate socio-economic data. Müller & Zeller (2002) generated Thiessen polygons based on village-centroids to approximate village boundaries. The socio-economic information collected at the village-level (via questionnaires) was then linked to Thiessen polygons. Finally, all geo-physical and socio-economic data were brought together in a raster GIS to make them spatially compatible with land-use change data from satellite images. A similar approach was used by Rindfuss et al. (2002) to study land composition and spatial organisation in Thailand. Walsh et al. (1999) used equal value spread functions to link socio-economic data measured at the village-level to the agricultural land within villages.

2.3.3 Modelling approaches

This section provides a brief overview of modelling approaches frequently used for LULCC research. To keep this overview short, no mathematical formulas are provided. For detailed descriptions of modelling approaches see Lesschen et al. (2005).

Ordinary least square (OLS) regression is one of the most frequently used linear regression techniques. In OLS regression, it is possible to test whether two variables (or transformed variables if there is a non-linear relationships between these variables) are linearly related and to calculate the strength of the linear relationship (Lesschen et al., 2005). LULCC studies based on OLS regression were conducted by Kobler et al. (2005), who studied spontaneous afforestation in a study area in Slovenia, and Wood & Skole (1998), who investigated the determinants of deforestation in the Brazilian Amazon. OLS regression is less popular in LULCC because it can only be applied to continuous response variables and LULCC studies often deal with categorical response variables (Lesschen et al., 2005). OLS is also not recommended if variables show spatial autocorrelation, which is often the case with data used for LULCC research (see Anselin, 1988; Florax et al., 2002; Perz & Skole, 2003).

In the presence of spatially correlated data, alternative modelling techniques have been proposed. Commonly used linear regression techniques for spatially correlated data are maximum-likelihood based **spatial lag models (MLLAG)** and **spatial error models (MLERR)** (Anselin, 2002). MLLAG models include an additional explanatory variable on the right hand side of the model equation which represents the weighted average of the response variable values of neighbouring observation sites. This variable is also referred to as a spatially lagged response variable (Anselin, 2002). Likewise, MLLERR models include a spatially lagged error term. MLLAG and MLERR have been used to model and examine the variability of soils (Florax et al., 2002), social determinants of secondary forests (Perz & Skole, 2003) and the relationships between environmental amenities and changing human settlement patterns (Gustafson et al., 2005). MLLAG and MLERR models were also used in this thesis. For details of these modelling approaches see section 4.4.3.

Contrary to the linear regression techniques described above, **logistic regression** can deal with categorical response variables. It is useful for situations where the response variable is dichotomous (e.g. presence/absence of forest re-growth) and the explanatory variables are categorical or continuous. Logistic regression yields coefficients and associated confidence intervals for each explanatory variable based on a calibration data set. It can be used to predict the probability that a case will be classified into one as opposed to the other of the two categories of the response variable (Hosmer & Lemeshow, 2000). In LULCC research, logistic regression models have successfully been used to investigate the patterns and causes of deforestation (Geoghegan et al., 2001) and agricultural land-use changes (Serneels & Lambin, 2001; Müller & Zeller, 2002). Logistic regression was also used in this thesis (see Papers B and C). For details of this modelling approach see section 4.4.2.

Data from different levels such as fields, farms and municipalities are ubiquitous in LULCC research. These data are not independent from one another but show a group structure (i.e. fields are grouped within farms, farms are grouped within municipalities). This grouped structure violates the assumption of data independence, and must, therefore, be considered in statistical analyses (Snijders & Bosker, 1999). One possible modelling approach for grouped data is **multilevel modelling**. Multilevel models include explanatory variables (called 'fixed effects') for the individual level and the group level. Both unexplained variation within groups and unexplained variation between groups is conceived as random variation and expressed as 'random effects' (Snijders & Bosker, 1999). Overmars & Verburg (2006) uses multilevel models for land-use research. They integrated data from three different levels (fields, households and villages) into a single multilevel model to predict the occurrence of crops on fields in the Philippines. Other LULCC studies based on multilevel models are provided by Hoshino (2001), Polksy & Easterling (2001) and Pan & Bilsborrow (2005). Cluster adjustment is an alternative approach to account for the group structure in data and has been used in this thesis (see Paper C). For details of this approach see section 4.3.5.

The above mentioned approaches are parametric modelling approaches. Another group of modelling approaches are the non-parametric models. Non-parametric models are typically used for data mining and predictions and often have less stringent statistical assumptions than parametric modelling approaches. An **Artificial neural network (ANN)** is a non-parametric modelling approach, and has been used for LULCC research (Lesschen et al., 2005). ANNs were originally developed to model the brain's interconnected system of neurons so that computers could be made to imitate the brain's ability to sort patterns and learn from trial and error, thus detecting relationships in data (Lesschen et al., 2005). Pijanowski et al. (2002) developed an ANN for the Michigan's Grand Traverse Bay Watershed (USA) to explore how factors such as roads, rivers, coastlines, recreational facilities, agricultural density, and quality of views can influence urbanization patterns. Li & Yeh (2002) used ANNs to simulate multiple land-use changes in a study area in southern China.

Another non-parametric modelling approach often used for LULCC research is **classification tree analysis**. In a classification tree, a data set is recursively partitioned into increasingly homogenous subsets called terminal nodes (Breiman et al., 1984). Splits defining how to partition the data are selected based on information statistics that measure how well the split decreases the heterogeneity of the training data at each terminal node. A developed classification tree encodes a set of decision rules in the form of if-then-statements which are analogous to the decisions made by individuals while managing their land. An application can be found by Zhang et al. (2006), who used classification trees to predict hill pasture productivity in a study area in New Zealand. Classification trees were also used in this thesis (see Paper D). A detailed description of this approach is provided in section 4.4.1.

A modelling approach that is increasingly used for simulations is that of the **cellular automaton**. Cellular automata are based upon a number of cells on a grid. Each cell is assigned one of several possible states, and inherits its own set of transition rules to change one state to another. These rules are sensitive to the content of the neighboring cells. Verburg et al. (2004a) developed cellular automata to investigate the influence of neighbourhood effects on land-use conversions in the Netherlands.

Another modelling approach often used for simulations is the **agent based model**. Agent based models are specific individual based computational models (Berger et al., 2006). These models stress the decision-making criteria of individual agents (e.g. owners or tenants). Changes in land use are the cumulative result of numerous individual and interacting decisions. For the establishment of an agent-based model, the definition of different agents is one of the primary challenges. Land owners and tenants, including farmers who decide about land-use in pre-defined areas, as well as planners and policy makers who set the legal framework for land management are typical spatial agents. Berger et al. (2006) illustrate the strength of empirical multi-agent models with simulation results from Uganda and Chile and indicate how they may assist policymakers in prioritizing and targeting alternative policy interventions especially in less-favored areas.

The modelling techniques described above are frequently used in LULCC research. It should, however, be noted that there are other regression techniques and approaches for exploratory data analysis available. **Ordered logit**, **Tobit analysis**, **simultaneous regressions**, **factor analysis**, **principal component analysis**, **canonical correlation analysis** and **cluster analysis** are other modelling approaches that have successfully been used for LULCC research. For details of these approaches and applications see Lesschen et al. (2005).

CHAPTER 3

Theoretical framework

In this thesis, natural forest re-growth is the result and indicator of agricultural land abandonment. Thus, understanding the patterns and causes of natural forest re-growth requires understanding agricultural land abandonment. Understanding agricultural land abandonment requires understanding of the factors influencing land-use decisions (Irwin & Geoghegan, 2001). Therefore, an economic framework was developed. Economic theory is based on the assumption that individuals act systematically and therefore predictably. They compare advantages (benefits) and disadvantages (costs) of possible actions considering the information available to them. The following is a description of the land rent theories by David Ricardo (Ricardo, 2002) and Johann Heinrich von Thünen (von Thünen, 1990). The combination of both theories provides a consistent theoretical framework to explain the pattern of natural forest re-growth in the Swiss mountains.

3.1 Ricardo's land rent theory

David Ricardo (1772-1823), an English economist, developed a theory to explain how land rent and profit are determined. He assumes that the farmer pays the landowner rent and the workers their wages; the rest belongs to the farmer as profit. Rent is defined as the compensation which is paid to the owner of the land for the use of its original and indestructible powers (Ricardo, 2002). In his theory, Ricardo assumes that land generates rent only when it becomes scarce; if land is not scarce, then it generates no rent. He supposes that there are three qualities of land (high quality, medium quality and low quality). The lowest quality land called into cultivation generates some profit (total revenue minus wages). This profit becomes the prevailing profit through competition among farmers. Any difference between the profit generated by higher quality land and the profit generated by the lowest quality land accrues to the landowner as rent. Figure 3.1 illustrates how land rent is determined[1].

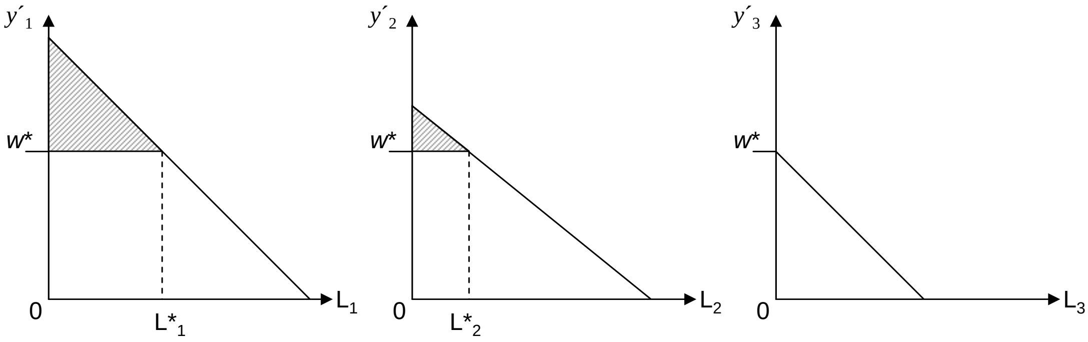


Figure 3.1 The land rent theory by David Ricardo. Figure modified after Söllner (2001).

The far left graphic in Figure 3.1 illustrates high quality land. The far right graphic illustrates low quality land. The graphic in the middle illustrates medium quality land. The y-axis shows the marginal revenue of labour. The x-axis shows the intensity of labour. The function y_1' illustrates the relationships between marginal revenue and intensity of labour L_1 (L_2, L_3) per area unit. Areas under the curves represent the yield of an agricultural product (e.g. wheat). Subsistence wage w^* is assumed to be independent of the quality of land. Provided that there is competition for land, the marginal revenue of labour will be equal to w^*. High and medium quality land is cultivated with intensities L_1^* and L_2^*. On low quality land, the intensity of labour is marginal because this land is less profitable. Due to the competition for land, landowners obtain a rent from the high and medium quality land. Rent is illustrated by the hatched area under the curves in Figure 3.1. The owners of the low quality land obtain no rent. According to Ricardo, land rent is the residuum of the wheat price and wages, but does not affect the wheat price itself (Söllner, 2001).

3.2 Von Thünen's land rent theory

The German economist and farmer Johann Heinrich von Thünen (1783-1850) emphasized the importance of transport costs for the development and the spatial arrangement of land-use structures around market locations. In his book *The Isolated State* (von Thünen, 1990), he introduced the notion of space to the analysis of the spatial patterns of land-use. Von Thünen's land rent theory

[1]Profit is not illustrated in this figure. It is equal for high, medium and low quality land.

is based on the following assumptions (Briassoulis, 2000):

1. The market is located centrally within an Isolated State, which is self-sufficient and exists without any external influences.
2. The Isolated State is surrounded by an unoccupied wilderness.
3. The land of the Isolated State is a uniform flat plain, equally traversable in every direction.
4. The soil quality and climate do not vary throughout the Isolated State.
5. Farmers in the Isolated State transport their own goods directly to the market across the land, therefore, abstracting from roads and rivers.
6. Farmers are profit maximisers.

Von Thünen assumes the landscape as a flat, uniform plain, where movements in all directions are equally comfortable, and absolute distances (e.g. kilometers) equal relative distances (e.g. travel time). Transport costs are a linear function of distance. Von Thünen abstracts from any variations in the productive potential of the land, thereby assuming that every hectare would produce the same output with the same amount of input. The market place in the center of the Isolated State has an absolute monopoly and receives its goods from surrounding farmers. Farmers are price takers of the stable market price. Von Thünen abstracts from outside influence and regards production as a reaction to economic conditions.

In von Thünen's *Isolated State*, farmers have perfect information and perfectly use this information to maximize profits. Land is devoted to the use in which it yields the highest rent. This leads to a certain spatial pattern of land-use. The basic idea of von Thünen's theory is illustrated in Figure 3.2. In a featureless plain, surrounding a central market, it is supposed that two crops are grown - wheat and vegetables. The land has identical production conditions, although the transport costs to the central market differ per crop. The price of vegetables in the central market (a) is higher than the price of wheat (b), although the transport of vegetables is more expensive. With increasing distance from the market, the farm vegetable price decreases more quickly than the farm wheat price. Beyond point (c), the farm price of wheat is higher compared to the price of vegetables. The result of farmers' land-use decisions is a series of concentric rings of land-use around the central market. In the shaded area in Figure 3.2, vegetables are grown; in the outer ring wheat. Beyond (d), neither crop is profitable and land is left in its natural state which may be, for example, primary forest.

In summary, Ricardo explains the existence of different land rents with differences in land quality that arise from a heterogeneous landscape. Land of better quality or higher soil fertility generates

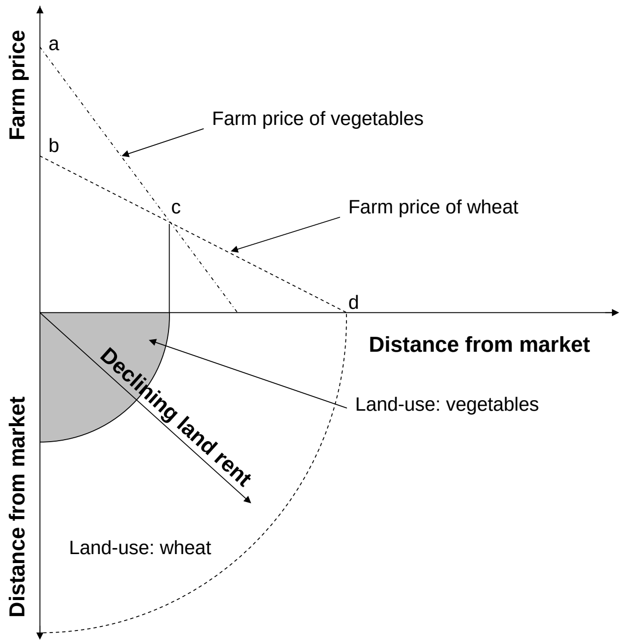


Figure 3.2
The von Thünen theory of farm price, land-use and land rent. Figure modified after Lesschen et al. (2005).

higher rents. Von Thünen found an explanation for the emergence of land use patterns and differing land prices in space as a function of distance from urban centers. These two theories are the basis for many empirical economic studies on land-use/land-cover change (see Chomitz & Gray, 1996; Serneels & Lambin, 2001; Briassoulis, 2000; Geoghegan et al., 2001; Munroe & York, 2003; Lesschen et al., 2005). Combining the two theories by integrating the inherent quality of the land (Ricardo) with distance measures (von Thünen) provides a consistent theory to explain the spatial pattern of land-use. Changes in land-use (as investigated in this thesis) are brought about by changing profitability of a particular use, which can be caused by changes in relative prices of agricultural inputs (e.g. fertilizers, motor fuels) and/or outputs (milk, cereals), changing policies (subsidies, regulations), or infrastructure developments (see e.g. Munroe & York, 2003).

CHAPTER 4

Materials and methods

4.1 Study areas

The areas under investigation in this thesis are the Swiss mountain area (Jura Mountains and Alps) and four case study municipalities (Tujetsch, Eggiwil, Soazza, Blitzingen), which are located within the Swiss mountain area. The mountain area was delineated by the "Act on Investment Aid for Mountain Regions" (= IHG, Wachter, 2002). For this thesis, the municipality of Davos and eleven municipalities of Oberengadin (eastern Central Alps) were included into the analysis, although they are not listed as IHG-regions. Figure 4.1 shows the study areas.

The Swiss mountain area as delineated in this thesis covers 68% of the total area of Switzerland (28 130 km^2) and is inhabited by 24% of the Swiss population (base 2000). The climate type ranges from oceanic in the northern parts to Mediterranean in the southern parts. Main tree species are Norway spruce (*Picea abies*), beech (*Fagus sylvatica*), fir (*Abies alba*), Scots pine (*Pinus sylvestris*), larch (*Larix decidua*), maple (*Acer pseudoplatanus*) and birch (*Betula pendula*) (Brassel & Brändli, 1999). In areas approaching the treeline, green alder (*Alnus viridis*) is widespread. Approximately 33% of the mountain area is used for agriculture, at altitudes between 200 m and 2800 m. Agriculture consists mostly of cultivation of hay meadows and alpine pastures (SFSO, 2005). Alpine pastures, which are grazed during summer with local livestock (i.e. cattle, sheep and goats from the municipalities to which the alpine pastures belong) and non-local livestock (from outside these municipalities), are mostly located near and above the climatological treeline, which increases along a continentality gradient to reach an altitude of approximately 2300 m in the southern parts of the Swiss mountain area (Körner, 1998). Figure 4.2 shows the land-use/land-cover of the Swiss mountain area.

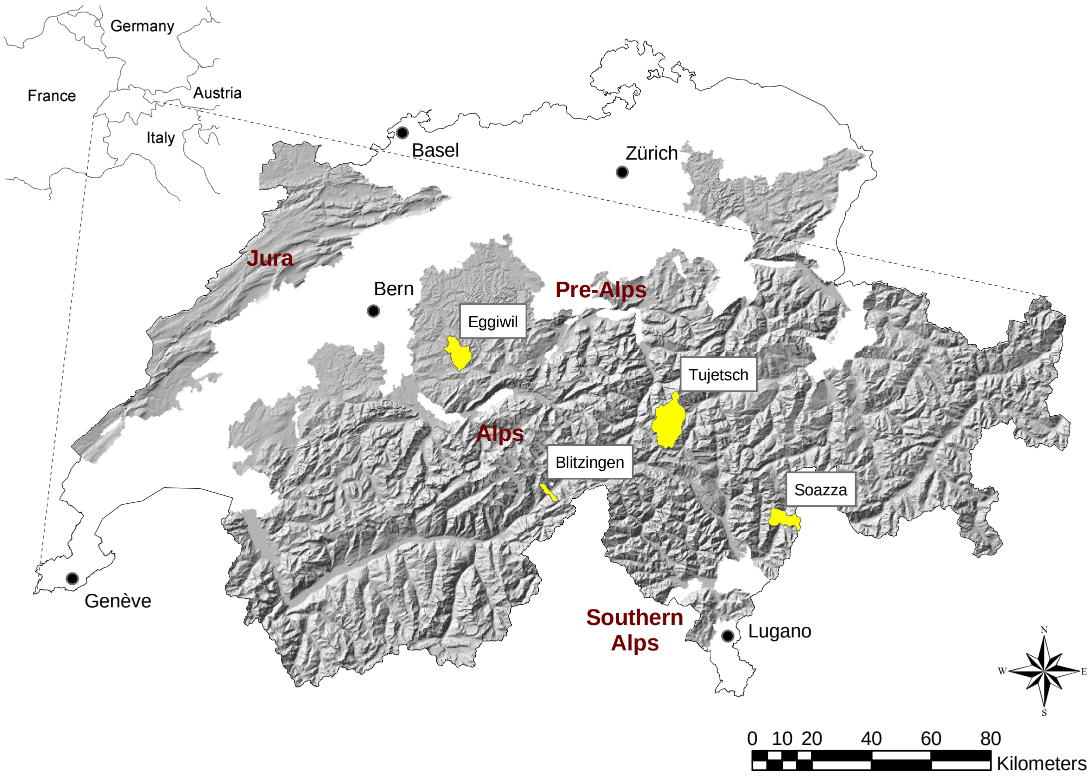


Figure 4.1
The hillshade represents the Swiss mountain area as delineated by the "Act on Investment Aid for Mountain Regions" (= IHG, Wachter, 2002), and additionally includes the municipality of Davos and eleven municipalities of Oberengadin. The municipalities of Tujetsch, Eggiwil, Soazza and Blitzingen are the case study municipalities investigated in this thesis. Data source: Swiss Federal Statistical Office, Swiss Federal Office of Topography. Figure: author.

The economic structure differs widely within the Swiss mountain area, although generally follows a north-south gradient: in the southern parts, tourism is very important; in the canton of Jura and in the northern parts, tourism is less important, although the accessibility of urban centers is often better (Figure 4.3)[1].

The agricultural structure in the Swiss mountain area mostly takes the form of small family farms: 37% of the total number of farms are smaller than 10 ha. The farms in the canton of Jura and

[1]The economic structure within the Swiss mountain area in the 1980s is of interest, because this is the evaluation year of the Swiss land-use statistics evaluated in the years 1979/85 (called ASCH85). The ASCH85 and the Swiss land-use statistics evaluated in the years 1992/97 (called ASCH97) provided the basis to investigate the mountain area wide patterns of natural forest re-growth in this thesis.

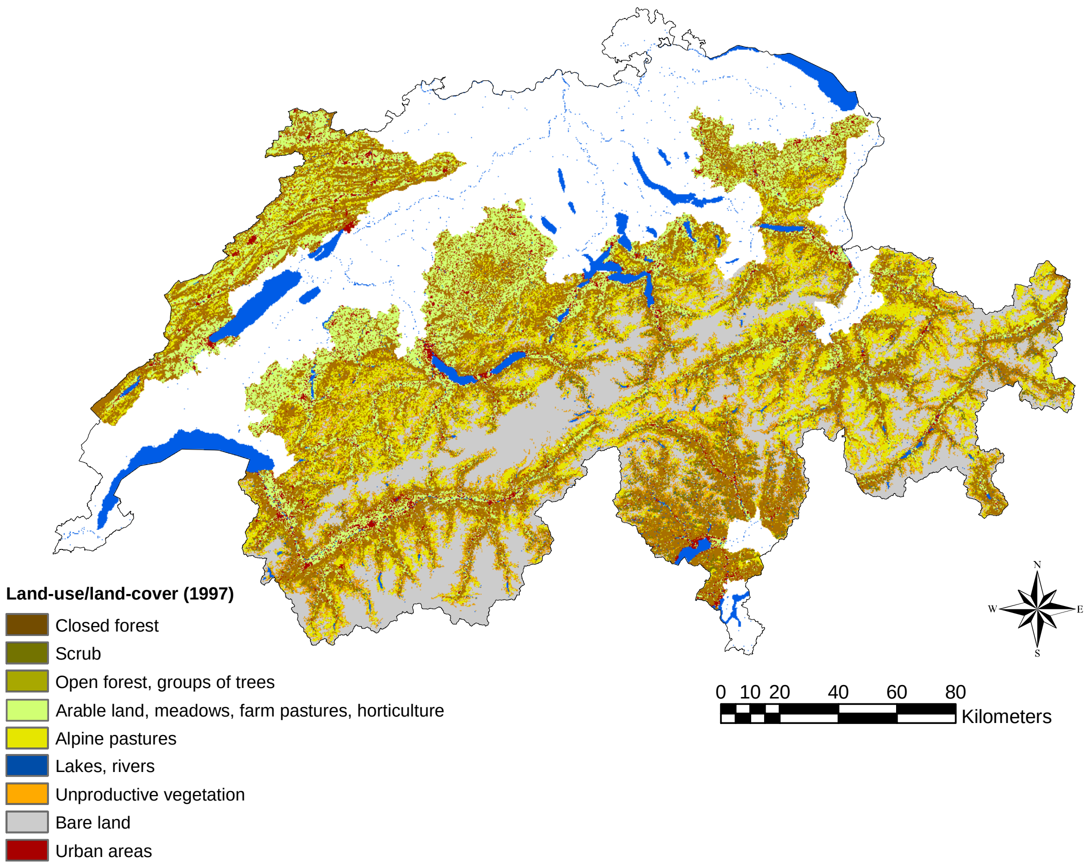


Figure 4.2
Land-use/land-cover within the Swiss mountain area. Data source: Swiss land-use statistics 1992/97. Figure: author.

northern parts of the Swiss mountain area are generally larger and dairy farming is common there. Between 1965 and 1990, the number of farms decreased from 83 600 to 56 220 (-33%). Simultaneously, the average farm size increased with the proportion of farms larger than 20 ha rising from 6% in 1965 to 18% in 1990 (source: agricultural censuses). In the southern parts, there is a higher proportion of part-time farms than in the canton of Jura and in the northern parts (Figure 4.4) and less intense cultivation forms, such as sheep pasturing, are common.

The case study municipalities (Figure 4.1) were selected in order to investigate the local patterns of natural forest re-growth, individuals' motives to abandon or maintain the cultivation of marginal land and allow forest re-growth to occur, and examine the causes of forest re-growth. The selection criterion was the presence of natural forest re-growth as indicated by the recent Swiss land-use statistics (SFSO, 2001) and, to represent part of the spectrum of the agro-climatic, topographic and

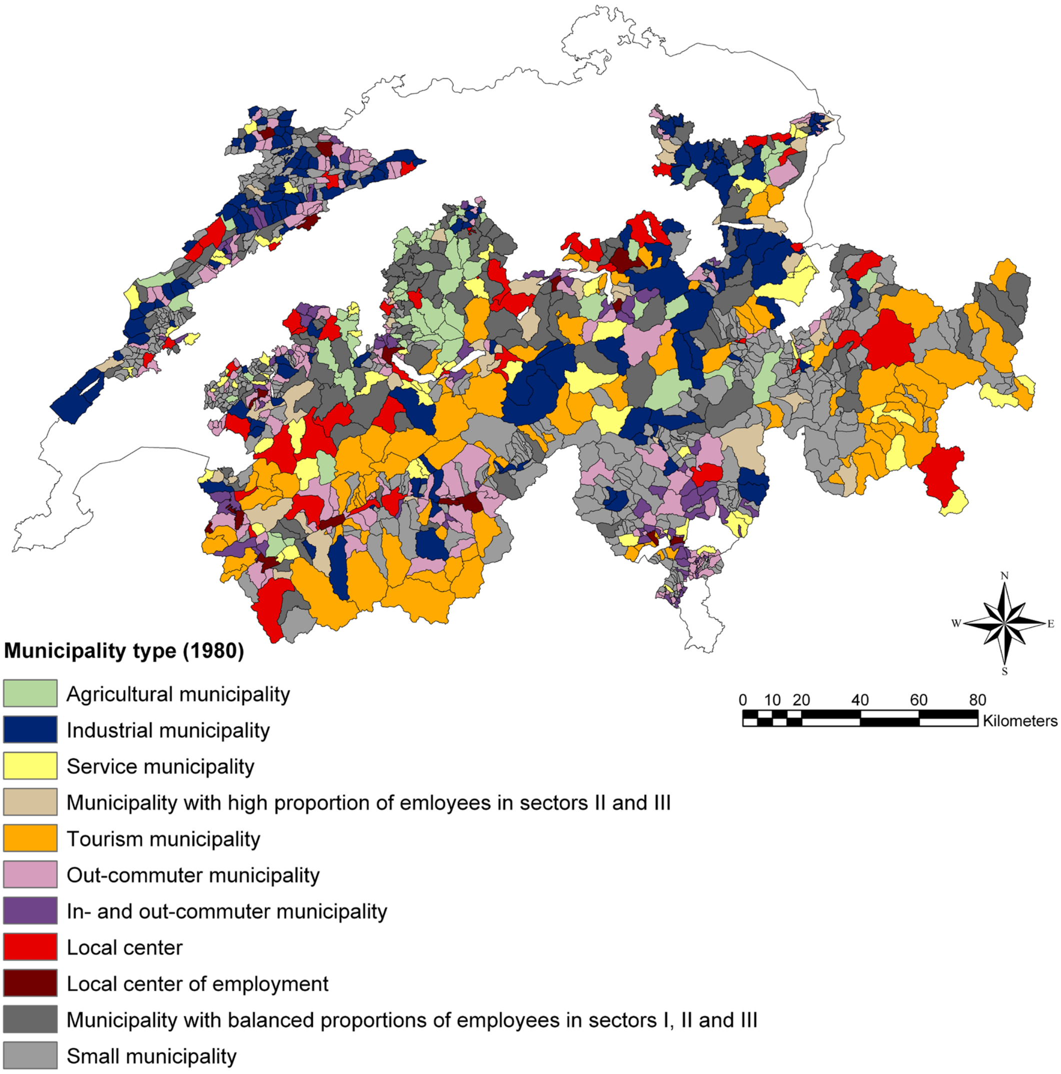


Figure 4.3
Classification of mountain municipalities after Bätzing et al. (1995). Data source: Dr. Manfred Perlik (WSL). Figure: author.

socio-economic conditions in the Swiss Alps, the location of municipalities at different altitudes and in different parts of the Swiss Alps. A detailed descriptions of the geo-physical and socio-economic conditions of each municipality is provided in Paper D, Table 1.

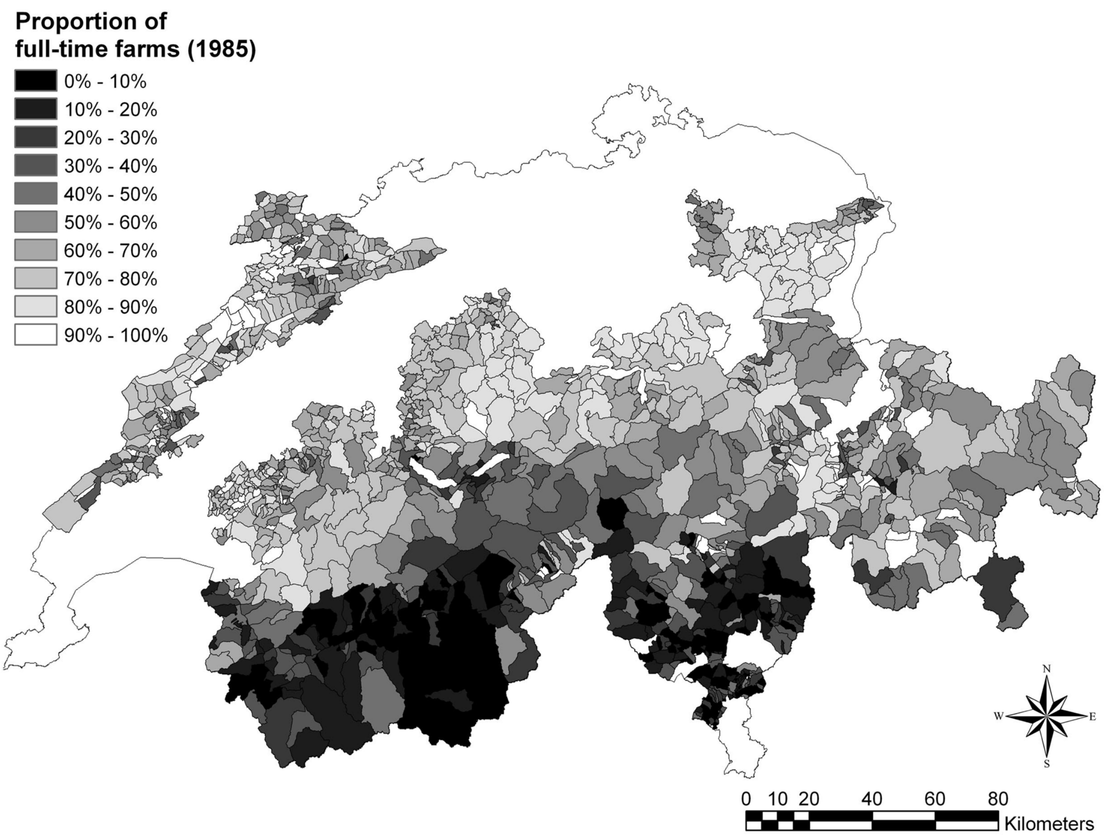


Figure 4.4
Proportion of full-time farms per municipality 1985. Data source: Swiss Federal Statistical Office. Figure: author.

4.2 Data

4.2.1 Land-use/land-use change data

For the mountain area wide studies, land-use/land-use change was derived from two surveys of the Swiss land-use statistics taken between 1979/85 and 1992/97 (SFSO, 2001). In both surveys (henceforth referred to as ASCH85 and ASCH97), 74 land-use categories were identified by overlaying aerial photographs with a regular 100 m grid. A single land-use category was manually assigned to each grid point by evaluating a so called *reference area* (size 50 m $\times$ 50 m) centered on the grid point (Figure 4.5). The map shown in Figure 4.2 is based on the Swiss land-use statistics conducted in the 1990s. Changes in land-use between both inventories were analysed through comparison of the land-use category assigned to a grid point in ASCH85 with that in ASCH97. Areas above the treeline, wetlands and refuges were excluded from the analyses. The ASCH85 and ASCH97 were used to derive the percentage change of agricultural areas (as indicated by forest re-growth) within the 55 Swiss mountain regions and the presence/absence of natural forest re-growth on agricultural land. These variables were used as the response variables in the regression models (see Papers A, B and C).

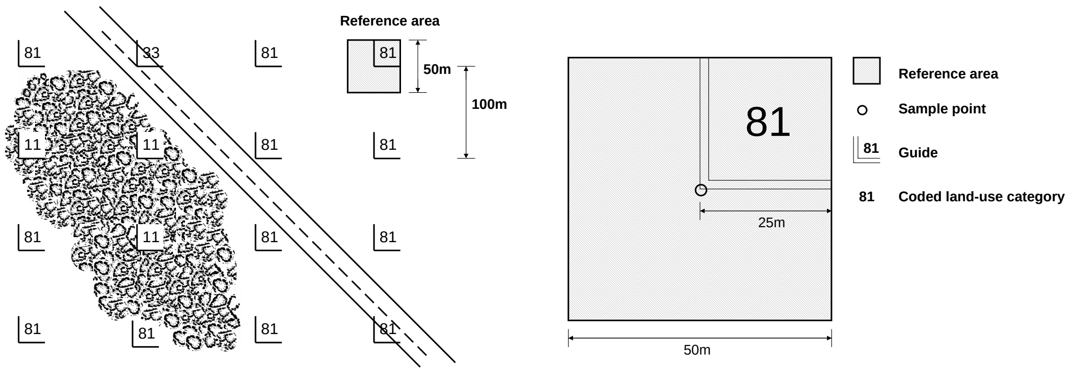


Figure 4.5
Left: the Swiss land-use statistics uses a regularly spaced grid (distance between grid-points 100 m) to evaluate land-use/land-use changes. Right: reference area (size 50 m × 50 m) to evaluate the degree of coverage of trees, shrubs and scrub vegetation at each grid-point. Figures modified after BFS (1992).

For the case studies, land-use/land-use change was derived from aerial photographs taken from two points in time (1953/1962 and 1998/2000). Aerial photographs were originally available in non-digitised form. To allow for overlay and comparison, all aerial photographs were scanned and ortho-rectified. All orthophotos belonging to the same municipality were mosaicked. The resulting ortho-images were overlaid with a regularly spaced raster (cell size 25 m × 25 m). The latter is illustrated in Figure 4.6. Within each raster cell, the degree of coverage of agricultural land-use and trees and shrubs was determined. This was done by means of visual interpretation. Visual interpretation was preferred over automated classification. This is because, due to the limited spectral information of the images, automated classification (using ERDAS IMAGINE 8.6) resulted in high classification errors. A raster cell was classified as *agriculture* if it showed >=50% agricultural land-use. Likewise a raster cell was classified as *forest* if it had a coverage of >50% trees and bushes. The definitions of agriculture and forest used in this study are subjective, although the Swiss land-use statistics use similar thresholds to delineate agricultural land and forest (see BFS, 1992). Areas above the treeline, planned afforestations and land that could not clearly be classified as *agriculture* and *forest* were excluded from the analyses. The latter also included shaded areas. Changes in land-use between both points in time were analysed by comparing land-use classifications made for the manually classified raster cells. Comparisons were used to derive the

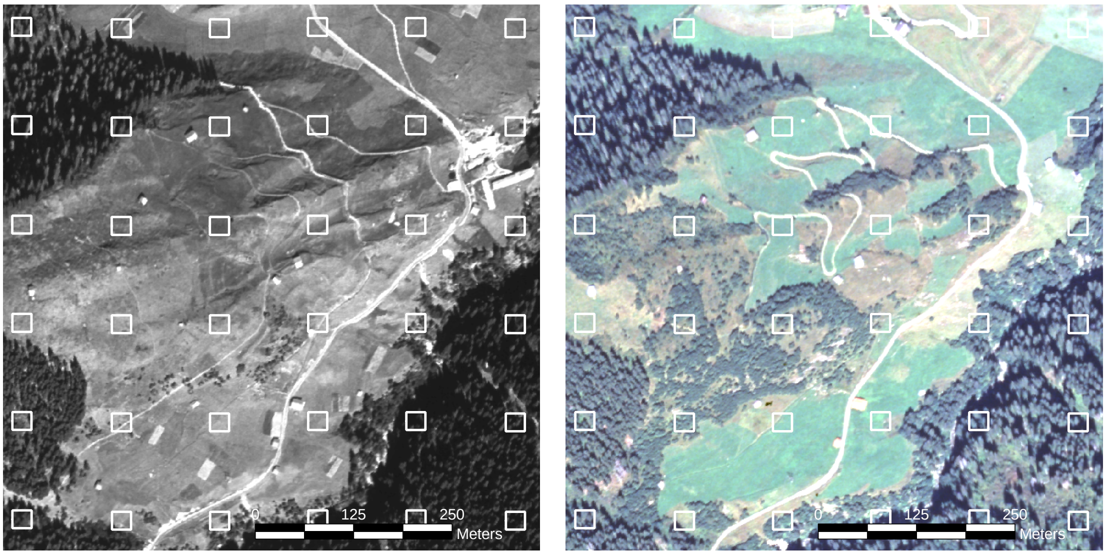


Figure 4.6
To evaluate natural forest re-growth in the case study municipalities, historical (black & white, BW) and contemporary (true color, RGB) ortho-photographs were overlaid with regularly spaced raster cells (cell size 25 m × 25 m). Land-use/land-use change was evaluated within raster cells. The ortho-photograph subsets show an area of the municipality Tujetsch in the year 1959 (left) and 2000 (right). Source: Swiss Federal Office of Topography.

presence/absence of forest re-growth on agricultural land, which was used as the response variable in the classification trees (see Paper D).

4.2.2 Geo-physical and socio-economic data

In this thesis, natural forest re-growth was explained as a function of geo-physical and socio-economic explanatory variables. Explanatory variables are proxies for the cultivation costs and benefits of agricultural land. In the mountain area wide studies (see Papers A, B and C), only variables that vary within the Swiss mountain area were considered in the statistical analyses (e.g. climate, topography, infrastructure related variables, socio-economic characteristics at the municipality level), and data that are equal within the Swiss mountain area (e.g. prices for agricultural products) were excluded. In the case studies (see Paper D), only variables that vary within municipalities (e.g. steepness of slopes, radiation, soil depth) were considered in the statistical analyses, and not variables that are equal within municipalities (e.g. rate of change of farms, population change).

Explanatory variables were calculated based on Swiss climate station data (Normals from the period between 1961 and 1990), a 1:200 000 digital soil suitability map ("Bodeneignungskarte der

Schweiz"), a digital elevation model with 25 m raster cell size (DEM25), a digital road network, a digital map of Swiss construction zones, Swiss land-use statistics data taken between 1979/85 and 1992/97, a digital map of Swiss construction zones and population and agricultural censuses from different years. The climate data layers (i.e. degree days, precipitation, potential direct short-wave radiation, potential evapotranspiration) and soil data layers (i.e. soil depth, soil stoniness) were provided by Dr. Niklaus Zimmermann (WSL). Detailed descriptions of climate variables may be found in Zimmermann & Kienast (1999). Soil data layers were calculated by reclassifying the 1:200,000 soil suitability map. Reclassification was used in order to improve the explanatory power of soil data in the spatial statistical models. For reclassification, the *soilprop.aml* - an Arc Macro Language (AML) routine by Zimmermann (1999) was used. This AML uses the pixel-wise varying topographic exposure (derived from a digital elevation model) and the minimum and maximum values of soil depth and soil stoniness per soil class (derived from the soil suitability map) to generate maps that contain values of soil depth and soil stoniness between minimum and maximum. The pixel-wise varying topographic exposure was calculated as (Kienast & Zimmermann, 2001):

$$TopExp = x_{\frac{m}{2},\frac{n}{2}} - \sum_{i=1}^{m}\sum_{j=1}^{n}\frac{x_{i,j}}{m*n}, \tag{4.1}$$

where x is the elevation of a grid cell centered in a *moving window* defined by $m*n$ grid cells. The moving window is used to relate x to the elevation of neighbouring grid cells in that window ($x_{i,j}$) and calculate a measure of the topographic exposure for the centered grid cell. The topographic exposure has positive values for convex shaped elements of the landscape (e.g. ridges) and negative values for concave shaped elements of the landscape (e.g. gullies). The continues values of the topographic exposure were reclassified into four classes: (i) bottom, (ii) toe slope, (iii) slope and (iv) ridge. The *soilprop.aml* assigns values of soil depth and soil stoniness to each of the four topographic classes taking into account the minimum and maximum values of soil depth and soil stoniness per soil class defined in the soil suitability map. As the result of soil data reclassification, the most acute ridges were assigned the minimum values for soil depth and maximum values of soil stoniness, while the most distinct gullies and toe slopes were assigned the maximum values for soil depth and minimum values of soil stoniness. The reclassification scheme is based on an expert system classification by R.F. Fischer (unpublished, see Roberts et al., 1993 for further explanation). The digital elevation model, road network, map of Swiss construction zones and census data were provided by the Swiss Federal Statistical Office (SFSO) and the Swiss Federal Office of Topography (SwissTopo). The digital elevation model was used to calculate the steepness of slopes. The distance related variables (i.e. distance to roads, distance to construction zones and distance to settlements) were calculated as Euclidian distance[2].

Population and agricultural censuses were originally provided in digitised form (as MS Excel-sheets), and non-digitised form (copies of historical agricultural census books). In order to obtain suitable data sets for spatial modelling, all data were brought into a digital form. To make census data spatially explicit, they where linked into a municipality coverage (see section 4.2.3). For detailed descriptions of the socio-economic and geo-physical explanatory variables used in the single studies, including their expected influence on forest re-growth see Papers A, B, C and D.

4.2.3 Data processing

All spatial data were processed by means of a Geographic Information System (GIS). Census data were originally not available in spatially explicit form. To make census data spatially explicit, they were linked to a digital municipality coverage (available for the year 1996). The Swiss mountain area as delineated in this thesis (see section 4.1) contains 1238 municipalities. Census data and the digital municipality coverage were not entirely compatible. The reason is that many municipalities have merged or were divided over the last decades. To make the census data and municipality coverage compatible, changes in municipality boundaries were considered, and the respective statistics adapted. In case adaptation was not possible (e.g. if municipalities were split), the respective municipalities were excluded from the analysis. Information about changing municipality boundaries was taken from the publication ”Bevölkerungsentwicklung der Gemeinden 1850-2000”[3] (BFS, 2002).

Land-use/land-use change data were available as grid points (Swiss land-use statistics data) and raster cells (own classification of aerial photographs). In order to obtain suitable data sets for spatial modelling, information from the thematic maps (e.g. soil depth, steepness, distance to roads, proportion of full-time farms, population change, etc.) at the locations where land-use/land-use changes have occurred was extracted. To visualise data extraction, imagine that all thematic maps were stacked (see example in Figure 4.7). A pin pierces the stack of the thematic maps at each grid point/raster cell representing a land-use/land-use change location (e.g. presence/absence of forest re-growth), and the mapped information for the point/raster cell - soil depth, steepness, distance to roads, proportion of full-time farms, population change, etc. - was recorded and stored in a data table. The data table was then imported into a statistics programm and used for statistical analyses. For data extraction, the *Gridspot.aml* - an Arc-Macro-Language (AML) routine provided by the

[2]The Euclidian distance can be considered to be the shortest distance between two points, and is basically the same as Pythagoras' equation when considered in two dimensions

[3]engl.: Population changes in municipalities 1850-2000

Environmental Systems Research Institute, Inc. (ESRI) was used.

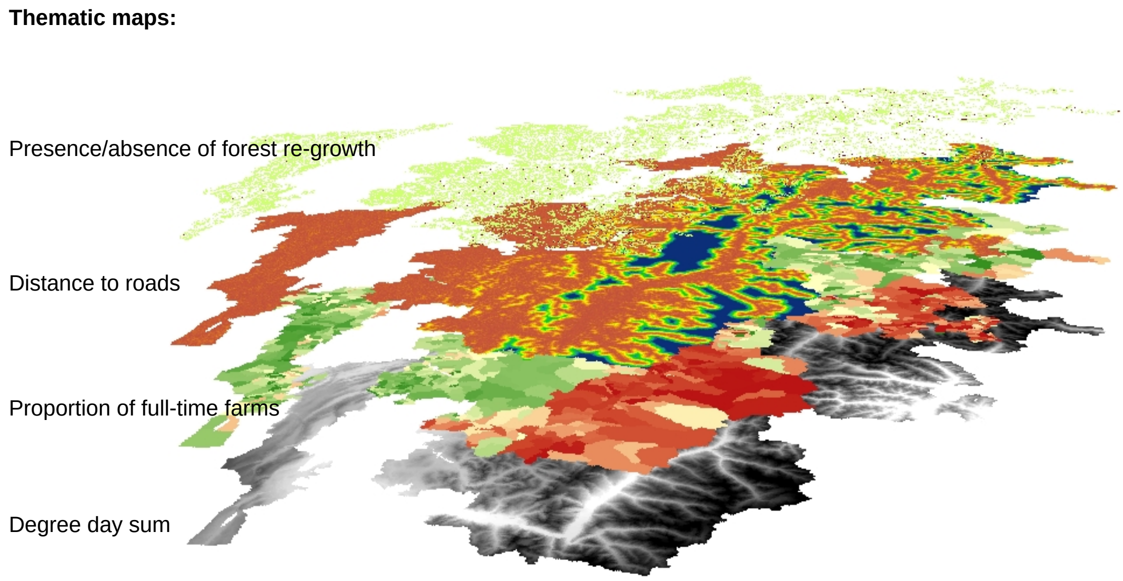


Figure 4.7
In order to obtain adequate data sets for spatial modelling, information from different thematic maps was extracted. This figure includes some of the thematic maps which were used in the mountain area wide studies (see Papers A, B and C). Figure: author

4.2.4 Interviews

Case studies were conducted in the municipalities of Tujetsch, Eggiwil, Soazza and Blitzingen (see Figure 4.1). In these studies, classification trees (see section 4.4.1) were used as the basis to conduct interviews. Visual comparisons of the actual presence/absence of forest re-growth with the corresponding model predictions provided the basis for the selection of land parcels in the field (referred to as 'interview sites'). This approach, i.e. to systematically derive the research design of field work on the basis of statistical models, followed the "finding answers in the errors" approach proposed by Wood & Skole (1998). After interview site selection, the x- and y-coordinates of the interview sites were given to the responsible surveying and mapping office in order to obtain the address of each landowner. Landowners were first contacted per mail then phoned to arrange a meeting. Interviews were conducted over a period of 11 months between August '04 and July '05. Each interview lasted approximately two hours. Semi-structured interviews were used, which is an approach where the interviewer aims to cover a range of pre-set topics and, within the frame of these topics, the respondent is free in answering questions (Berg, 2001). Pre-set topics related to the personal information of respondents, characteristics of interview sites and farms, individuals' motives to abandon and maintain the cultivation and the underlying causes of forest re-growth. A total of 48 interview sites were selected in the field and 31 landowners interviewed (18 full-time farmers, 1 part-time farmer, 2 hobby farmers, 2 retired farmers and 8 non-farmers). All interviews were first recorded on audiotape and later transcribed. Recorded interviews were used to systematically summarise interview results (see Paper D, Table 5 and text).

4.3 Statistical issues

In this thesis, spatial statistical models where used to answer the study questions and prove the hypotheses. In order to obtain reliable model results, i.e. those that allow correct inferences about the influence of single explanatory variables on natural forest re-growth to be made, several statistical issues had to be considered. These are: (i) the influence of the spatial scale on model results, (ii) endogeneity, (iii) multicollinearity, (iv) heteroskedasticity, and (v) spatial autocorrelation. The following sections explain these issues and describe how they were considered in the research studies of this thesis.

4.3.1 Scale

Scale is the spatial, temporal, quantitative, or analytic dimension used by scientists to measure and study objects and processes (Gibson et al., 2000). All scales have extent and resolution. Extent refers to the size of a dimension or the duration of time under consideration. Resolution refers to the precision used in measurement. The grain of an observation determines the smallest entities that can be seen in a study. In contrast, the extent determines the largest entities that can be detected in the data (Lesschen et al., 2005).

It is well known that the results of spatial statistical analyses are scale dependent (Lambin, 1997). The *modifiable areal unit problem* (MAUP) is often mentioned in this context (Green & Flowerdew, 1996). It states that the results from statistical analyses based on the same data set change if the spatial scale and/or zoning (e.g. region boundaries) change. From the modifiable areal unit problem follows that the results from spatial statistical models and/or significance tests can only be interpreted in the context of the spatial scale of the analysis. Models and/or significance tests at different spatial scales are necessary to prove findings across different scales. In this thesis, investigations on different spatial and temporal scales were conducted in order to check for scale dependencies of findings.

Another problem that is related to the scale of the analysis is the *ecological fallacy* (Haining, 2003). The ecological fallacy is an error in the interpretation of statistical data, whereby inferences about the nature of individuals are based solely upon aggregate statistics collected for the group to which those individuals belong. The ecological fallacy assumes that all members of a group exhibit characteristics of the group at large. For this thesis this means that no inferences about processes at lower level units can be made from aggregate data. For example, if data on population change are only available at municipality-level, no inference can be made about the processes within municipalities that caused population change. On the other hand, factors at aggregate levels often have an influence on the land-use decisions at lower level units. Geoghegan et al. (2001), for example, hypothesised an influence of factors at the *ejido* level (an agricultural cooperative in the southern Yucatán peninsular region), such as population and cattle density, on the decision of individuals to deforest land. Müller & Zeller (2002) predicted an influence of village-level factors (e.g. ethnic composition, age of village) on land-use changes within municipalities in the Highlands of Vietnam. Predicting and discussing an influence of higher level factors on land-use decisions at lower level units should not be confused with the ecological fallacy.

4.3.2 Endogeneity

In econometrics, variables are referred to as *exogenous* if they are fixed at current time and determined from outside the model (Maddala, 2001). Likewise, variables are referred to as *endogenous* if they are not fixed at current time and determined from inside the model. In statistical terms endogeneity arises, if an explanatory variable x is correlated with the error term u. If x and u are uncorrelated then x is said to be *exogenous*. Endogeneity issues are widespread in land-use/land-cover change research. Possible causes are omitted variables, measurement errors or simultaneity, which can also occur simultaneously (Wooldridge, 2001). The distinction of endogenous and exogenous variables is a controversial issue in many empirical studies (Greene, 1997). For example, Chomitz & Gray (1996) argue that the distance to roads may, at least partially, be endogenous in regard to deforestation. This is because the routing of roads may be influenced by agricultural development considerations (Chomitz & Gray, 1996):

> ”*If roads are preferentially routed through agriculturally suitable areas and if some aspects of suitability are not observed, then the model may overestimate the effect of distance from the road. A plot of land may be undeveloped not because it is far from the road - it may be far from the road because it is not suitable for development.*”

To avoid biased estimates from road endogeneity, Chomitz & Gray (1996) include instrumental variables in their model, i.e. those that are correlated with distance measures but not correlated with the fertility of soils. These variables were calculated based on the characteristics of the underlying terrain. Pfaff (1999) points out that population may be endogenous to forest conversion, due to unobserved government policies that encourage development of targeted areas. Including population as an exogenous 'driver' of land use change would produce a biased estimate and lead to misleading policy conclusions. To avoid endogeneity bias, he uses a temporally lagged value of population in the regression analysis. In this thesis, it was assumed that structural characteristics in agriculture may, at least partially, be endogenous in regard to land abandonment and forest re-growth (see Paper C). For example, natural forest re-growth can be the result and, at the same time, the cause of farm abandonment. This simultaneity can cause endogeneity (see Pfaff, 1999; Irwin & Geoghegan, 2001). In addition, farm abandonment, land abandonment and forest re-growth are often caused by the same factors such as changing relative prices and policies (Baldock et al., 1996; Selby et al., 1996; Strijker, 2005). Thus, when farm abandonment is used to explain land abandonment and forest re-growth and some of the factors that cause farm abandonment are not included into the model, then the model may overestimate the effect of farm abandonment.

One way to deal with endogeneity is the use of instrumental variables as applied by Chomitz & Gray (1996). Another way is to use structural models (for details of this approach see Irwin & Geoghegan, 2001 and Maddala, 2001). Endogeneity problems can also be avoided by using serial lagged explanatory variables, i.e. those evaluated in the time before land-use changes have been occurred (Pfaff, 1999; Müller & Zeller, 2002; Perz & Skole, 2003). These variables can be regarded as exogenous in regard to the observed land-use/land-cover changes, and consistent estimates can be achieved in that way (Greene, 1997). The latter approach was used in the studies presented in Papers A, B and C. In the study presented in Paper D, only time invariant geo-physical variables were used in order to avoid incorrect inferences from potentially endogenous distance related variables (i.e. distance to roads and farmhouses). It should be noted that the use of serial lagged explanatory variables might not totally eliminate the endogeneity bias in models. This is because unknown time-lags exist between the socio-economic causes of land abandonment, effective land abandonment and forest re-growth. For example, in the mountain area wide studies (see Papers A, B and C), it was not clear which period was authoritative for the abandonment of land leading to forest re-growth between the 1980s and 1990s.

4.3.3 Multicollinearity

Dependency between the explanatory variables in a regression model is referred to as multicollinearity (Maddala, 2001; Menard, 2002). Multicollinearity is common in regression models and many of the explanatory variables that are frequently used in land-use/land-cover change research, such as the distance to roads and markets, tend to be highly correlated (Lesschen et al., 2005). This correlation makes it difficult to distinguish separate effects of the explanatory variables in explaining the response variable (Maddala, 2001). With increasing collinearity between the explanatory variables, linear and logistic regression coefficients will be unbiased and as efficient as they can be (given the relationship between the explanatory variables), but the standard errors for linear or logistic regression coefficients will tend to be large (Lesschen et al., 2005).

In this thesis, suggestions by Menard (2002), were followed and models for multicollinearity checked. Therefore, each of the explanatory variable was treated in turn as the response variable in a model with all the other explanatory variables as explanatory variables. According to Menard (2002), the coefficient of determination of these models (R^2) should not exceed a critical value of 0.8. In case the R^2 was higher than the critical value, suggestions by Maddala (2001) were followed and some redundant explanatory variables from the models removed (see Papers A and C).

4.3.4 Heteroskedasticity

In linear regression models such as ordinary least square (OLS) regression or maximum-likelihood based spatial lag (MLLAG) and spatial error (MLERR) models, it is assumed that the error terms have constant variance (Maddala, 2001). If the errors vary or increase with each observation, they do not have constant variance, which is also referred to as heteroskedasticity. The complement of heteroskedasticity is referred to as homoskedasticity. In case the error terms are heteroskedastic, the standard errors of the regression model may be either understated or overstated. As a consequence, the test statistic is no longer valid. In the spatial lag and spatial error models used in this thesis (see section 4.4.3 and Paper A), errors were checked for heteroskedasticity. The spatial Breusch-Pagan test was used to do so. For details of this test statistic see Bivand (2004). In logistic regression models (see section 4.4.2), there is no homoskedasticity assumption (Baltes-Götz, 2005). Thus, there was no need to check the logistic regression models developed in this thesis (see Papers B and C) for heteroskedastic errors. Classification tree analysis, as used in this thesis (see Paper D), is a non-parametric modelling approach, i.e., there are no error terms associated with these models.

4.3.5 Spatial autocorrelation

Spatially explicit data often show a systematic spatial pattern, a phenomenon which is known as spatial dependence or spatial autocorrelation (Anselin, 2002). Spatial autocorrelation may be classified as either positive or negative. Positive spatial autocorrelation has all similar values appearing together, while negative spatial autocorrelation has dissimilar values appearing in close association. Figure 4.8 shows these two types of spatial autocorrelation. Figure (a) is an example of a spatial arrangement that shows positive spatial autocorrelation, while figure (c) shows negative spatial autocorrelation; figure (b) illustrates a spatial arrangement without spatial autocorrelation, i.e., the pattern is random. The black and white squares in Figure 4.8 can be thought of as high and low values of a continuous variable such as the steepness of slopes or regression residuals or a binary variable such as the presence/absence of natural forest re-growth. Spatial autocorrelation can occur in both types of variables (Anselin, 1988; Munroe et al., 2002; McDonald & Urban, 2006).

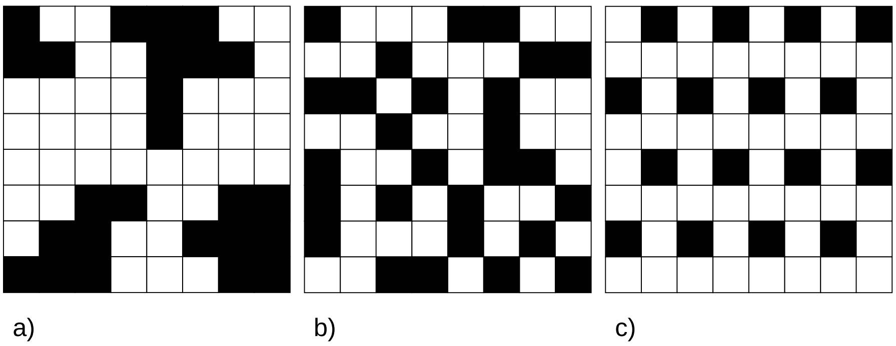


Figure 4.8
Spatial arrangements with (a) positive, (b) no and (c) negative spatial autocorrelation. Figure modified after Lesschen et al. (2005).

Positive spatial autocorrelation may render statistical tests too liberal, making them more likely to reject the null hypothesis when it is true, whereas negative spatial autocorrelation may produce the opposite effect (Legendre & Legendre, 1998). Spatial autocorrelation in regression residuals is an indicator of model misspecification. It can be the result of non-detected non-linear relationships between the response variable and explanatory variables. It can also arise if some important variables are omitted from the model (Anselin, 2002).

In this thesis, Moran's I statistic was used to check for spatial autocorrelation in the data. The value of Moran's I generally varies between +1 and -1, although values lower than -1 or higher than +1 may occasionally be obtained (Florax et al., 2002). Positive autocorrelation translates into positive values of Moran's I, whereas negative autocorrelation produces negative values. No autocorrelation results in a value close to zero. Moran's I statistic can be calculated as (Lesschen et al., 2005):

$$for \qquad h \neq i \qquad I(d) = \frac{\frac{1}{W}\sum_{h=1}^{n}\sum_{i=1}^{n} w_{hi}(y_h - \bar{y})(y_i - \bar{y})}{\frac{1}{n}\sum_{i=1}^{n}(y_i - \bar{y})^2} \tag{4.2}$$

in which y_h and y_i are the values of the observed variable at sites h and i. The values of w_{hi} are the weights which are written in a $n \times n$ weights matrix W. The weights matrix W is the sum of the weights w_{hi} for a given distance class. The spatial weights matrix depicts the relationship between an element and its surrounding elements. Weights can be calculated based on contiguity or on distance. According to Anselin (1992), a row standardized weights matrix is the preferred way to implement the Moran's I test. An example of a spatial layout and a related binary and row standardized weights matrix is provided in Figure 4.12. In this thesis, Moran's I statistic was used to investigate spatial autocorrelation in the data of the regional-scale study (see Paper A).

Spatial lag and spatial error models are maximum likelihood (ML) based linear regression techniques that can deal with spatial autocorrelation in data and regression residuals (Anselin, 2002). For details of these techniques see section 4.4.3. Other frequently used approaches to reduce spatial dependence in the data and model residuals are: (i) sampling (ii) the inclusion of the x- and y-coordinates of the modelling observations as additional explanatory variables, (iii) the inclusion of spatially lagged variables as additional explanatory variables and (iv) the use of robust estimation techniques. All these approaches were used in this thesis in order to obtain reliable model results, i.e. those that lead to correct interpretations of the significance of explanatory variables in explaining the response variable. The following is a description of these approaches.

> *(a) Sampling*: One frequently used method to reduce spatial autocorrelation in the data and regression residuals is sampling. Random sampling is often used for this purpose, but this cannot completely avoid spatial autocorrelation (Wagner & Fortin, 2005). The reason is that random sampling cannot avoid observations that are physical neighbours. To avoid observations that are physical neighbours, regular sampling is the preferred approach. Regular sampling was applied by Müller & Zeller (2002), who sampled every 5th raster cell (cell size 50 m $\times$ 50 m) in the x- and y-direction from Landsat images which then became the modelling observations in their logistic regression model. A similar approach was used by Munroe et al. (2002), who experimented with different sampling distances between raster cells (from 627 m to 1815 m) to investigate the 'behaviour' of statistical models in terms of the goodness-of-model fit and the decrease of spatial autocorrelation in model residuals. In this thesis, regular sampling (see Paper D) and random sampling combined with declustering (see

Papers B and C) were used to reduce spatial autocorrelation in the data and regression residuals.

(b) X- and y-coordinates as explanatory variables: To compensate for spatial autocorrelation in model residuals from unobserved factors that are spatially correlated with the response variable, some authors include the geographic coordinates of the modelling observations as additional explanatory variables in their statistical models. Some researchers include the x- and y-coordinates in their linear form (Müller & Zeller, 2002; Barbosa et al., 2003; Tasser et al., 2006). This approach controls for unobserved factors that are linearly related to the response variable. This approach was also used in this thesis (see Paper B). Other researchers include transformed x- and y-coordinates in their regression models (e.g. Pereira & Itami, 1991). This approach controls for unobserved factors that are non-linearly related to the response variable.

(c) Spatially lagged variables as explanatory variables: Another approach to compensate for spatial autocorrelation from unobserved factors is the use of spatially lagged variables. A spatially lagged variable is a variable which contains weighted averages of variable values measured at neighbouring observation sites (Anselin, 1988). Two types of spatially lagged variables can be distinguished: (i) spatially lagged response variables and (ii) spatially lagged explanatory variables. Examples for spatially lagged explanatory variables used in LULCC models are the average steepness of the surrounding observations (Müller, 2003) and the population and road density of neighbouring counties (Pfaff, 1999). Spatially lagged response variables were used by Florax et al. (2002), Perz & Skole (2003) and Gustafson et al. (2005). In this thesis, a spatially lagged response variable was included in one of the models in the regional-scale study (see Paper A). In one of the mountain area wide studies (see Paper C), a neighbourhood term was included in a logistic regression model that is similar to a spatially lagged response variable. This term contains the information, whether forest re-growth has occurred on neighbouring land or cultivation has been maintained. Similar neighbourhood terms have been used in logistic regression models by Augustin et al. (1996), Miller & Franklin (2002) and Rutherford (2006).

(d) Robust estimation techniques: Data from different levels (e.g. fields, farms, municipalities) are ubiquitous in land-use/land-cover change research (Hoshino, 2001; Polksy & Easterling, 2001; Overmars & Verburg, 2006). These data often show a distinct group structure (e.g. fields are grouped within farms, farms are grouped within

municipalities). This group structure causes dependencies between the data from different levels and must, therefore, be considered in statistical analyses (Snijders & Bosker, 1999). Robust estimators can be used to deal with grouped data. Cluster-adjustment is such a robust estimator (Primo et al., 2006). Cluster-adjustment is a variant of the Huber-White method, which allows for a general form of heteroskedasticity but does not allow for errors to be correlated across or within units (Huber, 1967; White, 1980). Cluster-adjustment accounts for both a general form of heteroskedasticity (not relevant in logistic regression models because there is no homoskedasticity assumption in these models) as well as for intra-cluster correlation (Froot, 1989; Williams, 2000; Primo et al., 2006). As this approach allows for any arbitrary correlation of observations within clusters, it also takes potential spatial autocorrelation of model residuals into account. The latter is of importance because individual-level and farm-level factors driving land abandonment and forest re-growth may only partially be captured by municipality-level covariates. This may lead to spatial autocorrelation in the model residuals (see Anselin, 2002). Cluster adjustment affects the variance-covariance matrix of the estimators and the estimated standard errors, but not the estimated coefficients (Primo et al., 2006). In this thesis, the suggestions by Müller & Munroe (2005) were followed and cluster adjustment used to account for municipality level effects on land abandonment and forest re-growth (see Paper C). For this, all observations (i.e. sample points representing presence/absence of forest re-growth) were grouped based on municipality boundaries, and each observation was assigned to its municipality. Then, the 'cluster ()' option available in STATA SE 8 was used, which performs cluster adjustment in standard logistic regressions (StataCorp, 2003).

4.4 Modelling approaches and model validation

Following the theoretical framework based on the theories of von Thünen and Ricardo (see chapter 3), natural forest re-growth is explained as a function of geo-physical and socio-economic variables describing the cultivation costs and benefits of agricultural land. The different modelling approaches described below allow the investigation of the hypothesised relationships between natural forest re-growth and each of the geo-physical and socio-economic explanatory variables (see Papers A, B, C and D). Spatial lag models and spatial error models were used for continuous response variables, i.e. the percentage change of agricultural areas as indicated by natural forest re-growth within mountain regions (see Paper A). Classification trees and logistic regression models were used for binary response variables, i.e. the presence/absence of natural forest re-growth on agricultural land (see Papers B, C and D). The statistical issues described in section 4.3 were considered in all analyses.

4.4.1 Classification tree analysis

In this thesis, classification trees (CTs) were used to examine the local pattern of natural forest re-growth within the case study municipalities and as the basis for conducting interviews (see section 4.2.4 and Paper D). CT analysis is a non-parametric statistical modelling approach used for data mining and predictions when the response variable is categorical and the explanatory variables are categorical or continuous (Breiman et al., 1984). In CTs, a data set is recursively partitioned into increasingly homogenous subsets called terminal nodes (Feldesman, 2002). Each terminal node is assigned the label of the majority class (presence/absence of forest re-growth in this thesis). Splits defining how to partition the data are selected based on information statistics that measure how well the split decreases heterogeneity within the terminal nodes (Venables & Ripley, 2002). The classification process starts at the root node (which encloses the complete data set) and ends at the terminal nodes. A developed CT encodes a set of decision rules in the form of if-then-statements. Figure 4.9 provides an example of a fitted classification tree. The topmost split is referred to as a *root node*; the nodes labeled with *pres* or *abs* are referred to as *terminal nodes*. The abbreviations refer to the explanatory variables used to develop the CT. The numbers in brackets at each terminal node refer to the total number of observations assigned to this node (left number) and the number of observations in the class as opposed to the class which is used to label that node (right number). CT model predictions are based on the proportion of presence and absence observations at each terminal node (Miller & Franklin, 2002).

To avoid over-fitting a CT (i.e. making it too sensitive to variation peculiar to the data sets used to develop this CT), CTs are usually pruned. Pruning entails reducing the number of nodes to determine how the misclassification error rate changes as a function of tree size (Breiman et al., 1984). In this thesis, 10-fold cross-validation was used to find the optimal complexity of a CT (Venables & Ripley, 2002). This means, 9 parts of the data set (the learning sample) were used to develop a CT and one part (the test sample) was used to test the classification accuracy of this CT. This process is repeated over all possible splits of the data into 9 and 1 partitions (Venables & Ripley, 2002). Figure 4.10 provides an example of a cross-validation plot.

In Figure 4.10, the cross-validated misclassification error rate (X-val Relative Error) is plotted on the vertical axis, the cost complexity parameters (cp) for different tree sizes are plotted on the lower horizontal axis and the corresponding tree-sizes, represented by the number of terminal nodes, are plotted on the upper horizontal axis. The pooled 10-fold cross validation error rate

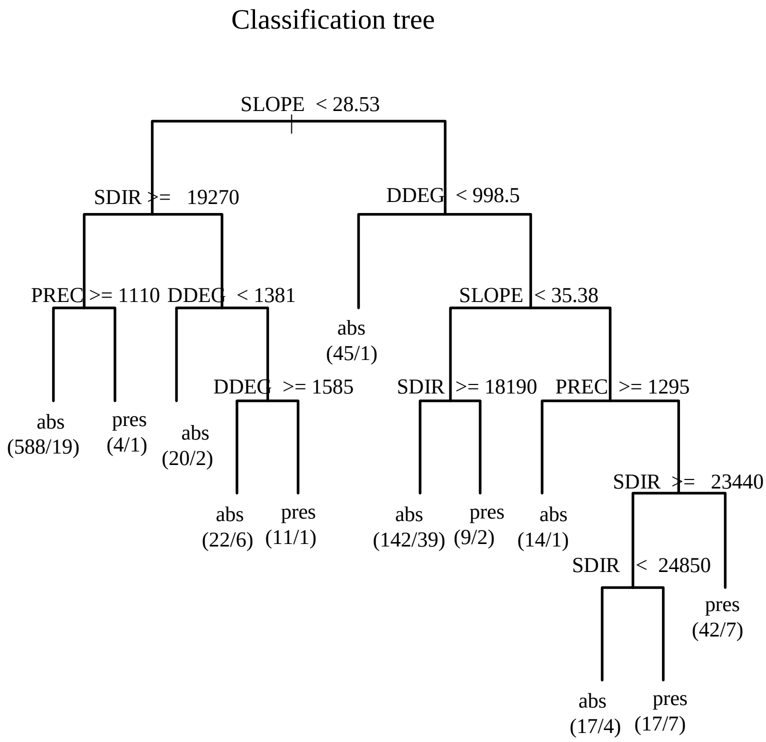


Figure 4.9 Example of a classification tree. Source: author.

(X-val Relative Error) is the misclassification error relative to the root node error. The cp-value for split i (cp_i) is defined as (Feldesman, 2002):

$$cp_i = \frac{RE_i - RE_{i+1}}{nsplit_{i+1} - nsplit_i}, \tag{4.3}$$

where RE_i is the relative error at split i and RE_{i+1} is the relative error at split $i+1$, $nsplit_i$ is a tree with n splits and $nsplit_{i+1}$ is a tree with $n+1$ splits (1 split = 2 branches). The cp-value can be interpreted as the improvement in fit compared to a tree with one less split. It also measures the accuracy lost by removing one or more terminal nodes (Feldesman, 2002).

Following the recommendations by Venables & Ripley (2002), the optimal tree size was chosen to minimise X-val Relative Error. In the example in Figure 4.10, the lowest X-val Relative Error is 0.93, which corresponds to a cp-value of 0.012 and thus a number of 12 terminal nodes in the final CT. The CTs were built and pruned following the recommendations by Venables & Ripley (2002) using the library *rpart* (Therneau & Atkinson, 2006) in the R statistical software (R, 2005).

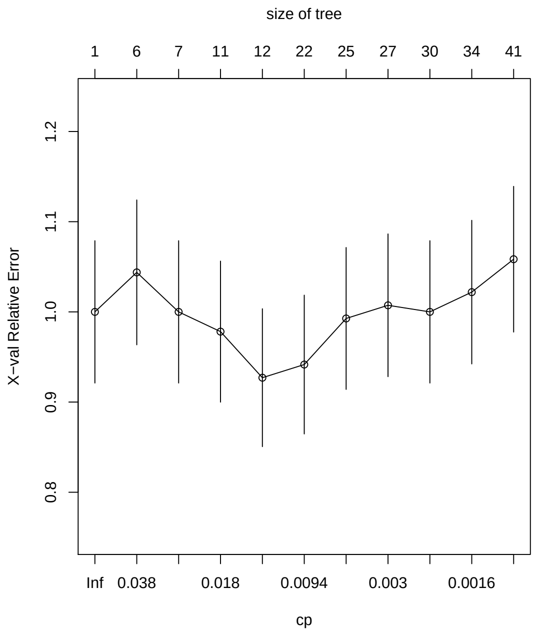


Figure 4.10
Example of a cross-validation plot. The pooled cross-validated error rate (X-val Relative Error) is plotted on the vertical axis. The cost-complexity parameter (cp) is plotted on the lower horizontal axis. The number of terminal nodes of the tree are plotted on the upper horizontal axis. The lowest point of the concave line refers to the lowest pooled cross-validated error rate, and determines the optimal tree size, which is 12 terminal nodes in this example. The corresponding tree is shown in Figure 4.9. Source: author.

4.4.2 Logistic regression

Logistic regression is designed to estimate the parameters in a model where the response variable is categorical and the explanatory variables are categorical or continuous (Hosmer & Lemeshow, 2000; Menard, 2002). Logistic regressions yield coefficients and associated confidence intervals for each explanatory variable based on a calibration data set. The equation of a logistic regression is given by (Hosmer & Lemeshow, 2000):

$$P(Y = 1) = \frac{exp(\alpha + \beta_k X_k)}{1 + exp(\alpha + \beta_k X_k)} \tag{4.4}$$

In this thesis, the term on the left-hand side of equation 4.4 is the probability that an agricultural area reverts to forest, α is a constant term, X_k is a $(n \times k)$ vector of explanatory variables and β_k is a $(k \times 1)$ vector of estimated coefficients.

To test for non-linear relationships between presence/absence of forest re-growth and the explanatory variables, univariate models which included the binary response variable and a single explanatory variable were fitted and the residuals of these models graphically examined (Baltes-Götz, 2005)[4]. In addition, non-linear relationships between variables were investigated by means of plots derived from generalised additive models (GAMs, Venables & Ripley, 2002). A GAM is a generalized linear model (GLM) in which the linear predictor is given by a user specified sum of smooth functions of the explanatory variables plus a conventional parametric component of the linear predictor (Wood, 2006). Figure 4.11 shows an example of a GAM plot. The response variable used to fit the GAM was the presence/absence of forest re-growth; the explanatory variable was the steepness of slopes. A number of 2000 presence/absence observations was included into the GAM model. The vertical axis of the GAM-plot shows the estimate of the smooth; the horizontal axis shows the steepness of slopes. The tick marks show the locations of the observations on the response variable. The solid black line is the estimate of the smooth. The upper and lower dashed lines indicate plus and minus two pointwise standard deviations. In the example in Figure 4.11, the plot of the fit shows an inverse U-shaped relationship between the estimate of the smooth and the steepness of slope. It suggests that the probability of forest re-growth first increases with increasing steepness of slope, then reaches a maximum and decreases if the steepness of slope becomes particularly high.

For explanatory variables that did not exhibit linear behaviour to the response variable, suggestions by Serneels & Lambin (2001) were followed and quadratic and linear terms of these variables added to the models.

To measure the overall goodness-of-model fit, McFadden's pseudo R^2 was calculated, which is defined as (Maddala, 2001):

$$R^2_{McF} = 1 - \frac{LL_M}{LL_0}, \tag{4.5}$$

where LL_0 is the maximised log-likelihood of the model that contains only the intercept. The LL_M is the maximised log-likelihood of the model that contains all explanatory variables. The same result as with McFadden's pseudo R^2 is obtained by another pseudo R^2 measure, the D^2,

[4]Note that in logistic regression models, other than in linear regression models, there is no assumption that the response variable and explanatory variables are linearly related (see Hosmer & Lemeshow, 2000). However, accounting for non-linear relationships between variables may provide further insights into the pattern of land-use/land-cover change, improve model fit and reduce spatial autocorrelation of model residuals (see Serneels & Lambin, 2001; Anselin, 2002). Thus, non-linear relationships between variables were taken into account in the logistic regression models.

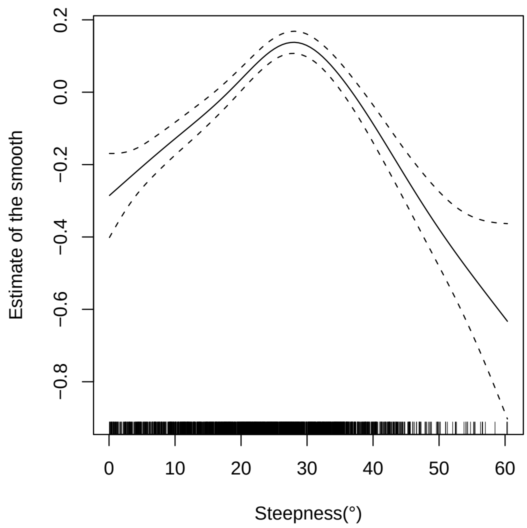


Figure 4.11
Generalised additive model (GAM) plot to test for non-linearity between the presence/absence of forest re-growth and steepness of slopes.

which is defined as (Guisan & Zimmermann, 2000):

$$D^2 = \frac{D_0 - D_R}{D_0}, \tag{4.6}$$

where D_0 is the deviance[5] of the model with the intercept only and the D_R is the deviance that remains unexplained by the model after all final explanatory variables have been included. For model comparison, Akaike's Information Criterion (AIC) was calculated for each model. It is defined as (Bozdogan, 1987):

$$\text{AIC} = -2LL + 2n, \tag{4.7}$$

where $-2LL$ is the log-likelihood of the fitted model multiplied by a constant of -2, and n is the number of parameters in this model. For nested models (i.e. those that are based on the same data set, but include different explanatory variables), smaller values of AIC and higher values of R^2_{McF} or D^2 indicate a better overall goodness-of-model fit.

[5]The deviance equals -2 times the log likelihood of a model.

In this thesis, logistic regression was used to investigate the mountain area wide pattern of forest regrowth at the disaggregated spatial scale (see Papers B and C). Following the recommendations by Geoghegan et al. (2001) and Serneels & Lambin (2001), the estimated coefficients of the logistic regression models were used to calculate the probability that agricultural land reverts to forest. In the studies presented in Papers B and C, unequal sampling proportions of presence and absence were used for model building[6]. Unequal sampling proportions do not influence the parameter estimates of a logistic regression model, although impact the model intercept (Maddala, 2001). Following the suggestions by (Maddala, 2001), the model intercept was adjusted for unequal sampling proportions when producing model predictions. In detail, the intercept was decreased by (ln p_1 - ln p_0), in which p_1 and p_0 are the proportions of observations chosen from the two groups for which the response variable takes the values of 1 (presence) and 0 (absence), respectively and the logarithm is the natural logarithm.

4.4.3 Spatial lag and spatial error models

Spatial lag (MLLAG) and spatial error (MLERR) models are maximum-likelihood (ML)[7] based linear regression techniques which account for spatial effects when dealing with spatially autocorrelated data (Anselin, 1988). The MLLAG model can be expressed as Anselin (1988):

$$y = \rho W y + \beta X + \varepsilon, \tag{4.8}$$

where Wy is a $(n \times 1)$ vector of the spatially lagged response variable, ρ is a coefficient, β is a $(k \times 1)$ vector of regression coefficients, X is a $(n \times k)$ vector of explanatory variables, and ε is a $(n \times 1)$ vector of independent identically distributed (abbreviated: i.i.d.) errors. The MLERR model is defined as an autoregressive process in the error terms (Anselin, 1988):

$$y = \beta X + u \qquad \text{with} \qquad u = \lambda W u + \varepsilon, \tag{4.9}$$

where β is a $(k \times 1)$ vector of coefficients, X is a $(n \times k)$ vector of explanatory variables, u is a $(n \times 1)$ vector of spatially autocorrelated errors, Wu is a $(n \times 1)$ vector of spatially lagged errors, λ is a coefficient and ε is a $(n \times 1)$ vector of i.i.d. errors.

[6] In both studies, 21 630 'presence' and 932 561 'absence' observations were available, from which 1000 'presence' and 1000 'absence' observations were sampled and for model building used.

[7] The maximum likelihood (ML) method is a technique of estimating parameters of a population by values that maximise the likelihood of the sample (see Maddala, 2001).

A significant spatially lagged error term indicates that the residuals of a standard regression model would be spatially correlated. Specifying a spatial autoregressive process for the error term by means of the MLERR model is equivalent to carrying out a standard regression on spatially filtered variables (Anselin, 2002). A significant spatially lagged response variable would indicate non-independence of observations of the response (Anselin, 2002). One possible interpretation of the latter is that the observed land-use/land-cover change is generated by processes that do not match the boundaries of the study regions (Perz & Skole, 2003). This scale mismatch generates a spatial "spillover" effect (Anselin & Bera, 1998). Model fit was measured using a pseudo R^2 measure recommended by Anselin (1992a):

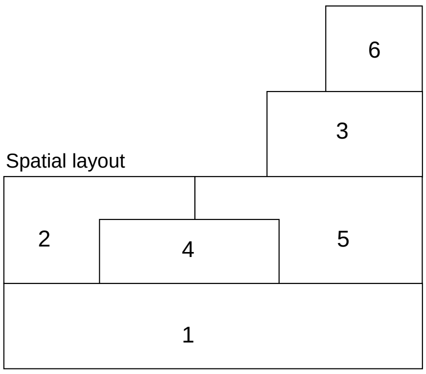
$$pseudo\ R^2 = \frac{\sigma^2_{pred}}{\sigma^2_{obs}}, \tag{4.10}$$

where σ^2_{pred} is the variance of the predicted response variable and σ^2_{obs} is the variance of the observed response variable.

A core element in MLLAG and MLERR error models as well as in Moran's I statistic (see equation 4.2) is the spatial weights matrix (W). It determines the strength of the correlation between neighbouring regions (Anselin, 1988). An example for a spatial layout and the corresponding spatial weights matrix is provided in Figure 4.12. The spatial layout can be thought of as a polygon map of mountain regions.

If two regions, h and i, have a common boundary or vertex, they are said to be contiguous. The order of contiguity specifies whether the neighbourhood includes only direct neighbours (first order) or additionally direct neighbours of direct neighbours (second order), and so on. In the example in Figure 4.12, the polygons labeled 1, 2, 4 and 5 are neighbours of the first order, whereas the polygons labeled 1 and 3, 4 and 6, 2 and 3 etc. are neighbours of the second order. In this example, spatial weights were calculated based on first order contiguity of regions. For contiguous regions, the cell w_{hi} in the $n \times n$ weights matrix (where n is the total number of observations) has a value of one. Self neighbours as well as non-contiguous regions obtained a zero weight in the corresponding cell w_{hi}, i.e. were not defined as neighbours. As in the example in Figure 4.12, in the regional-scale study conducted in this thesis (see Paper A), the spatial weights matrix was calculated based on first-order contiguity of mountain regions, i.e. only adjacent regions were defined as neighbours.

To improve the comparability between parameter estimations of different statistical models, suggestions by Anselin (2002) were followed and the weights matrix row-standardised. In a row-



binary weights

	1	2	3	4	5	6
1	0	1	0	1	1	0
2	1	0	0	1	1	0
3	0	0	0	0	1	1
4	1	1	0	0	1	0
5	1	1	1	1	0	0
6	0	0	1	0	0	0

row-standardised weights

	1	2	3	4	5	6
1	0.00	0.33	0.00	0.33	0.33	0.00
2	0.33	0.00	0.00	0.33	0.33	0.00
3	0.00	0.00	0.00	0.00	0.50	0.50
4	0.33	0.33	0.00	0.00	0.33	0.00
5	0.25	0.25	0.25	0.25	0.00	0.00
6	0.00	0.00	1.00	0.00	0.00	0.00

Figure 4.12
Example of a spatial layout and the corresponding binary and row-standardised spatial weights matrix. Figure modified after Anselin (2002).

standardised weights matrix the values for w_{hi} in each row of the weights matrix sum to one (see Figure 4.12). The row-standardised weights based on first order contiguity were used to calculate Moran's I test statistics (see equation 4.2) and the spatial lag and spatial error models (see section 4.4.3 and Paper A). Spatial weights matrices were constructed using the library *spdep* (Bivand, 2004) in the R statistical software version 2.0.1 (R, 2005).

4.4.4 Model validation

Three of four studies in this thesis deal with presence/absence data to investigate the patterns of natural forest re-growth (see Papers B, C and D). In these models the probability of a particular observation becoming abandoned and overgrown by trees and bushes was estimated, whereas in actuality, either an observation was abandoned and overgrown or not. So there was no clear way of calculating model residuals to compare predicted values versus actual values. That is, the prediction is a probability of change, while the actual value is either 'yes' the cultivation has been abandoned or 'no' the cultivation has not been abandoned. In addition, as the prediction results in a 'probability' that ranges from zero to 1.0 (in theory), what is the critical value of the 'probability' so that an observation 'counts' as an abandoned or not abandoned observation? Often researchers take 0.5 as the threshold to consider a predicted probability value to be a 'correctly' or 'incorrectly' predicted observation. This ad hoc choice of a threshold, however, has been criticised (e.g. Geoghegan et al., 2001).

A threshold independent measure of prediction accuracy is the "area under the receiver operating characteristics (ROC) curve" (=AUC, Metz, 1978). In a ROC-plot, the fraction of observed present, correctly predicted is plotted on the y-axis; the fraction of observed present, incorrectly predicted is plotted on the x-axis. The AUC measures the area under the curve in the ROC-plot. AUC values close to 1.0 indicate high similarity between the observed and predicted values. AUC values close to 0.5 indicate no similarity between the observed and predicted values. Figure 4.13 provides an example of a ROC curve.

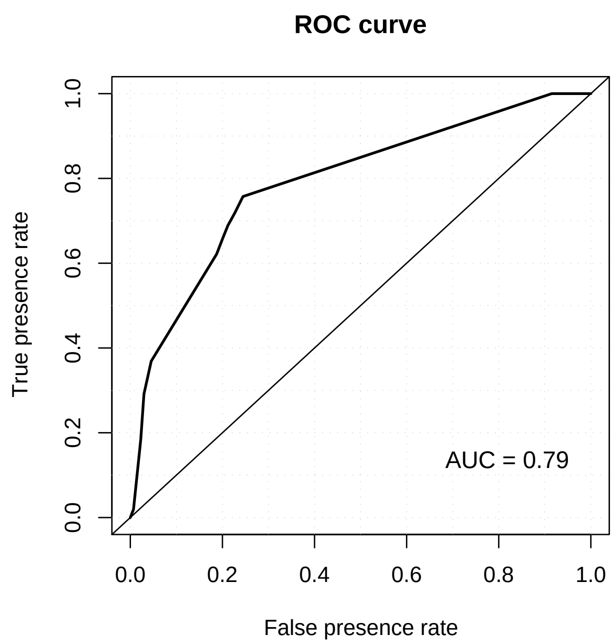


Figure 4.13
Example of a ROC-curve. The convex curve corresponds to an area under the curve (AUC) of 0.79. The diagonal line corresponds to an AUC of 0.5. This is the value where the observed values and the corresponding model predictions show no similarities. The AUC measures the prediction accuracy of the classification tree illustrated in Figure 4.9.

CHAPTER 5

Summaries of research studies

Four studies were conducted in order to answer the research questions and prove the hypotheses of this thesis (for research questions and hypotheses see section 1.3). Studies are represented in four research papers (referred to as Papers A, B, C and D) in the second part of this thesis. The first study (presented in Paper A) was conducted in order to answer the first research question. The second and third studies (presented in Papers B and C) were both conducted in order to answer the second research question. The fourth study (presented in Paper D) was conducted in order to answer the third research question. The first three studies deal with mountain area wide data. The main advantage of these studies lies in the availability of large data sets that cover the entire Swiss mountain area. This allowed the investigation of the patterns of forest re-growth over multiple gradients of geo-physical and socio-economic variables and different agricultural cultivation systems. Alternatively, case studies allowed the investigation of the smaller-scale patterns and causes of natural forest re-growth over longer time periods. Case studies also allowed the investigation of individuals' motives to abandon or maintain the cultivation of marginal agricultural land and allow natural forest re-growth to occur. Figure 5.1 shows the spatial and temporal scales of the studies and how the studies relate to the research questions.

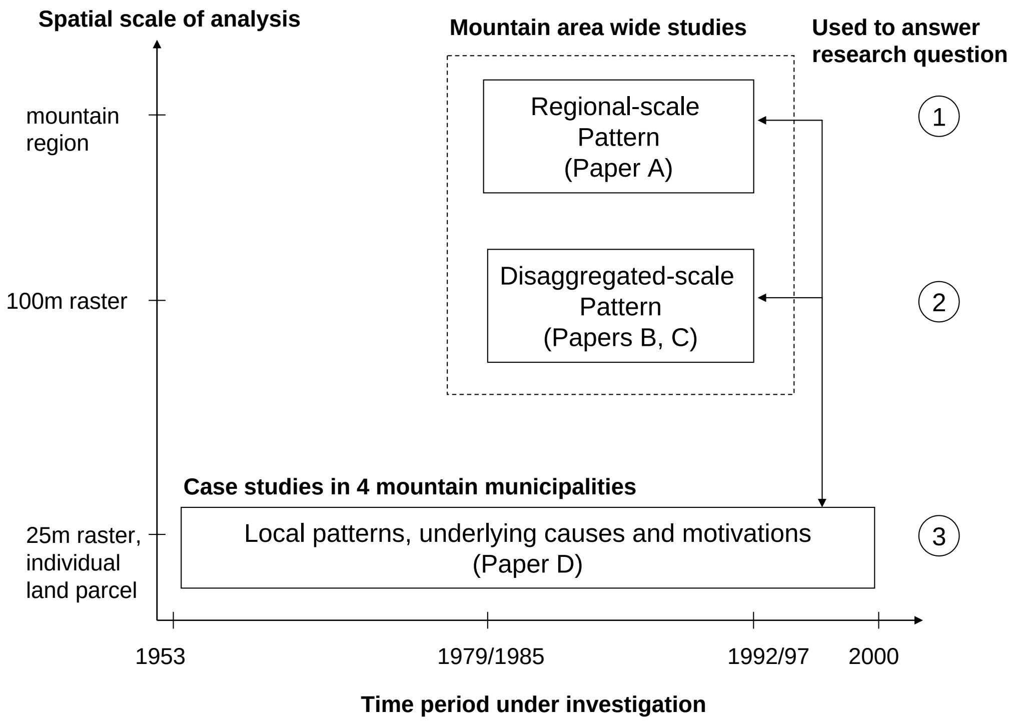


Figure 5.1 Overview about research studies

5.1 Regional-scale study - Paper A

5.1.1 Objective

The study presented in Paper A was designed in order to answer the first research question of this thesis. The objective was to investigate the regional-scale pattern of agricultural land abandonment (as indicated by natural forest re-growth) in the Swiss mountain area. It was hypothesised that mountain regions where the agro-climatic and topographic conditions were unfavorable for agricultural production, soils were of poor quality, road infrastructure was less developed, the proportion of agricultural land used as alpine pastures was high and off-farm employment was easily possible were favored in terms of land abandonment and forest re-growth.

5.1.2 Methods

The study area was the Swiss mountain area as described in section 4.1. Land-use/land-use change data were taken from two nationwide land-use statistics carried out over a 12-year period between the 1980s and 1990s (see section 4.2). The observation units were 55 mountain regions (see Paper A, Figure 1). Maximum-likelihood based spatial lag and spatial error models were developed to prove the study hypothesis (see section 4.4.3). The response variable used in the models was the percentage change of agricultural areas, as indicted by forest re-growth, within mountain regions multiplied by a constant of -1 (thus positive values reflect abandonment). The geo-physical and socio-economic explanatory variables were proxies for the cultivation costs and benefits of agricultural areas and opportunity costs of agricultural labour. Eleven explanatory variables were used: (1) average degree days, (2) average summer precipitation, (3) average soil depth, (4) average slope, (5) average distance to roads, (6) commuters, (7) employees in sectors II and III, (8) land used as alpine pastures, (9) full-time farms (10) population change and (11) a dummy for the mountain region 'Davos and Oberengadin'. For evaluation years and the expected relationship between each of the geo-physical and socio-economic explanatory variables and response variable see Paper A, Table 2. Spatial statistical models were complemented by scatterplots showing the bivariate relationships between the response variable and each of the geo-physical and socio-economic explanatory variables (Paper A, Figure 2).

5.1.3 Most important findings

Model results partially confirmed the study hypothesis, as they show that regions where agricultural land was characterised by steep slopes and off-farm employment was easily possible were favored in terms of natural forest re-growth (see Paper A, Figure 2 and Table 4). One model suggests a spatial spillover effect causing similar percentages of change of agricultural areas in adjacent regions (see Paper A, Table 4). Scatterplots show that forest re-growth occurred primarily where the heat sum was low, soils were shallow, road infrastructure was less developed, the proportion of full-time farms was low and the proportion of land used as alpine pastures was high. No statistically significant ($p < 0.05$) relationship could be found between neither average summer precipitation nor population change and the response variable (see Paper A, Figure 2 and Table 4). An interesting finding from the scatterplots is that forest re-growth did not occur until a certain threshold of the average steepness and soil depth of agricultural areas was reached (see Paper A, Figure 2). Below this threshold, almost no forest re-growth was observed, above this threshold, the percentage overgrown land increased progressively (see Paper A, Figure 2). Two regions in the southern canton of Ticino (Malcantone and Valli di Lugano) differ from other regions in several respects. They show, for example, the highest percentages of overgrown land of all regions, but intermediate steepness and comparably high heat sums. In some regions with good off-farm job opportunities (including Malcantone and Valli di Lugano), particularly high percentages of overgrown land were found, although this was not a general trend in the Swiss mountain area.

5.1.4 Main conclusions

Results confirm the expected pattern and show that land abandonment (as indicated by natural forest re-growth) took place where cultivation costs were high and benefits of agricultural land low. Results extend the knowledge about the pattern of land abandonment in the Swiss mountains. For example, the non-linear relationships between the steepness of agricultural land and soil depth and the response variable indicate that cultivation costs increase progressively with increasing steepness of slopes and benefits decrease progressively with decreasing quality of soils. It shows that the progressively graded agricultural subsidies paid to farmers could not compensate all the regional disadvantages related to the cultivation of steep land with shallow soils. This non-linearity in the pattern of forest re-growth and the fact that forest re-growth occurred primarily where part-time farming is common should be considered by decision makers when designing policy measures to react to land abandonment, forest re-growth and its consequences for the environment. A new finding from this study is that land abandonment and forest re-growth occurred independently from migration. This is contrary to what has been found in other European mountain regions (e.g. MacDonald et al., 2000). It is concluded that political measures require a more holistic view of the processes of land abandonment, which this study provides. Further research is necessary regarding scale dependency of the findings and neighbourhood effects.

5.2 Disaggregated-scale studies - Papers B, C

5.2.1 Objective

The studies presented in Papers B and C were both designed in order to answer the second research question of this thesis and complement the study presented in Paper A. The objective was to investigate the pattern of forest re-growth in the Swiss mountain area on a spatially disaggregated scale and over different agricultural land-use systems. In both studies, the same study area, definitions of forest and agriculture and similar geo-physical and socio-economic variables were used as in the study presented in Paper A. This allowed the comparison between and discussion of the differences and similarities between the three mountain area wide studies. The general hypothesis was that forest re-growth occurred primarily where cultivation costs were high and benefits low, i.e. costs were not covered by benefits. The first study (presented in Paper B) was a pre-study of the study presented in Paper C, and was used to guide the selection of further variables in the study presented in Paper C. This explains why both studies are similar, although the study in Paper C contains more and other socio-economic variables than the study presented in Paper B.

5.2.2 Methods

The study area was the Swiss mountain area as described in section 4.1. Land-use/land-use change data were taken from two nationwide land-use statistics carried out over a 12-year period between the 1980s and 1990s (see section 4.2). The observation units were 2000 lattice points of the Swiss land-use statistics (see Figure 4.5). In both studies, logistic regression models were used in order to prove the study hypothesis (for details of this approach see section 4.4.2). The binary response variable was the presence/absence of natural forest re-growth on agricultural land. In the study presented in Paper B, 14 proxy variables were used to explain the presence/absence of natural forest re-growth: (1) degree days, (2) potential direct shortwave radiation, (3) mean precipitation sum, (4) distance to forest edges, (5) soil depth, (6) soil stoniness, (7) slope, (8) distance to roads, (9) distance to settlements, (10) dummy for alpine pastures, (11) dummy for population change, (12) dummy for labor markets, (13) coordinate in x-direction and (14) coordinate in y-direction. The x- and y-coordinates of the model sample of observations were used to account for unobserved factors that are spatially correlated with the response variable. This approach reduces spatial autocorrelation of model residuals (see section 4.3.5). For the expected relationship between each of the geo-physical and socio-economic explanatory variables and response variable see Paper B, Table 1.

In the study presented in Paper C, 18 proxy variables were used to explain the presence/absence of forest re-growth: (1) degree days, (2) potential direct shortwave radiation, (3) mean precipitation sum, (4) potential evapotranspiration, (5) distance to forest edges, (6) soil depth, (7) soil stoniness, (8) slope, (9) distance to the closest construction zones, (10) rate of change of population, (11) dummy for pastures, (12) labour force participation rate, (13) proportion of employees in the primary sector, (14) distance to roads, (15) average number of parcels per farm, (16) proportion of full-time farms, (17) average agricultural area per farm and (18) rate of change of farms. For the expected relationships between each of the geo-physical and socio-economic explanatory variables and response variable see Paper C, Table 1. Contrary to the study presented in Paper B, where socio-economic explanatory variables were solely included in the form of binary (0/1) dummy variables, the study presented in Paper C uses socio-economic explanatory variables at the municipality level. This allowed the investigation of municipality-level effects on forest regrowth. Neighbourhood effects were considered by including a binary dummy variable with a value of one if any of the eight surrounding observations in the original data set contained natural forest re-growth and if not, with a value of zero. In addition, municipality level effects and the group structure in data were considered. For this, a robust estimation technique known as *cluster-adjustment* was used. For details of this approach see section 4.3.5 and Paper C. Logistic regression models were complemented by descriptive statistics of variables including histograms and barplots showing the frequency of presence and absence observations along slope and altitudinal gradients and the original land-use categories of the presence and absence observations (see Paper C, Figure 3). Parameter estimates of the logistic regression models were used to produce model predictions (see Paper B, Figure 2 and Paper C, Figure 4).

5.2.3 Most important findings

The highest frequency of forest re-growth was observed at altitudes between approximately 1400 m and 2100 m and on slopes between 20 and 40 degrees (see Paper C, Figure 3). Above and below these values, the frequency of forest re-growth decreased. Land where the cultivation has been maintained was found over a large range of altitudes, although mainly where slopes are slight. Overgrown land had its origin mostly in land-use categories representing transition states between agriculture and forest, such as bushy alpine and Jura pastures, land with grass and scrub vegetation and land with groups of trees. Non-linearity was found in the pattern of forest re-growth indicating that forest re-growth occurred primarily in areas with intermediate measures of steepness and soil stoniness (see Paper B, Table 2 and Paper C, Table 2). Most of the overgrown agricultural land was found relatively near roads (the median distance of the overgrown land to roads was 283 m, see Paper C, Appendix A). This unexpected result was explained by a few extreme values influencing the results of statistical models and the different accessibility requirements of meadows and arable land and alpine pastures. The results of both studies show that regions in which the majority of employees worked in the agricultural sector (i.e. labour markets were weak), were favored in terms of forest re-growth. The study presented in Paper C shows that forest re-growth occurred more frequently in municipalities with high proportions of part-time farms and high farm abandonment rates (see Paper C, Table 2). Different results were obtained in regard to the influence of population change on forest re-growth. The study presented in Paper B suggests no influence of population change on forest re-growth (see Paper B, Table 2). The study presented in Paper C suggests that municipalities in which population increased were favored in terms of forest re-growth (see Paper C, Table 2). In the model presented in Paper B, the x- and y-coordinates of the model sample of observations contributed significantly to the explanation of forest re-growth (see Paper B, Table 2). This indicates that important factors of forest re-growth were unobserved. Results of the models presented in Paper C show that forest re-growth occurred more frequently where forest re-growth occurred on neighbouring land (see Paper C, Table 2). The considerable residual deviance of all logistic regression models was interpreted as the result of undetected local characteristics such as poor water availability, small-scaled topographic peculiarities (e.g. small trenches, stonewalls, soil damages by cattle) and other unobserved factors such as the individual's motivation to abandon or maintain the cultivation of marginal agricultural land.

5.2.4 Main conclusions

Model results show that agricultural land was abandoned and became overgrown where the cultivation costs were high and benefits low, thus confirming the study hypothesis. Results extend the knowledge about the pattern of forest regrowth and agricultural land abandonment in the Swiss mountain area. For example, the non-linear relationships between steepness and soil stoniness and the presence/absence of forest re-growth indicate that forest re-growth is less prevalent in areas with favorable agro-climatic and topographic conditions and quality of soils, i.e. where agricultural production is profitable, and with extremely unfavorable agro-climatic and topographic conditions and quality of soils, i.e. where the limiting growth conditions of trees slow down the overall forest-dynamic. It also indicates that forest re-growth occurred primarily on the 'in-between' areas where labor costs were low, e.g., meadows and arable land in the valleys and alpine pastures approaching the treeline. Decision makers should consider these non-linearities in the pattern of forest regrowth when designing measures to prevent or support agricultural land abandonment and forest re-growth in the Swiss mountains. A new finding from both studies is that forest re-growth occurred more frequently in regions where the proportion of employees in the agricultural sector was high, i.e. labour markets were weak. This unexpected result was explained by the lower demand for agricultural land and the more profit-oriented management practices of farmers in regions with weak labor markets compared to regions with strong labor markets. The Mid-Grisons in the eastern central parts of the Swiss mountain area is such a region. Although this result is unexpected, it implies that labor markets have an influence on land abandonment and natural forest re-growth in the Swiss mountain area. Forest re-growth occurred more frequently in municipalities in which the majority of farms were managed on a part-time basis and farm abandonment was high. From this, the conclusion was made that land abandonment and forest re-growth are the result of the relative decline of the agricultural income. Studies show different results in regard to the influence of population change on natural forest re-growth. This indicates that understanding the processes of natural forest re-growth requires a more holistic view, which both studies provide. Overall, the results of both studies suggest that there is a variety of local determinants of natural forest re-growth. From this is was concluded that general policy measures for the whole mountain area (the current practise) are not suitable for the prevention of forest re-growth and its consequences for the environment, and that policy measures must pay more attention to local characteristics and needs.

5.3 Case studies - Paper D

5.3.1 Objective

The study presented in Paper D was designed in order to answer the third research question of this thesis and complement the studies presented in Papers A, B and C. The objectives were to (i) characterise the agricultural land where cultivation persisted and land that was abandoned and overgrown by trees and shrubs, (ii) investigate individuals' motives to abandon or maintain cultivation and allow reforestation to occur, and (iii) examine the causes of forest re-growth in the case study municipalities. The general hypothesis was that individuals balanced costs and benefits while deciding to abandon or maintain the cultivation of marginal agricultural land, and that natural forest re-growth can be related to indicators of the increasing opportunity costs of agricultural labour such as farm labour migration and shortages, and a switch over from labour intensive to labour extensive cultivation forms.

5.3.2 Methods

The study areas were four municipalities in the Swiss Alps - Tujetsch, Eggiwil, Soazza and Blitzingen (see section 4.1). The selection criteria were the presence of reforestation of sub-alpine grasslands as indicated by the recent Swiss land-use statistics (SFSO, 2001) and, to represent part of the agro-climatic, topographic and socio-economic conditions in the Swiss Alps, the location of municipalities at different altitudes and in different parts of the Swiss Alps. Land-use/land-use change was derived from aerial photographs taken in two points in time (1953/62 and 1998/2000). The aerial photographs, which were originally available in non-digitised form, were scanned and ortho-rectified (using ERDAS IMAGINE 8.6). All aerial photographs belonging to the same municipality were mosaicked. For land-use/land-use change classifications, aerial photographs were overlayed with regularly spaced raster cells (size 25 m $\times$ 25 m). Raster cells were taken as the observation units in this study. Within raster cells, the degree of coverage of trees, bushes and scrub was visually determined (see Figure 4.6). By comparing the land-use classifications within raster cells of the time period 1953/62 with that of 1998/2000, presence and absence of natural forest re-growth was derived. Presence/absence of forest re-growth was used as the response variable in the classification trees. Classification trees analysis (see section 4.4.1) was used to characterise the agricultural land where cultivation persisted (i.e. 'absence' observations) and land that was abandoned and overgrown by trees, bushes and scrub (i.e. 'presence' observations), and as the basis to conduct interviews. The explanatory variables used in the classification trees were: (1) annual degree days, (2) precipitation sum, (3) potential direct shortwave radiation, (4) soil depth and (5) slope. The influence of the accessibility of the land on reforestation was evaluated by means of interviews.

Following the ”finding answers in the errors” approach proposed by Wood & Skole (1998), classification tree model predictions were used to systematically select land parcels in the field (referred to as ’interview sites’). Interviews were conducted in order to investigate (i) individuals’ motives to abandon or maintain cultivation and allow reforestation to occur, (ii) examine the causes of natural forest re-growth in the case study municipalities, and (iii) investigate model misspecifications and potential spurious associations. A total of 48 interview sites were selected in the field and 31 landowners were interviewed (18 full-time farmers, one part-time farmer, two hobby farmers, two retired farmers and eight non-farmers). Interview questions related to the personal information of respondents, characteristics of interview sites and farms, individual motivation to abandon and maintain the cultivation and the causes of forest re-growth.

5.3.3 Most important findings

Three of the four classification trees accurately described the locations where natural forest re-growth has occurred, which was mostly on steep and north exposed slopes. However, further information from interviews was necessary to understand the patterns and determinants of forest re-growth thoroughly. Census data and interviews show that many farms have been abandoned during the 50-year study period. Remaining farms have often increased in size, whereas farm labour remained stable or decreased. Farm labour costs increased more rapidly than incomes, leading to undergrazing, the abandonment of the manual clearing of pastures from trees and bushes (the so called ”Schwenden”) and reforestation.

Policy factors were found to enhance forest re-growth. Landowners in the municipality of Soazza mentioned delayed land consolidation as one of the main reasons of reforestation. Land consolidation took more than 30 years (from the 1960s to the 1990s). Due to the tenure insecurities during this period, many landowners decided to abandon their land and allowed forest re-growth to occur. Another policy factor that enhanced forest re-growth in Soazza was the prohibition of the reconstruction of old stables for use as summer residences. It is currently forbidden because old stables in this region, (contrary to other regions in the Swiss mountains) have traditionally no space for farmers to stay overnight. This regulation has depressed land prices and has led to the reforestation of much of the land. Other respondents linked farm abandonment and forest re-growth to regulations concerning animal welfare discouraging farmers from investing in new stables. In Tujetsch, respondents mentioned the prohibition of free grazing as one of the main reasons for forest re-growth.

At some sites, the cultivation has been maintained although it was expected to be abandoned and reforested according to the classification tree predictions. This discrepancy could be explained by socio-economic factors such as the opportunity costs of farm labour (e.g. aged farmers retaining traditional farming practices), a switch-over to low cost cultivation practices (e.g. deer and horse pasturing), agri-environmental requirements (e.g. farmers require the land in order to not exceed the prescribed number of livestock per hectare) or other benefit related preferences of farmers (e.g. hobby farming, residential land-use). These factors reduce management costs, enlarge benefits or describe non-profit oriented behaviour. Interviews revealed furthermore that the land that was not directly accessible by roads was more often abandoned than land that was directly accessible by roads. The distance of the land to farmhouses had only a small influence on the decision to abandon or maintain cultivation.

5.3.4 Main conclusions

Results of this study show that individuals balanced costs and benefits while deciding to abandon or maintain the cultivation of marginal agricultural land which confirms the study hypothesis. As expected, natural forest re-growth could be linked to indicators of the increasing opportunity costs of agricultural labour such as farm labour migration and shortages, and a switch over from labour intensive to labour extensive cultivation forms.

A few main factors (e.g. steepness and aspect of slopes) and a variety of locally-specific factors (e.g. small trenches, wet soils, old stone walls) were found to enhance reforestation. Also policy factors (e.g. the prohibition of the reconstruction of old stables for use as summer residences, delayed land consolidations, regulations concerning animal welfare) enhanced reforestation. Contrary to this, a variety of local factors (e.g. extensive grazing, hobby farming, residential land-use) were found to slow down reforestation. From this it was concluded that the present policy measures are not suitable to prevent reforestation because they do not consider these specific local determinants of reforestation and focus rather on the support of agricultural production and income than on the maintenance of the cultivation of marginal land. If the prevention of reforestation is the announced aim of agricultural policy, then policy measures should focus on that specific objective, e.g. by establishing financial incentives to maintain marginal land with high biodiversity. This study is the first application of the ”finding answers in the errors” approach. Although the discussion references specific case studies, the experiences shown with this approach may be useful for others who aim to combine models and interviews to study land-use/land-cover changes.

CHAPTER 6

Summarised discussion

6.1 Patterns of natural forest re-growth

Studies that aim to investigate the spatial pattern of land-use/land-cover change generally address the question ”where have land-use changes taken place?”. This question has also been referred to as the ”location issue” (Serneels & Lambin, 2001). In this thesis, four studies were conducted in order to investigate the patterns of natural forest re-growth in the Swiss mountains. Results confirm the expected patterns as they show that forest re-growth occurred primarily where slopes were steep and/or north exposed, soils were shallow and/or stony, temperatures were low, land was located close to forest edges, and (as shown in the regional-scale study and case studies) road infrastructure was less developed and land was not directly accessible by roads. Results are in keeping with the land rent theories of David Ricardo and Johann Heinrich von Thünen, as they show that the quality of the land in terms of its agro-climatic and topographic conditions and quality of soils (Ricardian ideas) and the accessibility of the land (von Thünian ideas) are factors that determined agricultural land abandonment and natural forest re-growth.

Forest re-growth occurred primarily on bushy alpine pastures and land with grass and scrub vegetation and groups of trees, i.e. low intensively used land. This is as expected, because (according to Ricardo's land rent theory) marginal land is generally less intensively used than high quality land (see section 3.1). It is also in congruence with findings of case studies in the French Alps, northern Italy, Slovenia and Austria, where it was mostly pastureland and low-intensively used hay meadows which have been replaced by forests during the last years and decades, respectively (Douguédroit, 1981; Petretti, 1996; Anthelme et al., 2001; Kobler et al., 2005; Tasser et al., 2006).

In Western Europe, the replacement of low intensively used agricultural land by forests is not restricted to Alpine regions, but has also been observed in regions with unfavorable cultivation conditions in Sweden, the Netherlands, Poland, Denmark, Spain and the Baltic countries (Ihse, 1995; Compagnons, 1996; Kozak, 2003; Poyatos et al., 2003; Kristensen et al., 2004; Romero-Calcerrada & Perry, 2004; DLG, 2005). Some findings of this thesis, however, are new or were unexpected. These are discussed in the following.

According to Verburg et al. (2004b), changes in land-use/land-cover types are often non-linear and thresholds play an important role. In this thesis, non-linearity in the pattern of forest re-growth was found in all studies. On the regional scale, non-linearity was indicated by the progressive increase of the percentage of overgrown agricultural land with increasing average steepness and decreasing average soil depth of agricultural areas, respectively (see Paper A, Figure 2 and Table 4). The explanation is that cultivation costs increase nonlinearly and benefits decrease nonlinearly with increasing average steepness and decreasing average soil depth. The Swiss agricultural politics consider this non-linearity, for example by the progressively graded subsidies for the cultivation of steep slopes (BLW, 2002). That the non-linearity in the pattern of forest re-growth still exists shows that the subsidisation was not entirely successful in compensating all the regional disadvantages related to the cultivation of steep land with poor soils.

Non-linear relationships between forest re-growth and explanatory variables were also found in the mountain area wide studies on the disaggregated scale (see Papers B and C). Results of these studies show that the frequency of forest re-growth first increases with increasing steepness of slopes and stoniness of soils, then reaching a maximum, and decreases in areas with extremely steep slopes and stony soils (see Paper B, Table 2 and Paper C, Table 2)[1]. On less steep and stony land cultivation has been maintained due to the suitability of the land for agricultural production. That the frequency of forest re-growth decreased in areas with very steep slopes and stony soils can be explained by the limiting growth conditions of trees, bushes and scrub in these areas (due to snow avalanches, lower water holding capacity of soils, soil erosion etc.). Sheep pasturing, which is common in areas with very steep slopes and stony ground, also retard forest re-growth. Interestingly, Luder (2004) found an inverted U-shaped relationship between the steepness of slopes and labour costs that is similar to the inverted U-shaped relationship between the steepness of slopes and the presence/absence of forest re-growth found in the logistic regression models. It indicates that labour costs first increase with increasing steepness of slopes and decrease, if the steepness of slopes becomes particularly high. Luder (2004) explains this non-linear relationship as follows: where slopes are slight, the use of machines is common and labour costs are low. With increasing

[1] The non-linear relationship between the presence/absence of forest re-growth and steepness of slopes is illustrated in Figure 4.11.

steepness, labour costs increase because the use of machines becomes more labour intensive. If slopes become very steep, labour costs decrease again because farmers tend to use less labour intensive cultivation forms in these areas. Thus, the low frequency of natural forest re-growth in areas with very steep slopes and stony ground may also be explained by the extensive cultivation forms used in these areas, such as sheep pasturing. Non-linearities in the pattern of forest re-growth were also found in the case study municipalities (see Paper D). It confirms the findings of the mountain area wide studies (see Papers B and C), as it shows that forest occurred more frequently in the areas between valley floors and alpine pastures approaching the treeline. The importance of non-linearities in the pattern of land-use/land-cover change has also been stressed in other studies. For example Serneels & Lambin (2001) found that the probability of expansion of mechanised agriculture is low close to roads, increases with increasing distance to roads, reaches a maximum at intermediate distances to roads and decreases if the distance to roads becomes particularly high. Kozak (2003) showed for a study area in the Carpathians (Poland) that forest re-growth occurred more frequently on higher and lower altitudes compared to existing forest stands.

The accessibility of the land by roads influences land-use decisions as it relates to cultivation costs (Serneels & Lambin, 2001; Southworth et al., 2004). In this thesis, the average distance of the land to roads (see Paper A) and the distance of the land to roads (see Papers B and C) were used to test the influence of road access on forest re-growth. The regional-scale study (see Paper A) shows that regions with underdeveloped road infrastructure were favored in terms of land abandonment and forest re-growth, which is as expected. Interviews revealed that land remote from roads is more often abandoned and overgrown than land which is directly accessible by roads (see Paper D, Table 5 and text). This is as expected. It is also in congruence with findings by Pezzatti (2001), who showed that agricultural land close to roads is generally more intensively used than land remote from roads. The results of the two mountain area wide studies conducted on the disaggregated scale (see Papers B and C) show that land close to roads was more frequently abandoned and overgrown than land far from roads. This was unexpected. It is also contrary to findings by Pezzatti (2001). A closer examination of the data revealed that a small number of observations at very large distances from roads (above 2 km) were responsible for the unexpected negative linear relationship. By excluding these observations, the variable *distance to roads* shows a non-linear relationship to the response variable (i.e. presence/absence of forest re-growth) indicating that the frequency of forest regrowth first increases with increasing distance to roads (which is as expected), then peaks at rather large distances before finally decreasing again at very large distances. Again, this result suggests that the probability of forest re-growth decreases if the distance to roads becomes particularly high. This unexpected result may be explained as follows:

Firstly, forest re-growth was investigated over different land-use systems, i.e. meadows and arable land and alpine pastures. While the accessibility of meadows and arable land by roads is necessary because this land is cultivated with machines, alpine pastures often require no road access. The reason is that herdsmen often stay with the livestock over summer and milk is processed on site (Netting, 1972; Petretti, 1996). Sheep pastures do not even require herdsmen. That much of the agricultural land remote from roads is under cultivation explains why forest re-growth occurred less frequently in these areas. Secondly, agricultural areas remote from roads are often also close to the treeline. The limiting growth conditions of trees, bushes and scrub in these areas also explains why forest re-growth occurred less frequently in areas remote from roads.

It was expected that land speculations had an influence on forest re-growth. To prove this hypothesis, the distance of the land to construction zones and population change were used as proxy variables (see Paper C). The distance of the land to construction zones was used because landowners may be interested in converting marginal agricultural land to residential land. This is because residential land generally provides a higher income than marginal agricultural land. Such a conversion is often only possible in areas delineated as potential construction land. Thus future expectation in regard to agricultural land conversion is generally higher for land delineated as or near to potential construction land and lower for land remote from potential construction land. Future expectations in regard to the alternative use of marginal land might also be high in regions/municipalities where population increases. This is because immigration is often related to a higher demand for construction land and land prices increase accordingly. No relationships were found in the models between forest re-growth and the distance of the land to construction land (see Paper C, Table 2), and the positive relationship between population increase and forest regrowth found in the models (see Paper C, Table 2) was unexpected. It suggests that the factors influencing forest re-growth are complex and cannot be explained by the distance of agricultural land to potential construction land and population change.

Both, emigration and immigration have been linked to land abandonment and forest re-growth in western European countries (Baldock et al., 1996; MacDonald et al., 2000; Kozak, 2003; Romero-Calcerrada & Perry, 2004; DLG, 2005). The studies of this thesis show contradictory results in regard to the influence of population change on forest re-growth. The regional-scale study and the first mountain area wide study conducted on the disaggregated scale revealed no relationships between population change and forest re-growth (see Paper A, Table 4 and Figure 2 and Paper B, Table 2). The second mountain area wide study conducted on the disaggregated scale suggests that forest re-growth occurred more frequently in municipalities in which population increased (see Paper C, Table 2). Interestingly, no statistically significant ($p < 0.05$) relationship between emigration and forest re-growth was found. This is contrary to what has been found in other western European countries (e.g. MacDonald et al., 2000). This finding confirms the complex relationships between migration, land abandonment and forest re-growth discussed by Mather & Fairbairn (2000). They explain this complexity by the industrialisation of parts of the Swiss mountains, which prevented rural depopulation in spite of declining agriculture. The importance of tourism (see Figure 4.3) might be another explanation for the prevention of rural depopulation in the Swiss mountain area. An explanation for the complex relationship between population change and forest area changes is also provided by Rudel (1998). He concludes from his investigations on worldwide forest transitions in the period between 1922 and 1990:

> "*The decision to allow fields on the periphery to revert to forest is a decision to reduce labor inputs where they have little value. In many instances landholders migrate permanently or temporarily to cities, in effect redirecting their labor to a market where it has more value. In other instances landholders continue to reside in rural areas, but they find employment in non-farm occupations. Either way, these changes reduce the direct impact that the rural population has on the forests.*"

In Switzerland it is mostly the latter process that can be observed, i.e. landholders continue to reside in rural areas, but they find employment in non-farm occupations. This reduces the direct impact that the rural population (as opposed to the agricultural population) has on the cultivation of marginal land and explains why emigration is not related to forest re-growth. Also the case studies (see Paper D) showed that considerable forest re-growth rates occurred where population remained approximately stable (Soazza), increased (Tujetsch) and decreased (Blitzingen), i.e. a clear trend between population change and forest re-growth could not be observed.

People in regions with favorable off-farm employment opportunities generally have higher opportunity costs of farm labour than people in regions with unfavorable off-farm employment opportunities (Strijker, 2005). This explains why people in regions with favorable off-farm employment opportunities tend to invest their labour in jobs outside agriculture and farmers with access to strong labour markets often abandon their farmland and allow natural forest re-growth to occur (see Petretti, 1996; Rudel et al., 2000; Romero-Calcerrada & Perry, 2004). In this thesis, it was hypothesised that regions with strong labour markets and regions in which people had favorable access to strong labour markets were favored in terms of land abandonment and natural forest re-growth (see Papers A, B and C). To prove this hypothesis, the proportion of commuters and employees in the agricultural and non-agricultural sectors were used as proxy variables (see Papers A, B and C). Depending on the scale of the analysis and proxy variables, contradictory results were obtained in regard to the influence of economic strength on forest re-growth. On the regional scale (see Paper A), the percentage of overgrown agricultural land was higher where the proportion of commuters was high and low and the proportion of employees in the non-agricultural sectors was high, i.e. labour markets were strong or strong labour markets were easily accessible. This was expected, although it was not a general trend in the Swiss mountain area, but influenced by a small number of regions (see Paper A, Figure 2 and text). The studies conducted on the disaggregated scale (see Papers B and C) both revealed that forest re-growth occurred primarily where the majority of employees worked in the agricultural sector, i.e. labour markets were weak. This is contradictory to the result of the regional-scale study. An explanation for this unexpected result is the comparably high forest re-growth rate in the Mid-Grisons - a region in the eastern central part of the Swiss mountain area. Over the past decades, agriculture in the Mid-Grisons underwent considerable changes. As a result, comparably large but few farms can be found in this region. Most of these farms are managed on a full-time basis, and off-farm employment is uncommon because tourism and industry are less developed. Because many farms have reached a maximum size, and farm labour is scarce, it is likely that farmers restrict their activities to the more favourable land and abandon the marginal land. That farmers in the Mid-Grisons rely on more profit-oriented management practices to secure farm income would explain why much of the marginal land has been abandoned and overgrown by trees and bushes.

The scale dependencies of the influence of off-farm employment opportunities on forest re-growth may be explained by the different zonation of the explanatory variables, i.e. mountain regions in the regional-scale study and municipalities in the disaggregated-scale studies. Taken together, the results of the mountain area wide studies suggest a local influence of off-farm job opportunities on forest re-growth in the Swiss mountain area. An influence of off-farm job opportunities on land abandonment and forest re-growth was also found in other studies. Petretti (1996) found for the Valle d'Aosta in northern Italy that the availability of off-farm jobs enhanced structural change in agriculture and land abandonment. Romero-Calcerrada & Perry (2004) found for a study area in central Spain that easily accessible strong labour markets caused farm labour migration, land abandonment and forest re-growth. Hietel et al. (2005) conclude from their analysis of land-cover changes in different study areas in central Germany that transitions to fallow land are indicated in particular by environmental variables characterising unfavorable agricultural conditions, together with socio-economic indicators showing unfavorable non-agricultural employment alternatives within case study areas. Other studies have shown that the lack of off-farm employment opportunities can force farmers to maintain cultivation. The case of Extremadura (eastern central Spain) shows, for example, that the lack of economic development in the region, and consequently very high unemployment, was a key factor in maintaining many apparently marginal farms (Beaufoy, 1996).

Forest re-growth occurred more frequently in regions and municipalities in which the majority of farms were managed on a part-time basis. Part-time farming is common in the southern parts of the Swiss mountain area (see Figure 4.4). According to Surber et al. (1973), farms in these regions are often smaller, cultivation is less optimised and land is often fragmented due to hereditary customs ("Erbteilungen"). Interviews revealed the extent of land fragmentation. In the municipality of Blitzingen, one farmer stated that he cultivates more than 750 single parcels (farm size 40 ha). In the municipalities of Soazza and Tujetsch, land consolidations were necessary to improve the small-scaled and scattered structure of agricultural properties. Respondents in Soazza mentioned that scattered properties and delayed land consolidation led to tenure insecurities which discouraged many farmers from investing in new stables and machines. This confirms findings by Rieder et al. (1990), who state that part-time farming is associated with low fix-costs because part-time farmers often do not invest in buildings and machines. Low investments, according to Rieder et al. (1990), also explain why part-time farmers are often competitive compared to full-time farmers. Thus, the fact that forest re-growth occurred more frequently in regions and municipalities in which part-time farming was common can be explained as the result of high cultivation costs and tenure insecurities due to the unfavorable agricultural structures caused by previous hereditary customs. Another explanation is that part-time farmers often have less time to work on the farm. This is equivalent to saying that part-time farmers have high opportunity costs of agricultural labour (see Strijker, 2005). Thus, that forest re-growth occurred more frequently where part-time farming was common also indicates that farmers abandoned their land because opportunity costs of farm labour were high, which is as expected.

Relationships between part-time farming and/or pluriactivity (i.e. the sum of farm and off-farm activities of farm households) and land abandonment have also been found in other countries. Hietel et al. (2005) show for different case study areas in central Germany that land abandonment occurred more frequently where farms were managed on a part-time basis. MacDonald et al. (2000) showed from their analyses of 24 case studies in European mountain regions that the time required for pluriactivity often contributed to farmers abandoning agriculture. Other studies have showed that the relationships between part-time farming, pluriactivity and land abandonment can be complex. Hetland (1986), for example, shows for rural Norway that pluriactivity secured farm incomes and prevented the abandonment of farms and cultivation. Daniels (1986) showed for the U.S.A that hobby farming can be an incentive to maintain cultivation. Baldock et al. (1996) point out that low agricultural incomes do not necessarily mean low farm family incomes and that in certain areas, a large proportion of farm family income is earned outside agriculture. This explains why low farm income is not necessarily related to land abandonment and forest re-growth.

Forest re-growth occurred more frequently in municipalities in which the rate of change of farms was high than in municipalities in which the rate of change of farms was low (see Paper C, Table 2). This confirms findings from other European countries such as Sweden, Norway, Italy, Poland, Spain and the Baltic countries, which show that farm labour migration and farm abandonment often lead to land abandonment and forest re-growth (Ihse, 1995; Petretti, 1996; Kozak, 2003; Romero-Calcerrada & Perry, 2004; Sickel et al., 2004; DLG, 2005). It also confirms expectations by Messerli (1989), Bätzing (1996) and Broggi et al. (1997), who assumed a direct relationship between farm-labour migration and land abandonment. Other studies have shown that farm labour migration and farm abandonment must not necessarily be related to land abandonment. Beaufoy (1996) analysed changes in agricultural structures and land-use in Extremadura (eastern central Spain) in the period after World War II. Despite considerable changes in agricultural structures, agricultural land abandonment was not widespread, which he mostly related to the Common Agricultural Policy (CAP) payments for farmers from the beginning of the 1990s onwards. In Switzerland Naegeli-Oertli (1986) showed for the municipality of Grindelwald that, despite the considerable decrease of the number of farms during the last decades, almost no farmland has been abandoned. On the aggregated level, Baur (1999) showed that the rate of change of farms in the Swiss mountain area between 1950 and 1990 was not higher but lower compared to the Swiss Plateau. At the same time, land abandonment and forest re-growth occurred more frequently in the Swiss mountain area (Surber et al., 1973; Brassel & Brändli, 1999; SFSO, 2005). The explanation is that land is generally not abandoned if the available labour and machinery of farms allow the procurement of land from abandoned neighbouring farms. In the Swiss Plateau, mechanisation is easily possible as is the cultivation of land from abandoned farms. In the mountains, mechanisation is often difficult. This explains why the procurement of land from abandoned neighbouring farms is often economically unviable, and mountain farmers thus abandon marginal land and allow forest re-growth to occur.

In Switzerland, farmers obtain fewer subsidies for the cultivation of alpine pastures than for the cultivation of arable land and meadows. Thus, it was expected that forest re-growth occurred more frequently on alpine pastures than on other agricultural land. To prove this hypothesis, different proxy variables were used. In the regional-scale study (see Paper A), the proportion of agricultural land used as alpine pastures was used as a proxy variable. In the disaggregated-scale studies (see Papers B and C), binary dummy variables (alpine pastures/other agricultural land) were used as proxy variables. In the models based on regional-scale data, no statistically significant ($p < 0.05$) relationship was found between the percentage change of agricultural areas and the proportion of agricultural land used as alpine pastures (see Paper A, Table 4). Also the binary dummy variables used in the disaggregated-scale studies were insignificant (see Paper B, Table 2 and Paper C, Table 2). It suggests that the different subsidisation of alpine pastures compared to other agricultural land had no influence on forest re-growth in the 12-year study period between the 1980s and 1990s. The explanation may be found in the fact that much of the overgrown agricultural land, but also much of the land on which the cultivation persists can be found on alpine pastures (see SFSO, 2005). In the Alps, farmers rely on the mixed cultivation of pastures and meadows (Netting, 1972; Petretti, 1996). This explains why alpine pasturing is common, although alpine pastures have less suitable cultivation conditions than meadows and arable land in valleys.

Results of this thesis show that forest re-growth occurred more frequently where forest re-growth occurred in neighbouring regions and on neighbouring land, respectively (see Paper A and C). One of the models based on regional-scale data suggests a spatial spillover effect causing similar land abandonment and forest re-growth rates in neighbouring regions. Due to the lack of adequate data, the basic mechanism behind this spillover effects could not be investigated. On the disaggregated scale (see Paper C), the influence of the neighbourhood variable was partially explained by the design of the Swiss land-use statistics, where areas larger than 2 ha are represented as a group of grid-points representing presence and absence of forest re-growth. Within such groups, some observations were modelled well by the ordinary logistic regression model, while others were not. It is likely that some observations within such groups have better cultivation conditions than other. On larger land parcels, farmers seemed to abandon or maintain the whole parcel, regardless of whether there were parts of this parcel with more favourable cultivation conditions. The model is not able to determine whether neighbouring observations belong to a single parcel and farmer or not. Including information about forest regrowth on neighbouring parcels is a way of accounting for this lack of information, because it indicates higher probabilities of land abandonment where nearby land has been abandoned.

The importance of neighbourhood effects has also been stressed in other land-use/land-cover change studies. Pfaff (1999) used spatially lagged variables such as the road and population density of neighbouring counties to explain deforestation in the Brazilian Amazon. Geoghegan et al. (2001) included a variable representing the richness of neighboring land uses to explain deforestation in the southern Yucatán peninsular region. Perz & Skole (2003) developed spatial lag and heteroskedastic error models to account for neighbourhood effects in their model on the social determinants of secondary forest growth in the Brazilian Amazon. Verburg et al. (2004a) developed cellular automata to analyse neighbourhood characteristics in a study area in the Netherlands. Gustafson et al. (2005) developed spatial lag and spatial error models to consider neighbourhood effects in their models on changing human settlement pattern in the Midwestern USA.

Brueckner (2003) and Anselin (2002) provide theoretical explanations for the influence of neighbourhood variables on land-use/land-cover changes. These explanations are based on the assumptions that interacting agents and/or social interaction exists. One explanation is referred to as the *spillover model*, in which an agent chooses the level of a decision variable, and the values chosen by other agents affect this decision. According to Anselin (2002), this would be relevant in a situation where a farmer would determine the amount of farmland devoted to a crop by taking into account the amounts allocated by the other farmers in the system. A second theoretical framework is referred to as the *resource flow model*. Here, the agent's decision variable is not directly affected by the levels chosen by other agents, but only indirectly. The indirect effect follows from the presence of the value of a resource in the individual agent's objective function (Anselin, 2002). The interaction between agents follows from the way in which the resource is distributed among them, which depends both on the characteristics of each agent (for example, the type of crop grown on the field), as well as on the decisions taken by the other agents (how much fertiliser farmers use). The influence of social interactions on the land-use decisions of individual landowners could not be investigated in this thesis. This would require further analysis in the field (e.g. by means of interviews).

6.2 Causes of natural forest re-growth

According to economic theory, land-use/land-cover changes are influenced by exogenous factors such as changing labour markets, relative prices of agricultural inputs (e.g. fertilisers, motor fuels) and outputs (e.g. cereals, milk), changing policies (e.g. regulations, support measures) and technological and infrastructural developments (Meyer & Turner II, 1994; Baldock et al., 1996; Kaimowitz & Angelsen, 1998; Irwin & Geoghegan, 2001; Munroe & York, 2003; Strijker, 2005). In Switzerland, as in many other western European countries, these factors have led to the relative decrease of the agricultural income during the past decades (Surber et al., 1973; Selby et al., 1996; MacDonald et al., 2000; Strijker, 2005). A decrease of the income in the agricultural sector, relative to the income in other sectors means that the opportunity costs (i.e. the value of the alternative use) of agricultural labour increase (Strijker, 2005). In this thesis, it was hypothesised that natural forest re-growth can be related to indicators of the increasing opportunity costs of farm labour such as farm labour migration and shortages and a switch over from labour intensive to labour extensive cultivation forms.

The mountain area wide studies (see Papers A, B and C) were primarily used to investigate the pattern of forest re-growth. However, they also provide insights into the causes of natural forest re-growth. Forest re-growth was primarily found where the majority of farms were managed on a part-time basis. Part-time farmers tend to invest their labour in off-farm jobs because off-farm jobs generally provide higher incomes than farm jobs. This indicates that the increasing opportunity costs of farm labour had an influence on land abandonment and forest re-growth, which was as expected. The influence of the opportunity costs of farm labour on the decision to abandon land and allow forest re-growth to occur has been discussed in other studies. Strijker (2005) concludes from his study on the causes of the declining marginal agricultural land in Europe that the increase of the opportunity costs of agricultural labour is one of the most important drivers of agricultural land-use change, including land-use intensification, extensification and land abandonment. From their analyses on natural reforestation in post World War II Puerto Rico, Rudel et al. (2000) concluded that economic development raised the opportunity costs of agricultural labour to the point where farm labour migrates; in response to the growing scarcity of farm labour, landowners shifted to more extensive, less labour intensive land uses such as forests.

Case studies allowed for detailed investigations of the causes of natural forest re-growth including the motivations of individuals to maintain and abandon the cultivation of marginal land and allow natural forest re-growth to occur. In three of the four municipalities (i.e. Tujetsch, Soazza and Blitzingen), the economic development from the 1950s onwards caused considerable structural changes in agricultural. In these municipalities, many farms have been abandoned. Remaining farms have often increased in size, whereas farm labour remained stable or decreased. In all municipalities, respondents mentioned farm labour shortages as one of main reasons for land abandonment and forest re-growth. Farm labour is scarce because it does not pay to invest labour in farming - this is the economic interpretation of the labour shortages mentioned by the respondents (see Strijker, 2005). The abandonment of the manual mowing of steep pastureland and clearing of pastures from trees and bushes (the so called ”Schwenden”), the establishment of low cost cultivation forms such as deer and horse pasturing and the conversion of former meadows to pastures for Highland-cattle is the result of the labour shortages mentioned by respondents. The abandonment of labour intensive work and the establishment of labour extensive forms of cultivation are indicators of the increasing opportunity costs of agricultural labour. That these indicators could be linked to natural forest re-growth confirms the study hypothesis.

Similar developments as in the four case municipalities have been observed in neighbouring Alpine countries. Petretti (1996) investigated the process of agricultural marginalisation and abandonment in the Valle d’ Aosta in northern Italy. Results of this study showed that there has been a shift from labour intensive dairy farming to less labour intensive breeding of calves and steers during the last decades. According to Petretti (1996), the main reasons for the observed land-use and farm management changes were the diminishing economic viability stemming from both high costs, in particular for the lease of pasturing rights and labour and relatively low income. According to Baldock et al. (1996), the economic development in western Europe during the last decades caused arable land and mixed farming systems to be abandoned on a large scale and be replaced by extensive livestock systems, plantation forestry or natural succession. MacDonald et al. (2000) show on the basis of 24 case studies in European mountain regions that in traditional grassland systems, overgrazing and undergrazing often occur simultaneously within an area or individual farm and many former meadows were substituted with permanent grasslands.

That intensification and extensification often occur simultaneously within an area or individual farm has also been observed in the case study municipalities. One farmer in Blitzingen stated that he has abandoned parts of the farmland, but at the same time invested in irrigation facilities on other parts of the farm. In Eggiwil, farmers stated that today, cattle are often not brought to alpine pastures as in former days, but graze on the pastures of nearby farms. In Tujetsch, some farmers invested in modern stables and switched from dairy farming to the less labour intensive breeding of cattle and calves. In Soazza, large parts of the alpine pastures have been abandoned, while at the same time farmers cleared old forest stands on the valley floors in order to secure meadows that are suitable for mechanised mowing. An economic explanation for the simultaneity of intensification and extensification is provided by Hayami & Ruttan (1985) and Strijker (2005). According to them, in the case of economic growth, favorable opportunities for labour outside the agricultural sector do not only increase the cost of labour in agriculture, but also create a high pay-off for techniques that promise to increase the agricultural production per unit of labour. This implies a tendency towards mechanisation, including re-allotment, irrigation and other measures to make land better suitable for mechanised agriculture. Where mechanisation is not possible, and alternative land-uses (e.g. pasturing) economically unviable, land is abandoned and left to become overgrown by trees and bushes.

Baldock et al. (1996) and Strijker (2005) point out the important role that policy factors have on land-use. Changing policy factors and regulations enhanced forest re-growth in the case study municipalities. Delayed land consolidation, the prohibition of the reconstruction of old stables for use as summer residences, regulations concerning animal welfare which discouraged farmers to invest in new stables, and the prohibition of free grazing are such policy measures. These factors led to tenure insecurities, increased cultivation costs or prevented higher benefits from the alternative use of marginal land. An influence of policy factors on agricultural land-use changes, has also been found in other European countries. Petretti (1996) investigated structural changes in agriculture in an Alpine region (Valle d' Aosta) in northern Italy. He points out that regional laws (in compliance with EU regulations) impose hygiene and sanitary standards which are unlikely to be easily satisfied by most alps both for cheesemaking and agritourism. Although the regional government lent money with good loan conditions, farmers still avoid financial investments for improvements. Petretti (1996) explains this by the high lease prices of alp rights and wages for seasonal workers, the bad conditions of alp buildings and high costs of maintenance of paths and the system of ditches needed to disperse slurry on the meadows. In southern Portugal, a significant proportion of the land currently under cereal cultivation was converted from grassland and forest during the 1930s as the result of very high cereal prices and market protection under the 'wheat campaign' for self sufficiency (Baldock et al., 1996). The lower prices of the EU, combined with the effects of the internal market, have made many of these areas now appear highly marginal for cereal cultivation. In Finland, many farmers converted their agricultural land to forest during the last decades because the government financially supported reforestation (Selby, 1996). Beaufoy (1996) showed that the payments from the common agricultural policy (CAP) prevented farm abandonment and the abandonment of marginal land in the Extremadura (eastern central Spain). CAP payments even resulted in much of the land that lay fallow in the 1960s and 1970s (the period prior CAP payments) being brought into production in the 1980s and 1990s (the period of CAP payments). More drastic affects of changing policies are documented for many of the EU's new members. In the Baltic countries, Estonia, Latvia and Lithuania, between 10% and 21% of the agricultural land was categorised as abandoned in 1999 and 2002, respectively. In these countries, many farmers were confronted with considerable structural problems (small farm sizes, scattered land parcels) caused by the breakup of large collective or state farms in the post socialist era from the beginning of the 1990s onwards (DLG, 2005; Nikodemus et al., 2005).

Contrary to the policy factors that enhanced forest re-growth in the case study municipalities, a variety of factors on the level of individual landowners and farms were found to slow down natural forest re-growth. Examples are aged farmers who retain traditional farming practices because they have no alternatives to work off the farm (Eggiwil), farmers who brought already overgrown land into cultivation and use low cost cultivation forms such as deer and horse pasturing (Blitzingen), farmers that maintain the cultivation of marginal land because they require the land in order to not exceed the prescribed number of livestock per hectare (Soazza), or landowners and farmers which maintain the cultivation of marginal land because farming is a hobby or the land is used for residential purposes (Soazza, Blitzingen). These factors and cultivation forms reduce management costs, enlarge benefits or describe non-profit oriented behaviour.

In summary, the results of the mountain area wide studies and case studies confirm the hypothesis that natural forest re-growth can be attributed to indicators of the increasing opportunity costs of agricultural labour, i.e. farm labour migration and shortages and the switch over from labour intensive to labour extensive cultivation forms. Results also confirm the hypothesis that individuals acted systematically and compared costs and benefits when deciding to maintain or abandon the cultivation of marginal agricultural land and allow natural forest re-growth to occur.

6.3 Practical relevance of findings

In Switzerland, agricultural support measures could not compensate for all of the disadvantages related to the cultivation of marginal land resulting in land abandonment and forest re-growth. This has been recognised by decision makers. The canton of Grisons, for example, has recently begun to financially support the removal of scrub from pastures. The findings of this thesis may assist decision makers in the canton of Grisons and other Swiss cantons in the formulation of regionally adapted agricultural support measures to prevent agricultural land abandonment, natural forest re-growth and the related consequences for the environment.

No relationship between emigration, land abandonment and forest re-growth was found in the Swiss mountains. This finding is important because rural depopulation is regarded as one of the main reasons of agricultural land abandonment and natural forest re-growth in European mountain regions (e.g. MacDonald et al., 2000). It shows that understanding the processes leading to land abandonment and forest re-growth requires a more holistic view, which this thesis provides.

Results show that forest re-growth occurred more frequently where farm abandonment rates were high. This finding is of importance, as it shows that agricultural land abandonment and forest re-growth can, at least partially, be prevented by the prevention of farm abandonment. However, results also show that natural forest re-growth occurred primarily where the majority of farms were managed on a part-time basis. This indicates that the prevention of farm abandonment alone is not sufficient to prevent land abandonment and natural forest re-growth. It suggests that more incentives for part-time and hobby farmers should be provided to ensure that the cultivation of marginal agricultural land is maintained.

Agricultural land is primarily abandoned and overgrown in the southern regions of the Swiss mountains. These regions are predestined for the 'encouragement' of natural forest re-growth, e.g. through the establishment of new 'wilderness areas' as in the Val Grande National Park in northern Italy (Höchtl et al., 2005) and the Oostvaardersplassen in the Netherlands (Baldock et al., 1996). Such measures can help to save on agricultural subsidies and might offer opportunities for an alternative use of marginal agricultural land, e.g. in the form of wildlife reserves. The results of this thesis can support decision makers that aim to delineate areas that are suitable (or less suitable) for the establishment of new wilderness areas.

Decision makers might be interested in the question of how much of the agricultural land will revert to forest in the near future, where it will occur and what will be the consequences for the environment. For example, the incidence of many endangered species directly depend on the availability of semi-natural habitats (DLG, 2005; Graf et al., 2006). Natural forest re-growth alters these habitats, which may lead to negative consequences for the abundance of these species (Baldock et al., 1996; MacDonald et al., 2000; Anthelme et al., 2001; Sickel et al., 2004). The findings of this thesis provide the basis for scenario models. These models can be used to simulate future forest re-growth and assess its consequences for the environment.

6.4 Strengths and limitations of approaches

Compared to previous Swiss studies on agricultural land abandonment and forest re-growth, the approaches used in this thesis have a variety of strengths. These are listed below.

Strengths:

1. Previous Swiss studies on the patterns and causes of agricultural land abandonment and natural forest re-growth are solely based on smaller case studies (see studies by Surber et al., 1973 and Walther, 1984). This thesis investigated the patterns and causes of natural forest re-growth in the entire Swiss mountain area, and provide insights into the patterns and processes of natural forest re-growth that go beyond the insights of small-scaled case studies.

2. In the former Swiss studies conducted by Surber et al. (1973) and Walther (1986), non-statistical methods were used to investigate the patterns and causes of land abandonment and/or forest re-growth. These studies could not be used for statistical hypothesis testing. On the contrary, the spatially explicit models developed in this thesis allowed for the testing of statistical hypotheses.

3. One of the main challenges in land-use/land-cover change research is the integration of both geo-physical and socio-economic explanatory variables into a single spatial statistical model (Liverman et al., 1998; Walsh et al., 1999; Irwin & Geoghegan, 2001; Walsh & Crews-Meyer, 2002). An aspect of the challenge is that geo-physical data and socio-economic data are often only available at different spatial scales. In this thesis, data were either aggregated to a common spatial scale or binary (0/1) dummy variables or robust estimation methods

were used. This allowed the integration of both geo-physical and socio-economic variables into statistical models. New insights into the determinants of natural forest re-growth were obtained in this way.

4. Another challenge in land-use/land-cover change research is to link peoples to the land and develop models at decision relevant levels so that the behaviour of individuals can be studied meaningfully in relation to changes in land-use/land-cover types. An aspect of the challenge is that individuals and households are often remote in space from the land making it difficult to link data from these levels to the observed land-use/land-cover changes. In this thesis, suggestions by Wood & Skole (1998) were followed and models and interviews combined (see Paper D). This revealed the individuals' motives to abandon or maintain the cultivation of marginal agricultural land and allow forest re-growth to occur. An advantage of this approach compared to pure interview approaches is that models provide further information about the influence of single geo-physical factors on natural forest re-growth. An advantage of this compared to approaches in which data from interviews are included in statistical models (in particular when interviews are conducted over large areas) is that it is less time and money consuming. The combination of models with interviews also allowed the investigation of model misspecifications and potential spurious associations. The latter is often neglected or only 'remotely' discussed, for example by means of predicted probability or residual maps (e.g. Geoghegan et al., 2001; Munroe et al., 2002; McDonald & Urban, 2006).

5. Patterns and processes of land-use/land-cover changes are often investigated at only one spatial scale (e.g. Serneels & Lambin, 2001; Müller & Zeller, 2002; Perz & Skole, 2003; Kobler et al., 2005). In this thesis, studies at different spatial and temporal scales were conducted. Results of these studies complement each other and provide a 'sound picture' of the patterns and causes of natural forest re-growth in the Swiss mountain area.

6. Although recommended for theoretical reasons (see Anselin, 2002) neighbourhood effects are rarely considered in land-use/land-cover change research (for exceptions see Pfaff, 1999; Geoghegan et al., 2001; Perz & Skole, 2003; Verburg et al., 2004a). In this thesis, neighbourhood variables were included in the statistical models (see Paper A and C). Results suggest an influence of neighbourhood effects and allow the extension of the current discussion on the determinants of agricultural land abandonment and natural forest re-growth in the Swiss mountains.

Along with the strengths of the approaches used in this thesis, there are also some limitations. These are listed below.

Limitations:

1. Due to the lack of adequate data, proxy variables for costs and benefits were used to examine the patterns of natural forest re-growth. The use of proxy variables is a common practice in land-use/land-cover change research (e.g. Chomitz & Gray, 1996; Geoghegan et al., 2001; Serneels & Lambin, 2001; Müller & Zeller, 2002; Kobler et al., 2005). The disadvantage of proxy variables, however, is that they are (or are not) representative for the unobserved cultivation costs and benefits of agricultural land. For example, in the case study municipalities, some of the 'non-mainstream' farmers compensated the high cultivation costs of steep slopes by low cost cultivation forms such as deer and horse pasturing. This enabled these farmers to cultivate land that is economically unviable for the professional farmers. The models were not able to correctly predict the maintenance of cultivation in these areas, because information about extensive pasturing was not available for spatial statistical modelling. This shows that the use of proxy variables can only be a compromise if information about the cultivation costs and benefits of agricultural land is not available. If such information is available, it should be used rather than proxy variables to explain land-use/land-cover changes.

2. In the mountain area wide studies (see Papers A, B and C), most socio-economic variables were only available at the municipality-level. Individual level factors (e.g. age and education of farmers) or farm household-level factors (e.g. off-farm employment, degree of mechanisation), that are likely to have affected forest re-growth, could not be considered in the statistical analyses. The comparably poor fits of the models based on disaggregated land-use change data (see Papers B and C) are most likely the result of these unobserved factors at the individual landowner and farm household level. Model fits could be improved by including additional explanatory variables derived from mountain area wide interviews with farmers.

3. Correlations found between variables were assumed to reflect 'true' causality. However, in some cases, unmeasured factors - which are not included in the model, but correlated with the variables in the model - might be the 'true' determinants of land abandonment and forest re-growth. This discrepancy is also referred to as 'spurious association' (Wood & Skole, 1998). Due to the lack of adequate data, mountain area wide models could not be checked for spurious associations. This could only be investigated in the case studies (see Paper D). To check for potential spurious associations in the mountain area wide models, additional investigations in the field would be necessary. This could be done by means of interviews.

4. Unknown time lags exist between the socio-economic causes of land abandonment, effective land abandonment and 'observable' land abandonment, i.e. natural forest re-growth.

Similar time lags have been found by Perz & Skole (2003). The existence of such time lags make the choice of appropriate socio-economic explanatory variables difficult. For example, in the mountain area wide studies, it was not clear which period was authoritative for the abandonment of land leading to forest re-growth in the period between the 1980s and 1990s, and the socio-economic variables were used to explain the patterns of forest re-growth in this period (see Papers A, B and C). To account for these time lags, suggestions by Rudel et al. (2000), Müller & Zeller (2002) and Perz & Skole (2003) were followed and socio-economic variables evaluated in the time before forest re-growth occurred used in the statistical models. In addition, changes of agricultural structures and population were calculated for large time periods (i.e. between 1939 and 1985, 1950 and 1985, 1930 and 1990). However, because time lags are unknown, there is still uncertainty in regard to the time period which was authoritative for the abandonment of land leading to natural forest re-growth between the 1980s and 1990s.

5. Due to the lack of adequate data, the basic mechanism behind neighbourhood effects could not be investigated in this thesis. This would require additional investigations in the field. Interviews with farmers in the entire Swiss mountain area could be used to investigate the existence of human driven neighbourhood effects. Another approach to investigate neighbourhood effects are agent based models (see section 2.3.3).

6. This thesis investigated forest re-growth on land that was totally or partially under agricultural cultivation. It should be noted that there are other areas in which natural forest re-growth has occurred. Examples include forest re-growth on bare land and in urban areas (see Figure 1.2). Investigations of the patterns of forest re-growth on non-agricultural land were not within the scope of this thesis. However, the patterns and causes of forest re-growth on land used for purposes other than agriculture might also be of interest for researchers and decision makers (see Surber et al., 1973). Similar modelling approaches as used in this thesis could be used to investigate the pattern of forest re-growth on non-agricultural land.

6.5 Future forest re-growth

Future predictions of land-use/land-cover changes are difficult. This is because the influence of economic development, changing prices and policies on land-use is not clear. That future predictions are difficult can be shown by Surber et al. (1973). On the basis of case studies conducted in the 1970s, they predicted 260 000 ha of fallow land[2] in Switzerland at the end of the 20th century. From the recent Swiss land-use statistics (SFSO, 2005) it is known that the quantity of fallow land

[2]For comparison, alpine pastures in Switzerland cover an area of 537 801 ha (SFSO, 2001).

was clearly overestimated. The explanation is that Swiss agricultural politics have introduced a variety of support measures during the last decades (Rieder, 1996). Some of these measures could not be considered by Surber and colleagues because they were introduced in the period after their study.

Keeping in mind that unknown socio-economic factors exists which may either enhance or slow down natural forest re-growth in the future, some cautious predictions can be made from the results of this thesis. Below are characteristics of areas in which future forest re-growth is expected.

1.) Future forest re-growth is expected in regions/municipalities with a high quantity of marginal agricultural land below the climatological treeline. In the southern parts of the Swiss mountain region such as the canton of Ticino, the proportion of agricultural land is low as is the proportion of marginal land below the treeline that can revert to forest (SFSO, 2005). On the contrary, many regions in the Alps and Pre-Alps (e.g. in the Canton of Valais and Canton of Grisons) have relatively high proportions of marginal land below the treeline. It is likely that much of the pastureland in these regions will revert to forest in the near future.

2.) Future forest re-growth is expected in areas with steep slopes, low temperature sums, stony and/or shallow soils and that are not directly accessible by roads. In particularly land which cannot be cultivated by machines and that is not suitable for pasturing (too small, no watering places for livestock) is vulnerable to future forest re-growth.

3.) Future forest re-growth is expected to occur less frequently in areas close to the treeline and where slopes are very steep and soils very shallow and/or stony. This is because the growth dynamics of trees and bushes are limited in these areas (due to snow avalanches, lower water holding capacity of soils, soil erosions, etc.) and sheep pasturing is common there which slows down forest re-growth.

4.) Low intensively used land close to forest edges that is partially overgrown by trees, bushes and scrub such as land with grass and scrub vegetation, bushy alpine pastures and agricultural land with groups of trees is vulnerable to future forest re-growth. This is because areas close to forest edges are often unfavorable for agricultural production (due to tree shade, poor and stony soils, steep slopes) and bushes, trees and scrub provide seed sources for new bushes, trees and scrub, which may enhance forest re-growth.

5.) Future forest re-growth is expected in municipalities in which the majority of farms is managed on a part-time basis and farm labour migration continues. Figure 4.4 in section 4.1 shows in which municipalities part-time farming dominated in the mid 1980s. These municipalities were and are vulnerable to future forest re-growth.

6.) Regions in which the majority of farms are managed on a full-time basis, where many farms have reached their maximum size and farm abandonment continues are vulnerable to future forest re-growth. This is because remaining farms often have not enough farm labour to cultivate the land which is set free by the abandoned farms. In these regions it is likely that land abandonment and forest re-growth continue. The Mid-Grisons in the eastern central part of the Swiss mountain region is such a region.

7.) Municipalities with a high proportion of poorly accessible alpine pastures managed by older farmers are vulnerable to future forest re-growth. This is because the traditional pasturing form used by these farmers, i.e. to stay with the livestock over summer and process milk on-site is labour intensive and provides comparably low income. The incentives for younger farmers to manage alpine pastures is low, which will lead to the abandonment of alpine pastures and natural forest re-growth.

CHAPTER 7

Conclusions and outlook

7.1 Conclusions

This thesis investigated the patterns and causes of natural forest re-growth on agricultural land in the Swiss mountains based on spatial statistical models and interviews. The land rent theories of David Ricardo and Johann Heinrich von Thünen provided the theoretical framework to explain individuals' land-use decisions, agricultural land abandonment and the pattern of natural forest re-growth. Results confirm the expected patterns as they show that forest re-growth occurred primarily where slopes were steep and/or north exposed, soils were shallow and/or stony, temperatures were low, land was located close to forest edges, and (as shown in the regional-scale study and case studies) road infrastructure was less developed and land was not directly accessible by roads. Results are in keeping with the land rent theories of David Ricardo and Johann Heinrich von Thünen, as they show that the quality of the land in terms of its agro-climatic and topographic conditions and quality of soils (Ricardian ideas) and the accessibility of the land (von Thünian ideas) are factors that determined land abandonment and natural forest re-growth. It is concluded that decision makers should pay more attention to the agro-climatic and topographic conditions, quality of soils and accessibility of the land, when designing measures to support or prevent natural forest regrowth and its consequences for the environment.

Some findings of this thesis are new or were unexpected. Unexpected was the non-linearity in the pattern of forest re-growth. On the regional scale, nonlinearity indicates that natural forest re-growth did not occur until regional cultivation conditions were extremely unfavorable. On the disaggregated scale, non-linearity indicates that forest re-growth occurred more frequently in areas showing neither favorable nor extremely unfavorable cultivation conditions and less frequently where cultivation costs were low, i.e. on meadows and arable land close to the valley bottom and alpine pastures approaching the treeline. Results indicate that the current considerations of these non-linearities by agricultural politics (e.g. by the progressively graded subsidies for the cultivation of steep slopes) are not entirely successful in preventing natural forest re-growth. From this it is concluded that decision makers should pay more attention to the non-linearity in the pattern of forest re-growth when designing measures to support or prevent forest regrowth and its consequences for the environment.

Depending on the spatial scale of the analysis, different results were obtained in regard to the influence on forest re-growth of the accessibility of the land by roads. The regional-scale study shows that regions with underdeveloped road infrastructure were favoured in terms of forest re-growth, which was as expected. Interviews revealed that land that was not directly accessible by roads was more frequently abandoned and overgrown than land that was directly accessible. This was also as expected. On the contrary, the two mountain area wide studies show that forest re-growth occurred more frequently closer to roads. This unexpected result was explained by a few extreme values influencing the results of statistical models, the different accessibility requirements of meadows and arable land and alpine pastures and the limiting growth conditions of trees and bushes on alpine pastures approaching the treeline, i.e. remote from roads. It is concluded that decision makers should ensure that meadows and arable farmland are directly accessible by roads to avoid land abandonment and natural forest re-growth. Although of lesser importance for the maintenance of cultivation, the direct accessibility of alpine pastures also could retard forest re-growth. This is because extensive pasturing only partially compensates for the high accessibility costs of these areas.

New findings of this thesis are that forest re-growth occurred primarily where the majority of farms were managed on a part-time basis and farm labour migration was high. From this it is concluded that forest re-growth is the result of decreasing agricultural incomes and increasing opportunity costs of agricultural labour. From an economic viewpoint, in regions in which part-time farming is common and farm labour migration is high, more financial incentives to maintain the cultivation of marginal land should be provided. This is because part-time farmers generally have higher opportunity costs of farm labour than full-time farmers and do not rely on the cultivation of marginal agricultural land. Another new finding is that forest re-growth occurred independently from emigration. This is contrary to what has been found in other European mountain regions (e.g. MacDonald et al., 2000). It confirms the complexity of the relationships between population change and forest re-growth in Switzerland discussed by Mather & Fairbairn (2000). It is concluded that designing political measures to react to land abandonment and forest re-growth requires a more holistic view on the processes of land abandonment and forest re-growth, which this thesis provides.

Depending on the spatial scale of the analysis, studies show contradictory results in regard to the influence of off-farm job opportunities on forest re-growth. The regional-scale study suggests that forest re-growth occurred more frequently in regions where strong labour markets existed or were easily accessible. This was as expected, although it was not a general trend in the Swiss mountain area. On the contrary, the disaggregated-scale studies suggest that forest re-growth occurred more frequently where labour markets were weak. This was unexpected. Overall, this suggests a local influence of off-farm job opportunities on natural forest re-growth. Decision makers should consider this local influence of off-farm job opportunities when designing measures to prevent or support forest re-growth and its consequences for the environment.

Case studies were conducted in order to complement the mountain area wide studies and investigate the local patterns and causes of forest re-growth and individuals' motives to abandon or maintain the cultivation of marginal land and allow natural forest re-growth to occur. Results confirm the study hypothesis as they show that natural forest re-growth can be related to indicators of the increasing opportunity costs of agricultural labour such as farm labour migration and shortages, and the switch over from labour intensive to labour extensive cultivation forms. Results also confirmed the hypothesis that individuals balanced costs and benefits when they decided to abandon or maintain the cultivation of marginal agricultural land. A few main factors (e.g. steepness and aspect of slopes) and a variety of locally-specific factors (e.g. old stonewalls, wet soils, stony ground, small trenches) enhanced forest re-growth. Forest re-growth was also enhanced by locally-specific agricultural structures in combination with changing policy factors such as delayed land consolidations, prohibition of the modification of old stables for use as summer residences, regulations concerning animal, and the prohibition of free grazing. These factors increased cultivation costs, decreased benefits or discouraged farmers from investing in new stables and machines. On the contrary, a variety of factors at the individual landowner and farm household level retarded forest re-growth. Examples are: aged farmers who retain traditional farming practices, farmers which use extensive pasturing with deers and horses, farmers which maintain the cultivation of marginal land in order to not exceed the prescribed number of livestock per hectare, or farmers which use agriculture as a hobby or old stables and the surrounding land for residential purposes. These factors reduced cultivation costs, increased benefits or describe non-profit oriented behaviour.

Overall findings from case studies confirm the findings of the mountain area wide studies in that they show that many locally-specific factors exist that influenced landowners in their decisions to abandon or maintain the cultivation of marginal land and allow forest re-growth to occur. From this it it concluded that the present policy measures are not suitable to prevent forest re-growth and its consequences for the environment. This is because present policy measures do not consider the specific local determinants of forest re-growth including the motivation of individuals to maintain or abandon the cultivation of marginal land and allow forest re-growth to occur. Recent policy measures focus on the support of agricultural production and income rather than on the maintenance of the cultivation of marginal land. If the prevention of forest re-growth is the announced aim of agricultural policy, then policy measures should focus on that specific objective, e.g. by establishing financial incentives to maintain marginal land with a high biodiversity. Furthermore, if the aim of agricultural, regional and/or environmental politics is to prevent forest re-growth and its consequences for the environment, more financial incentives for the cultivation of alpine pastures should be provided.

7.2 Outlook

Investigations and findings of this thesis raised a variety of further questions. Further studies have been conducted, are in progress or planned in order to answer some of these questions. The following two sections provide an overview about current research on natural forest re-growth as well as suggestions for further research.

7.2.1 Current research on natural forest re-growth

Decision makers might be interested in the question how much of the agricultural land will revert to forest in the near future and where it will occur. To answer these questions Rickebusch et al. (forthcoming) developed probabilistic land-use change models and combined these models with forest dynamics models. In this study, the probability of land-abandonment was expressed by a logistic regression equation and is a function of degree-day sum, distance to forest edge, soil stoniness, slope, proportion of employees in the secondary and tertiary sectors, proportion of commuters and proportion of full-time farms. This model was implemented in the TreeMig forest model (Lischke et al., in press) by assigning the simulation grid cells to one of three categories: ”forest” (in which forest dynamics can be simulated), ”agriculture” (which can turn into forest according to the output of the abandonment model) or ”other” (unsuitable for forest growth). The new model was first tested on a series of theoretical landscapes with different values for the variables in the land-abandonment model. This showed that distance to forest edges and slope have a strong influence on the probability of land abandonment and forest re-growth. Degree-day sum has a more complex role, with contradicting influences on land-abandonment and forest growth.

The new model was applied to a case study area in the Upper Engadine (Swiss Alps), along with two different modelling approaches: natural succession only and a constant probability of abandonment for all ”agriculture” grid cells, based on past transition proportions (2.1% in that area). The former showed new forest growing in all but the highest-altitude locations. The latter was more realistic in terms of numbers of reforested cells, however their location was random and the resulting landscape very heterogeneous. The new model based on the logistic regression equation gave results consistent with observed patterns of land-abandonment, namely: expansion of existing forests and the closure of gaps, leading to an increasingly homogeneous landscape.

As could be shown in this thesis, no relationships between emigration and forest re-growth exists in the Swiss mountains. This finding contrasts with findings in other European countries, where both immigration and emigration has been related to land abandonment and forest re-growth (e.g. MacDonald et al., 2000; Kozak, 2003; Romero-Calcerrada & Perry, 2004). To shed further light on the influence of population change on agricultural land-use change and natural forest re-growth, further investigations are in progress. In order to do so international literature is reviewed and land-use and population change data from different European countries are examined.

7.2.2 Suggestions for further research

The research presented in this thesis could be extended to other Alpine countries such as Italy, Austria, Germany, and Slovenia. The objective of such a study could be to show how similarities and differences in the patterns of forest re-growth can be explained by different topographic, soil and agro-climatic conditions and different agricultural support measures and regulations. A challenge in such a study would be to make the data from different sources and at different spatial and temporal resolutions compatible.

As showed in this thesis, neighbourhood effects are of importance in explaining natural forest re-growth. Due to the lack of adequate data, the basic mechanism behind neighbourhood effects could not be investigated in this thesis. One possible approach to investigate neighbourhood effects are agent based models (see section 2.3.3). In an agent based model, similar patterns of land-use changes on neighbouring land/in neighbouring regions could be explained as the result of interacting farmers. In such as model, different agents must be defined. Land owners and tenants, including farmers who decide about land-use in pre-defined areas, as well as planners and policy makers who set the legal framework for land management are typical spatial agents. The agent-based model on the level of the individual farm established for regional land use modelling in the Swiss Alps by Lauber et al. (2006) could provide a valuable basis to investigate the influence of neighbourhood effects on agricultural land abandonment and natural forest re-growth.

Due to the lack of adequate data, the direct influence of the opportunity costs of agricultural land and labour on farmers' land-use decisions could not be investigated in this thesis. Only proxy variables could be used to test this influence. Also the existing literature provides little work on this topic (for exceptions see Rudel et al., 2000; Strijker, 2005). An influence of the opportunity costs of agricultural labour on the land-use decision could be investigated by means of interviews. Data about the age, health, education, relative income of farmers and non-farmers and off-farm income opportunities would be required for such an analysis.

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