Agricultural land abandonment and natural forest re-growth in the Swiss mountains: A spatially explicit economic analysis

Mario Gellrich a,*, Priska Baur a,1, Barbara Koch b,2, Niklaus E. Zimmermann a,3

a Swiss Federal Institute for Forest, Snow and Landscape Research WSL, Zuercherstrasse 111, CH-8903 Birmensdorf, Switzerland
b Department of Remote Sensing and Landscape Information Systems, University of Freiburg, Tennenbacher Strasse. 4, D-79106 Freiburg, Germany

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Abstract

Natural forest re-growth reflects a decline in traditional agricultural practices that can be observed worldwide. Over the last few decades, natural forest re-growth has replaced much of the agricultural land in the Swiss mountains. This is a region where forms of traditional cultivation have preserved unique landscapes and habitats of high ecological value. This study aimed to characterise the locations in the Swiss mountains where agricultural land has been abandoned and overgrown by trees and bushes. Therefore, multivariate statistical models based on geo-physical and socio-economic variables were developed. Land-use change data were taken from two nationwide land-use surveys carried out in the 1980s and 1990s. In order to obtain reliable models, neighbourhood effects and the group structure in our data were accounted for. For the latter a robust estimation technique known as cluster-adjustment was used.

Results show that forest re-growth is largely restricted to former alpine pastures, land with grass and scrub vegetation and agricultural land with groups of trees at mid to high altitudes, steep slopes, stony ground and a low temperature sum. Some relationships were not as expected, e.g. many of the new forest areas were found to be relatively close to roads. A new finding from this study was that forest re-growth is largely restricted to regions with immigration, higher proportions of part-time farms as opposed to full-time farms and high farm abandonment rates. By accounting for neighbourhood effects, the model fit was improved. The considerable residual deviance of the 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 the individual’s motivation to abandon or maintain cultivation. The conclusion made was that general policy measures for the whole mountain area are not suitable for the prevention of land abandonment and forest re-growth, and that policy measures must pay more attention to local characteristics and needs.

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1. Introduction

Natural forest re-growth reflects a decline in traditional agricultural practices that can be observed worldwide (Baldock et al., 1996; Rudel et al., 2000; MacDonald et al., 2000; Müller and Zeller, 2002; DLG, 2005). In many European countries, this trend is not new. Considerable forest re-growth rates are documented for the period after the Black Death in the Middle Ages, for the industrialisation period at the beginning and middle of the 19th century as well as for the post World War II period (Baldock et al., 1996; Selby et al., 1996; Mather, 2001; Van Hoof et al., in press). In many of the EU’s new members, such as the Baltic countries, forest re-growth 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).

In Western Europe, it is often the case with infrequently used pastureland and land with steep slopes, poor soils or underdeveloped road infrastructure, which is abandoned and
left to become overgrown by trees and bushes (Douguédroit, 1981; Walther, 1986; MacDonald et al., 2000; Kozak, 2003; Romero-Calcerrada and Perry, 2004; Kobler et al., 2005; DLG, 2005). Often ‘marginalisation’ of agricultural land is responsible for this. This is a process characterised by a step-by-step reduction of the intensity of land-use per unit of land (Baldocek et al., 1996). The degree of this specific form of extensification is often determined by location-specific social, economic, political and environmental conditions (Baldocek et al., 1996; MacDonald et al., 2000).

Land abandonment and forest re-growth are related to a variety of environmental consequences. 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), the long-term loss of species-rich habitats (Anthelme et al., 2001) and the higher probability of wild-fires (Romero-Calcerrada and Perry, 2004). Due to these consequences, land abandonment and forest re-growth are of importance in the recent political discussion in many European countries (Baldocek et al., 1996; MacDonald et al., 2000; DLG, 2005).

In Switzerland, considerable land abandonment and forest re-growth rates have been observed since the mid 19th century (Mather and Fairbairn, 2000). Conservative estimates are that the forest area has increased by one third during the last 150 years (Brändli, 2000). Thereby, the largest part of the new forest area can be attributed to the natural forest re-growth on abandoned agricultural land (Surber et al., 1973; Walther, 1986; Mather and Fairbairn, 2000). Income differences between farm and non-farm jobs, the inability to modernise land-use and road infrastructure developments have been identified as important drivers of changing land-use intensity, land abandonment and forest re-growth in earlier case studies (Surber et al., 1973; Walther, 1986; Pezzatti, 2001). The replacement of agricultural land by forests is of increasing concern in the Swiss mountains because traditional cultivation forms have preserved unique landscapes and habitats of high ecological value (Hunziker, 1995). The recent extent of forest re-growth is shown by the Swiss land-use statistics: over a 12-year period during the 1980s and 1990s the wooded area increased by 17,000 ha or 1.4%. Thereby, with 87% of the newly wooded areas, it was natural re-growth of trees and bushes that had occurred (SFSO, 2001).

To date, empirical studies on land abandonment and forest re-growth in Switzerland are rare and exist solely in the form of smaller case studies (see studies by Surber et al., 1973; Walther, 1986). Thus, knowledge about the processes and patterns of land abandonment and forest re-growth is limited. This study aimed to characterise the locations in the Swiss mountain region where agricultural land has been abandoned and overgrown by trees and bushes. The characteristics of the locations where land-use changes have occurred are typically referred to as the “spatial pattern of land-use change” (Pontius et al., 2001). According to Rudel et al. (2000) and Kobler et al. (2005), natural forest regrowth was used as an indicator of changing agricultural practises. Our focal interest was to identify the pattern of natural forest re-growth over different agricultural production systems. The main hypothesis was that land where cultivation costs were not covered by the yields was favoured in terms of land abandonment and forest re-growth.

To prove this hypothesis, multivariate statistical models were developed on the basis of mountain-wide land-use change data and selected geophysical and socio-economic variables.

2. Theoretical framework

In this study, natural forest re-growth indicates agricultural land-use change. Understanding land-use change requires understanding of the factors influencing land-use decisions (Irwin and Geoghegan, 2001). To gain understanding, an economic framework was developed. The theory used to explain land abandonment and forest regrowth, is based on economic models of human behaviour. Similar concepts were recently applied to explain deforestation in developing countries (e.g. Chomitz and Gray, 1996), agricultural land-use conversion (e.g. Serneels and Lambin, 2001) and residential land-use development (e.g. Irwin and Geoghegan, 2001). The theoretical concept underlying these studies focuses on the economy of individual parcels. According to the definitions used by Nelson and Geoghegan (2002), the land-use decision at each parcel is made by an “operator”, who may be “a single person, household or group of people in the case of common property ownership”. Economic theory is generally based on the assumption of rational choice, i.e. the operator makes the land-use decision by comparing costs and benefits of alternative land uses. The land-use option maximising the utility is then selected. If it is assumed that a given land-use has a single marketed product, the net present value of the return to that land-use, its net present rent \(_{n,T}\) at time \(T\), can be expressed according to Chomitz and Gray (1996) as:

\[
R_{n,T} = \int_{t=0}^{\infty} (P_{hT+t} Q_{hT+t} - C_{hT+t} V_{hT+t}) e^{-i t} \, dt, \tag{1}
\]

where \(P\) is the output price, \(Q\) the quantity of output, \(C\) a vector of input costs, \(V\) a vector of inputs and \(i\) is the location-specific discount rate all for each land-use \(h\) at location \(l\) at time \(t\). By equating utility and profit maximisation, it follows that the land-use chosen by the operator has the highest \(R_{n,T}\).

In this study, it was assumed that the operator decides between two distinct choices of land-use: (i) maintenance of agricultural land-use and (ii) discontinuation of agricultural land-use (without alternative use). Furthermore, it was assumed that profit maximisation is replaced by loss...
minimisation. The cultivation is stopped, if the operator identifies $R_{hlT}$ to be negative. The latter is a simplification, because each operator may have individual thresholds for $R_{hlT}$ that can be equal or greater than zero. The main reason why a landowner would be expected to stop cultivating a parcel only if returns are negative is due to the persistence of traditional cultivation. This means that cultivation will not be abandoned until cultivation costs lead to substantial financial losses (see Strijker, 2005). The underlying response function is expressed through:

$$R_{hlT} = \alpha + \beta_k X_k + u_k,$$

where $\alpha$ is a constant term, $X_k$ a vector of covariates, $\beta_k$ a vector of coefficients to be estimated and $u_k$ are the associated random disturbance terms. In Eq. (2), the $X_k$ are representations either of $P \times Q$ or $C \times V$ as given in Eq. (1). In our study, $R_{hlT}$ was not directly observable since the land-use at parcel $l$ was determined by means of aerial photographs. Thus, forest re-growth was assumed to be an indicator of the negative returns of a parcel. Likewise, if forest re-growth did not occur, this was interpreted as an indication that cultivation was continued because the returns were not negative. Therefore, a dummy variable $R_{hlT}^{*}$ was introduced:

$$R_{hlT}^{*} = \begin{cases} 1 & \text{if } R_{hlT} < 0 \\ 0 & \text{otherwise} \end{cases}$$

Forest re-growth has thus occurred on any given parcel, if $R_{hlT}^{*}$ takes the value 1, otherwise it was assumed that cultivation was continued. To empirically estimate the terms in Eq. (2), the distribution function for the error terms must be selected (Bockstael, 1996). If it is assumed that the cumulative distribution function of the errors follows a logistic distribution, then the probability that a specific parcel of land will convert to forest can be calculated by using logistic regression. This can be expressed through (Maddala, 2001):

$$P(R_{hlT}^{*} = 1) = \frac{\exp(\alpha + \beta_k X_k)}{1 + \exp(\alpha + \beta_k X_k)},$$

where the term on the left-hand side is the probability that an agricultural area will convert to forest and $\alpha$, $X_k$ and $\beta_k$ are as defined above.

3. Methods

3.1. Study area

The study area (Fig. 1) is situated in the Swiss mountains as delineated by the “Act on Investment Aid for Mountain Regions” (=IHG, Wachter, 2002). For this study, the municipality of Davos and eleven additional municipalities in the Oberengadin (Eastern Central Alps) were added to the study region, although they were not listed as IHG-regions. The study area (2813 km$^2$) covers 68% of the total area of Switzerland and is inhabited by 24% of the Swiss population (base 2000).

The economic and agricultural structures differ widely within the study area, although in general follow a north–
south gradient. In the southern parts, tourism is very important. In an agriculture sense, small-scale ownership structures and part-time farming dominate (Surber et al., 1973). In the canton of Jura and in the northern parts of our study area, tourism is less important but the accessibility of urban centres is often better and agriculture is characterised by larger farms and a higher proportion of full-time farms. 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). Agriculture is mostly characterised by grassland cultivation. Three seasonal cultivation types can be distinguished: (i) hay meadows in the valleys, (ii) mountain pastures, which are grazed in spring and autumn and (iii) alpine pastures that are grazed during summer (Netting, 1972). Cattle, sheep and goats are the most common livestock.

Our study object was natural forest re-growth on abandoned agricultural land, although this cannot occur above the treeline. Thus, areas above the treeline were masked out. Since an exact measure of the climatological treeline was not available for this study, the potential treeline was used as delineated in the distribution atlas of vascular plants (Sutter and Welten, 1982). A validation exercise revealed that considerable new forest areas were located above this demarcation line. Thus, this line was modified by applying a buffer of 300 m (vertical distance on the digital elevation model). Above this demarcation line, only a very small fraction of new forest areas were found. These areas of forest re-growth were excluded from the analysis, as well as any areas located above the demarcation line and areas within refuges and wetlands. The spatial pattern of natural forest re-growth in the study area is illustrated in Fig. 1.

3.2. Derivation of the response variable

The response variable used in the statistical models refers to the presence or absence of agricultural land abandonment as indicated by natural forest re-growth and was calculated according to our economic framework (see Eq. (3)). Since spatially explicit information about land-use on the single parcel level was not available, land-use data available from the Swiss land-use statistics (ASCH) was used. The ASCH is a nationwide aerial photography based statistic providing two comparable datasets for the years 1979/85 and 1992/97 (also referred to as ASCH85 and ASCH97). The years indicate the evaluation time span of aerial photographs (SFSO, 2001). In both surveys, 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 × 50 m) centred on the grid point. Changes in land-use between both surveys can be analysed through comparison of the land-use category assigned to grid points in ASCH85 and ASCH97.

The ASCH provides several land-use categories for forest and agriculture. Other ASCH land-use categories represent transition states between forest and agriculture. Since preliminary investigations showed that many of the new forest areas have their origin in these transitional land-use categories, definitions of ‘agriculture’ and ‘forest’ pre-defined by ASCH were extend. The definition in this study of ‘forest’ includes all ASCH-categories representing reference areas completely or partially covered by trees, bushes or scrub and showed no agricultural land-use. This includes the ASCH-categories of closed forest, open forest, scrub, bush and scrub vegetation and groups of trees. The definition in this study of ‘agriculture’ includes all agricultural ASCH-categories, i.e. horticulture, meadows and arable farmland, farm pastures, mountain pastures and meadows, sheep pastures, stony alpine and Jura pastures, bushy alpine and Jura pastures, other alpine and Jura pastures. In addition, it includes ASCH-categories representing reference areas partially covered by trees and shrubs but still showing some agricultural use. This includes hedges and groups of trees in agricultural areas and grass and scrub vegetation. For detailed definitions of each ASCH land-use category see BFS (1992).

The binary response variable was derived from ASCH grid points. Grid points where agricultural land-use was noted for both ASCH surveys are referred to as ‘absence’ observations in this study. Likewise, grid points where a transition from agriculture to forest has occurred are referred to as ‘presence’ observations. Within the study area, 21,630 ‘presence’ observations and 932,561 ‘absence’ observations were available.

In order to reduce spatial dependence in the response variable, a sample of observations for model building was used. Random sampling is often used for this purpose, but this cannot completely eliminate spatial dependence (Wagner and Fortin, 2005). Therefore, several authors recommend regular sampling techniques (Munroe et al., 2002; Müller and Zeller, 2002). Regular sampling aims to avoid observations that are physical neighbours reducing spatial dependence (Munroe et al., 2002). In this study, regular sampling was not straightforward because after classification, presence/absence observations were irregularly distributed within the study area and the number of absences differed largely from the number of presences. Thus, an alternative sampling technique was applied. To avoid observations that are physical neighbours, all absences and presences 100 m apart were grouped (the smallest distance between observations on the ASCH-grid). Within each group of presences and absences only one observation was randomly sampled. This approach avoids sampling of multiple observations from the same agricultural area. In addition, the sample size was reduced, which effectively increased the overall distance between observations within the study area (Munroe et al., 2002). The modelling dataset contains 1000 presences (5% of the total number of presences in the full data set) and the same number of absences, i.e. in total there are 2000 observations incorporated into the models.
3.3. Derivation of covariates

The covariates were selected on the basis of the theoretical framework showed above. They were divided into: (i) benefit related geo-physical variables, (ii) cost-related geo-physical variables, (iii) benefit related socio-economic variables, (iv) cost-related socio-economic variables and (v) structural characteristics in agriculture. For factors approximately equal within the study area (e.g. prices for agricultural products), or for which an influence can be neglected within the 12-year study period (e.g. accessibility improvement due to infrastructure development), no variables were included in the statistical models.

Proxies for cultivation costs and benefits were generated for each presence/absence observation. In contrast, data from individual landowners and farms were not available for this study: most socio-economic variables were only available on the municipality-level. Thus, following recommendations by Walsh et al. (1999), Rudel et al. (2000), Geoghegan et al. (2001), Müller and Zeller (2002) and Kobler et al. (2005), information from the municipalities to which the observations belong was added to each observation. This approach controls local supply and demand of labour and land affecting landowners’ choices (Walsh et al., 1999; Geoghegan et al., 2001; Müller and Zeller, 2002). It was assumed, for example, that population growth is related to the higher demand for land. Higher demand for land at the municipality-level slows down land abandonment (and forest re-growth) because it increases the future expectations of landowners regarding the rent of their parcels.

Time variant socio-economic variables might, at least partially, be endogenous in regards to land abandonment. This is an assumption, which applies in particular to the agricultural structure-related variables (in this study the average agricultural area per farm, the rate of change of farms and the proportion of fulltime farms). For example, land abandonment can be the result and, at the same time, the cause of farm abandonment. This can lead to wrong inferences about the influence of farm abandonment on land abandonment. To avoid endogeneity bias in the models, Müller and Zeller (2002) were followed and only ‘serial lagged’ socio-economic variables were used, i.e. those evaluated in the time before and up to the Swiss land-use statistics evaluated in 1985. Note that unknown time-lags exist between the socio-economic causes of land abandonment, effective land abandonment and forest re-growth (Fig. 2). Therefore, it was not clear which period was authoritative for the abandonment of land leading to forest re-growth in the 1980s and 1990s. Thus, the serial lagged socio-economic variables may not totally eliminate the endogeneity bias in our models.

Changes in population and farms were calculated by using a compounded interest function:

\[ R_k = \left( \frac{V_{jk}}{V_{ik}} \right)^{1/n} - 1, \]

where \( R_k \) is the rate of change of variable \( k \), \( V_{jk} \) the initial variable value for year \( i \), \( V_{ik} \) the terminal variable value for year \( j \) and \( n \) are the number of years between year \( i \) and \( j \).

The expected relationship between each covariate and the response variable is shown in Table 1. A positive sign indicates that the probability of land abandonment and forest re-growth increases with an increasing value of the corresponding covariate. Likewise, a negative sign indicates that the probability decreases with an increasing value of the corresponding covariate.

Benefit related geo-physical variables are proxies for the yield potential. Forest re-growth was expected to be found, where yield potential was low. The variables degree days, soil depth, potential direct short-wave radiation and mean precipitation sum were used as proxies. The effect of radiation and precipitation was not a priori determined because yield potential can be low at locations with high and low values for these variables, resulting in non-linear relationships. In addition, the distance to forest edges was used as a proxy for cultivation costs and yield potential. Remaining forest islands are often located in areas unfavourable for agricultural use. Thus, land close to forest edges has, in general, less favourable growing and cultivation conditions than land remote from forest edges (due to shade, woody plant seed rain, etc.). The distance to forest edges was calculated as the Euclidian distance from ‘forest’ observations on the ASCH grid.

Cost-related geo-physical variables determine the cultivation costs of agricultural land because they influence the degree of mechanisation possible, as well as the on foot accessibility. Forest re-growth was expected to be found where accessibility and mechanisation are difficult. Slope and soil stoniness were selected as proxy variables.

Benefit-related socio-economic variables are proxies for the opportunity costs (i.e. the value of the alternative use) of agricultural land. Forest re-growth was expected to be found at locations where opportunity costs were low. The variables distance to the closest construction zone and rate of change of population and a binary dummy variable for pastureland/other agricultural land were used as proxies. Future oriented expectations, such as benefits from selling construction land, decrease with increasing distance to construction zones. This represents the distance to settlements, plus the distance to potential construction land in this study. The opportunity costs of land may also be low where population decreases (see Walsh et al., 1999; Geoghegan et al., 2001). Thus, forest re-growth was expected to be found remote from construction zones and in municipalities characterised by immigration. Note also that the Swiss forest legislation strictly
prohibits the clearing of forests, which may have affected farmers’ decisions to continue the cultivation in order to avoid irreversible income losses. Finally, in Switzerland, farmers receive lower subsidies for alpine pasturing than for moving which led to the expectation that forest re-growth occurred more frequently on alpine pastures than on other agricultural land.

Cost-related socio-economic variables are proxies for the accessibility and opportunity costs of agricultural labour. Forest re-growth was expected to be found at locations where the accessibility costs and opportunity costs of agricultural labour were high. Proxies for accessibility costs used here are the distance to roads and the average number of parcels per farm. The distance to roads was calculated as the Euclidian distance from the digital Swiss road network. Since variables addressing each operator’s opportunity costs of labour directly were not available for this study, proxies for labour markets were used to describe the potential opportunity costs of agricultural labour (Strijker, 2005). The chosen proxies are the labour force participation rate and the proportion of employees in the primary sector. It was assumed that the opportunity costs of agricultural labour increase with increasing values of the labour force participation rate and also with decreasing values of the proportion of employees in the primary sector.

The literature suggests that structural characteristics in agriculture impact land abandonment (e.g. Baldock et al., 1996; MacDonald et al., 2000; DLG, 2005), although predictions for the relationships between related variables are difficult because of conflicting influences. For example, where farms are large, more abandoned land could be expected because of labour shortages. On the other hand, land may be less frequently abandoned on large farms because these farms are generally better equipped. At the same time, relationships between agricultural structures and land abandonment are of importance in the political discussion (e.g. Baldock et al., 1996; MacDonald et al., 2000; DLG, 2005), although structural variables were included, not in order to put hypothesis to the test, but rather to obtain additional information about their relationships to land abandonment and forest re-growth. Three structural variables were used: the rate of change of farms, the average agricultural area per farm and the proportion of fulltime farms. The average agricultural area per farm was

<table>
<thead>
<tr>
<th>Variable description (evaluation years in parentheses)</th>
<th>Spatial resolution</th>
<th>Expected sign</th>
<th>Source</th>
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<tbody>
<tr>
<td>Benefit related geo-physical variables</td>
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<tr>
<td>Degree days (day × °C)</td>
<td>100 m</td>
<td>–</td>
<td>CSD/DEM25</td>
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<tr>
<td>Potential direct shortwave radiation (kJ/day)</td>
<td>100 m</td>
<td>?</td>
<td>CSD/DEM25</td>
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<tr>
<td>Mean precipitation sum (1/10 mm/month)</td>
<td>100 m</td>
<td>?</td>
<td>CSD/DEM25</td>
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<tr>
<td>Potential evapotranspiration (1/10 mm/day)</td>
<td>100 m</td>
<td>–</td>
<td>CSD/DEM25</td>
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<tr>
<td>Distance to forest edge (m)</td>
<td>100 m</td>
<td>–</td>
<td>ASCH (SFSO)</td>
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<td>Soil depth (cm)</td>
<td>100 m</td>
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<td>BEK200 (SFSO)</td>
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<td>Cost-related geo-physical variables</td>
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<tr>
<td>Soil stoniness (%)</td>
<td>100 m</td>
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<td>BEK200 (SFSO)</td>
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<td>Slope (°)</td>
<td>100 m</td>
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<td>DEM25 (SwissTopo)</td>
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<td>Benefit-related socio-economic variables</td>
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<tr>
<td>Distance to the closest construction zones (1987) (m)</td>
<td>100 m</td>
<td>+</td>
<td>BZ (SFSO)</td>
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<tr>
<td>Rate of change of population (1930–1990) (%/year)</td>
<td>Municipality –</td>
<td>Population census (SFSO)</td>
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<tr>
<td>Dummy for pastures (0/1)</td>
<td>100 m</td>
<td>+</td>
<td>ASCH (SFSO)</td>
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<tr>
<td>Cost-related socio-economic variables</td>
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<tr>
<td>Labour force participation rate (1980) (%)</td>
<td>Municipality +</td>
<td>Population census (SFSO)</td>
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<tr>
<td>Proportion of employees in the primary sector (1980) (%)</td>
<td>Municipality –</td>
<td>Population census (SFSO)</td>
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<tr>
<td>Distance to roads (m)</td>
<td>100 m</td>
<td>+</td>
<td>Vector 25 (SwissTopo)</td>
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<tr>
<td>Average number of parcels per farm (1985) (number/farm)</td>
<td>Municipality +</td>
<td>Agricultural census (SFSO)</td>
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<tr>
<td>Structural characteristics in agriculture</td>
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<tr>
<td>Proportion of full-time farms (1985) (%)</td>
<td>Municipality ?</td>
<td>Agricultural census (SFSO)</td>
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<tr>
<td>Average agricultural area per farm (1985) (ha/farm)</td>
<td>Municipality ?</td>
<td>Agricultural census (SFSO)</td>
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<tr>
<td>Rate of change of farms (1939–1985) (%/year)</td>
<td>Municipality ?</td>
<td>Agricultural census (SFSO)</td>
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</table>

a The expected sign refers to the expected relationship between the response and covariates: (−) negative, (+) positive, (†) undetermined.
b The following sources were used: CSD: climate station data (normals 1961–1990); DEM25: digital elevation model at 25 m resolution; SFSO: Swiss Federal Statistical Office; ASCH: Swiss land-use statistics; BEK200: Bodeneignungskarte der Schweiz—soil suitability map at 1:200,000; BZ: Bauzonen der Schweiz (Stand 1987)—Swiss construction zones; Vector 25: Mapped Vector25 data © 2003 SwissTopo (DV033594); SwissTopo: Swiss Federal Office of Topography.

c The variable distance to forest edges is also a cost-related geo-physical variable.
d For details of variable calculation see Zimmermann and Kienast (1999).
e The variable degree days is equivalent to the daily heat sum above a threshold of 3 °C integrated over the whole year. The values were calculated based on monthly average temperatures from 1961 to 1990 and the DEM25.
f The variable was calculated as average for the growing season (May–September).
calculated as the total agricultural area in use divided by the number of farms. The proportion of fulltime farms was calculated as the ratio of fulltime farms to the total number of farms. The rate of change of farms was calculated using Eq. (5).

3.4. Neighbourhood effects and spatial scale

Recently, scholars have begun to consider neighbourhood effects in land-use/land-cover change research (e.g. Geoghegan et al., 2001; Müller and Zeller, 2002). One possible approach to consider neighbourhood effects in statistical models is through the inclusion of a covariate containing information about the response variable values (e.g. presence or absence of land-use change) at neighbouring observations. This approach assumes that land-use decisions are, at least partially, a reaction to the land-use decisions at neighbouring observations (Anselin, 2002). A logistic regression model that includes such a neighbourhood term is formally called an autologistic model (Miller and Franklin, 2002). Autologistic models have been used to model the presence or absence of plants (Miller and Franklin, 2002) and animals (Augustin et al., 1996). The neighbourhood term included in this study is a simple binary dummy variable containing a value of one if any of the eight surrounding observations in the original dataset contains natural forest re-growth and if not, containing a value of zero. Since this is a binary dummy variable, no distance-based weights were considered as applied by Augustin et al. (1996). For model comparison two models were calculated: one model including the neighbourhood term, and a second model without this term.

In this study, the geo-physical and distance-related variables were available as raster maps, whereas most socio-economic variables were available as polygon maps. To facilitate model predictions on a pixel-by-pixel basis, we had to make our variables spatially compatible. Following the recommendations by Walsh et al. (1999), Geoghegan et al. (2001), Serneels and Lambin (2001), Müller and Zeller (2002) and Kobler et al. (2005), we brought all variables together in a raster GIS. As a result, all variables were calculated at or resampled to a common resolution of 100 m. This resolution was largely determined by the mesh-distance of the ASCH-lattice. In Switzerland, the hectare is increasingly used as a spatial unit for biodiversity surveys and regional planning (GEOSTAT, 2001; Graf et al., 2005). Thus, using the hectare as the unit for spatial modelling it allows for synergies with future research projects, such as wildlife-habitat studies. Data extraction was performed using Arc/Info procedures.

4. Logistic regression models

In this study, we used logistic regression (see Eq. (4)) as the modelling approach. Logistic regressions yield coefficients and associated confidence intervals for each covariate based on a calibration data set (Hosmer and Lemeshow, 2000; Menard, 2002). If covariates are available as raster maps, the model can be presented as a predictive map expressing the probability of land-use change in each raster cell. Since unequal sampling rates do not influence the parameter estimates, but impact the model intercept, we followed suggestions by Maddala (2001) and adjusted the intercept for unequal sampling proportions when producing model predictions. Therefore, \((\ln p_0 - \ln p_1)\) was added to the intercept, where \(p_0\) and \(p_1\) are the proportions of sampled observations from the two groups representing presence and absence of forest re-growth. In preliminary models, the hypothesised relationships between each of the covariates and the response variable were tested (see Table 1).

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

Logistic regression is based on the assumption of independence of observations (Hosmer and Lemeshow, 2000). For model building, 2000 observations were sampled within an area covering 2813 km\(^2\), i.e. on average less than one observation per square kilometre. As farms within this study area were rarely larger than 0.5 km\(^2\), it could generally be assumed that observations were independent at the farm-level. However, if municipality-level factors have an influence on land abandonment (which was assumed), the sampled observations belonging to the same municipality may not be independent from one another. This is because farmers belonging to the same municipality are influenced by the conditions in this municipality, and the sampled observations are of these farmers. This group structure in data must be considered in statistical analyses (Snijders and Bosker, 1999).

In this study, following the recommendations by Müller and Munroe (2005), the assumption of independence of observations was relaxed by using a robust estimator. Assuming that observations are independent across municipalities, but not necessarily within them, we grouped observations based on municipality boundaries, assigning each observation to its municipality and relaxing the assumption of independence of observations within municipalities. The robust estimation technique used in this study is referred to as the ‘modified-sandwich estimator’ or ‘cluster adjustment’ (Froot, 1989; Williams, 2000; Primo et al., 2006). In this study, a ‘cluster’ is a group of observations belonging to the same municipality. 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 from of heteroskedasticity (irrelevant in logistic regression models because there is no homoskedasticity assumption in these models) as well as for intra cluster correlation (Froot, 1989; Williams, 2000). 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, which may lead to spatial autocorrelation in 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 (Froot, 1989; Williams, 2000).

Model evaluations were performed by tests for goodness-of-model-fit, multicollinearity and prediction accuracy. To measure the overall goodness-of-model-fit two pseudo $R^2$ measures were calculated, the McFadden’s pseudo $R^2$ and its adjusted version (StataCorp, 2003):

$$R^2_{\text{McF}} = 1 - \frac{LL_M}{LL_0}$$

(6)

$$\text{adj.} R^2_{\text{McF}} = \frac{(LL_M) - K}{LL_0},$$

(7)

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 covariates and $K$ is the number of parameters in this model. For model comparisons, we used Akaike’s information criterion (AIC). It is defined as (Bozdogan, 1987):

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

(8)

where the $-2LL$ is the log-likelihood of the fitted model multiplied by constant of $-2$ and $n$ is the number of parameters in the fitted model. The smaller the AIC of a model the better the goodness-of-fit.

To assess the prediction accuracy of each model, the area under the receiver operating characteristics (ROC) curve was calculated (=AUC, Metz, 1978) based on an independent data set. In a ROC-plot, the fraction of observed ‘presence’ correctly predicted is plotted on the y-axis; the fraction of observed ‘presence’ incorrectly predicted is plotted on the x-axis. The AUC measures the area under the curve in the ROC-plot. It provides a threshold-independent measure of overall model accuracy. AUC values close to 0.5 indicate low similarity between the observed and predicted values. AUC values close to 1.0 indicate high similarity between the observed and predicted values. Models were calculated using STATA SE 8 (StataCorp, 2003).

High levels of multicollinearity between covariates were found in preliminary models. The coefficients of determination ($R^2$) of the multivariate relationships between one of the covariates and all the others ranged from 0.13 to 0.95, which is above the critical value of 0.80 (Menard, 2002). By removing the variables elevation and potential evapotranspiration from the statistical models, the level of multicollinearity was reduced to $R^2$ values of 0.50. Both variables were highly correlated with the variables degree days and direct short-wave radiation included in the models.

The two models presented here (Table 2) were constructed in order to characterise the locations in the Swiss mountains where agricultural land has been abandoned and overgrown by trees and bushes. The first model is an ordinary logistic model. The second model (in the following referred to as autologistic model) additionally includes a covariate reflecting forest re-growth at neighbour- ing observation sites. Model results are represented in Table 2.

As shown by their Wald-Chi-square tests (Table 2), both models are statistically highly significant ($p < 0.001$). Their overall explanatory power, however, is comparably low as indicated by pseudo $R^2$ values ranging from 0.09 to 0.14. According to Hosmer and Lemeshow (2000), low pseudo $R^2$ values in logistic regression models are the norm rather than the exception and should not be judged by the standards of what is normally considered a ‘good fit’ in conventional regression analysis. Goodness-of-model fit based on pseudo $R^2$ values must, therefore, be interpreted with caution.

Another indicator of goodness-of-model fit is the prediction accuracy measured by the area under the ROC-curve (AUC) based on an independent dataset. The AUC is 0.67 for the ordinary logistic model and 0.69 for the autologistic model. According to DeLeo (1993), the AUC value can be translated as the probability that the model will correctly distinguish between two cases. This means with a probability of 67% and 69%, the models are able to correctly distinguish between presence and absence of forest regrowth. Given that (i) the model predictions are much better than predictions by chance (which would correspond to AUC values of approximately 0.5), (ii) land-use change was modelled at the disaggregated scale and the study area is comparably large (i.e. variation in data is high) and (iii) information from landowners and farms were not available, the prediction accuracy of the models was considered satisfactory.

The autologistic model (AIC = 2437) fits better than the ordinary logistic model (AIC = 2529) showing that the neighbourhood term is an important predictor. The odds ratio of the neighbourhood term is 3.2 (Table 2). This means forest re-growth is 3.2 times more likely to be found on land where neighbouring land has been abandoned and overgrown than on land where the cultivation of neighbouring land has been maintained.

The variables degree days and distance to forest edges are significant ($p < 0.05$) with their expected signs. The
significant \((p < 0.05)\) linear and squared terms of the variables slope and soil stoniness suggest that the frequency of forest re-growth firstly increases with increasing values for steepness and soil stoniness (which is as expected), then reaches a maximum at intermediate values of both variables and finally decreases if the values for steepness and soil stoniness become particularly high.

Three covariates showed an unexpected relationship to the response variable. The variable proportion of employees in the primary sector was positively correlated with the response. This suggests that forest re-growth occurred primarily where agriculture is of economic importance which was not as expected. The variable distance to roads showed an unexpected negative relationship to the response suggesting that forest re-growth occurred more frequently in areas close to roads than in areas remote from roads. The positive relationship between the response and the rate of change of population was also unexpected. It suggests that forest re-growth occurred along with immigration.

The relationships between the response variable and the variables proportion of part-time farms and the rate of change of number of farms could not be foreseen. Both variables showed a significant \((p < 0.05)\) positive relationship to the response which indicates that forest re-growth occurred more frequently in municipalities where part-time farming was common and the rate of farm abandonment was high.

The estimated coefficients of the autologistic model were used to produce predictions for all grid points representing agricultural land-use in 1985 (Fig. 4). For the unadjusted model, the predicted probabilities of forest re-growth range from 0 to 0.94. After adjusting the model intercept for

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**Fig. 3.** Frequency of observations where agriculture has been maintained (absence) and where forest re-growth has been observed (presence) along the altitudinal and slope gradients and per land-use category in 1985. Graphics are based on the model sample of observations. The land-use categories are coded according to the Swiss land-use statistics as: (HC) horticulture, (MP) mountain pastures and meadows, (SA) stony alpine and Jura pastures, (HW) hedges and groups of trees on cultivated land, (SP) sheep pastures, (MA) meadows and arable farmland, (FP) farm pastures, (OA) other alpine and Jura pastures, (GT) groups of trees in agricultural areas, (GS) grass and scrub vegetation, (BA) bushy alpine and Jura pastures.
Table 2
Logistic regression results (response variable: presence/absence of forest re-growth)

<table>
<thead>
<tr>
<th>Variables</th>
<th>Ordinary logistic model</th>
<th>Autologistic model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Coefficient</td>
<td>z-Statistic</td>
</tr>
<tr>
<td>Constant</td>
<td>−1.02E+00</td>
<td>(−1.23)</td>
</tr>
<tr>
<td>Degree days</td>
<td>−5.11E−04</td>
<td>(−3.90)***</td>
</tr>
<tr>
<td>Potential direct short-wave radiation</td>
<td>−8.28E−06</td>
<td>(−0.61)</td>
</tr>
<tr>
<td>Mean precipitation sum</td>
<td>7.53E−05</td>
<td>(0.38)</td>
</tr>
<tr>
<td>Distance to forest edges</td>
<td>−1.54E−03</td>
<td>(−2.69)***</td>
</tr>
<tr>
<td>Soil depth</td>
<td>2.01E−03</td>
<td>(0.21)</td>
</tr>
<tr>
<td>Soil depth (squared)</td>
<td>2.07E−06</td>
<td>(0.02)</td>
</tr>
<tr>
<td>Soil stoniness</td>
<td>5.85E−02</td>
<td>(4.98)***</td>
</tr>
<tr>
<td>Soil stoniness (squared)</td>
<td>−6.30E−04</td>
<td>(−4.37)***</td>
</tr>
<tr>
<td>Slope</td>
<td>1.28E−01</td>
<td>(6.20)***</td>
</tr>
<tr>
<td>Slope (squared)</td>
<td>−2.58E−03</td>
<td>(−6.88)***</td>
</tr>
<tr>
<td>Distance to the closest construction zone</td>
<td>3.40E−05</td>
<td>(0.89)</td>
</tr>
<tr>
<td>Rate of change of population</td>
<td>2.58E−01</td>
<td>(2.54)†</td>
</tr>
<tr>
<td>Dummy for pastures</td>
<td>1.01E−01</td>
<td>(0.73)</td>
</tr>
<tr>
<td>Labour force participation rate</td>
<td>−1.10E−02</td>
<td>(−1.41)</td>
</tr>
<tr>
<td>Prop. employees primary sector</td>
<td>2.66E−02</td>
<td>(2.53)†</td>
</tr>
<tr>
<td>Prop. employees primary sector (squared)</td>
<td>−8.44E−05</td>
<td>(−0.65)</td>
</tr>
<tr>
<td>Distance to roads</td>
<td>−4.27E−04</td>
<td>(−3.92)***</td>
</tr>
<tr>
<td>Avg. number of parcels per farm</td>
<td>−6.45E−03</td>
<td>(−1.48)</td>
</tr>
<tr>
<td>Prop. full-time farms</td>
<td>−1.75E−02</td>
<td>(−3.94)***</td>
</tr>
<tr>
<td>Avg. agricultural area per farm</td>
<td>5.51E−02</td>
<td>(1.23)</td>
</tr>
<tr>
<td>Avg. agricultural area per farm (squared)</td>
<td>−2.72E−04</td>
<td>(−0.19)</td>
</tr>
<tr>
<td>Rate of change of farms</td>
<td>1.97E−01</td>
<td>(2.74)***</td>
</tr>
<tr>
<td>Neighborhood term</td>
<td>−</td>
<td>−</td>
</tr>
</tbody>
</table>

Number of observations: 2000
Wald-Chi-square: 236.14 (p < 0.000)
R_MF/adj. R_MF: 0.100.09
AIC: 2529.50
AUC (based on an independent dataset): 0.671

Significance is indicated with *** for p < 0.001, ** for p < 0.01 and * for p < 0.05, respectively. Coefficients in boldface type indicate significance at p < 0.05 or higher. Odds ratios (OR) were calculated as exp(β) where β is the estimated coefficient.

unequal sampling rates, following the suggestions by Maddala (2001), the predicted probabilities range from 0 to 0.30.

6. Discussion

6.1. General findings

Natural forest re-growth is an indicator of changing agricultural practices, which can be observed worldwide (Baldoe et al., 1996; Rudel et al., 2000; MacDonald et al., 2000; Muller and Zeller, 2002; DLG, 2005). The results of this study characterise the locations in the Swiss mountain area where agricultural land has been abandoned and overgrown by trees and bushes and can be summarised as follows: forest re-growth is largely restricted to former alpine pastures, land with grass and scrub vegetation and agricultural land with groups of trees at mid to high altitudes, steep slopes, stony ground and a low temperature sum. Most of the overgrown areas have been found relatively near roads (the median distance to roads is 283 m, see Appendix A). Forest re-growth is a regional phenomenon, largely restricted to municipalities with an increasing population, higher proportions of part-time farms and higher farm abandonment rates in the past. The results generally confirm the study hypothesis as they suggest that forest re-growth took place where the cultivation costs were high and yield potential was low.

Results confirm findings from case studies in neighbouring Alpine regions, such as the French Alps, northern Italy and parts of Slovenia, where it is mostly pastureland and low-intensively used hay meadows which are replaced by forests (Dougué droit, 1981; Petretti, 1996; Anthelme et al., 2001; Kobler et al., 2005). In Western Europe, the replacement of marginal agricultural land by forests is not restricted to Alpine regions but has also been observed in parts of Sweden, Poland, Denmark, Spain and the Baltic countries (Ihse, 1995; Kozak, 2003; Kristensen et al., 2004; Romero-Calcerrada and Perry, 2004; DLG, 2005).

Forest re-growth occurred more frequently on land with intermediate measures of steepness and stoniness. This may be explained as follows: while on less steep and stony land cultivation has been maintained due to the suitability of the land for agricultural production, very steep and stony land is generally used for pasturing (Netting, 1972). Pasturing is related to low cost because pastures are extensively grazed...
with cattle, sheep and goats. Furthermore, on very steep and stony land, forest re-growth is limited due to the unfavourable growing conditions for trees (lower water holding capacity, snow avalanches). Thus, the combination of pasturing and limited growing conditions slowed down forest re-growth on very steep and stony terrain. These non-linear relationships also reflect the specific characteristics of agriculture in the Alps, where land is cultivated in the valleys and above the treeline (Netting, 1972). Non-linear patterns of forest re-growth have also been found in the Carpathians, where forests expanded to higher and lower altitudes compared to the existing forest but generally less frequently close to the treeline (Kozak, 2003).

Models show that the frequency of forest re-growth decreases with increasing distance from roads. This is contrary to expectations and to previous findings. Pezzatti (2001) found, for example, that land-use intensity decreases with distance from roads. However, a validation revealed that a small number of observations (presence and absence) at very large distances from roads (above approximately 2000 m) were responsible for the negative linear relationship. By excluding these observations, the distance to roads showed a squared relationship to the response variable. This would indicate that the frequency of forest re-growth first increases with increasing distance to roads, then peaks at rather large distances before finally decreasing again at very large distances. This relationship also reflects the different land-use systems. On mechanically mowed meadows, the cost of cultivation (and therefore the probability of land abandonment) is high, where parcels are remote from roads.

On alpine pastures, the remoteness only has minor effects on land-use decisions because the accessibility of these areas for agricultural vehicles is often not necessary (Netting, 1972). Nevertheless, eliminating observations displaying extreme values would violate the quest for generality concerning the statistical models. Therefore, these observations were not removed from the models. This means the negative relationship of the variable distance to roads to forest re-growth should be interpreted with caution.

A binary dummy variable for pastures/other agricultural land was included in the models in order to investigate the influence of the different subsidisation of pasturelands compared to other agricultural land on land abandonment and forest re-growth. This variable was not significant in the statistical models. The explanation may be found in the fact that not only much of the abandoned and overgrown land, but also much of the cultivated land can be found on alpine pastures. Mountain farmers in the Alps rely on the mixed cultivation of meadows and alpine pastures (Netting, 1972; Petretti, 1996). This explains why they maintain pasturing although the cultivation conditions of pastures differ largely from the cultivation conditions of the meadows in valleys.

According to MacDonald et al. (2000), land abandonment and forest re-growth are often related to rural depopulation to which isolated and poorer regions are most vulnerable. The results of this study suggest the opposite as they show that forest re-growth is related to immigration. Positive relationships between immigration, land abandonment and forest re-growth are not unusual as studies in the Carpathians (Kozak, 2003) and central Spain (Romero-
Calcerrada and Perry, 2004) show. However, it is unexpected in this study because immigration was assumed to be related to a higher demand for land and thus lower abandonment and forest re-growth rates. One explanation is that immigration is related to off-farm job opportunities. Off-farm job opportunities lead to higher opportunity costs of agricultural labour, which is one of the main determinants of land abandonment (Strijker, 2005). Another explanation is that immigration does not affect the demand for marginal agricultural land. The demand for marginal agricultural land might rather be affected by a declining agricultural population—an assumption confirmed by the positive relationship between farm abandonment and forest re-growth found in the models.

It was assumed that the speculation on land value had an effect on land abandonment and forest re-growth. To test this assumption the variable distance to the closest construction zone was included. This variable was insignificant in the models. It suggests that the factors influencing land-use decisions in this study area are complex and cannot be explained by the distance of agricultural land to settlements and potential construction land. Other factors, such as the local land prices and land regulations and individuals’ interests in speculation on land value might have larger impacts on land-use decisions. The latter information was not available for the main study area, although it is part of ongoing research in selected case studies where interviews with landowners are planned.

Forest re-growth occurred more frequently where the proportion of employees in the primary sector was high. This is unexpected and would lead to the conclusion that land abandonment occurred more frequently where the economic importance of agriculture is high. However, there are municipalities showing a high proportion of employees in the primary sector and high forest-re-growth rates. These municipalities can mostly be found in the Mid-Grisons, a region in the eastern central part of the study area. Over the past decades, municipalities in this region underwent considerable changes in agriculture resulting in comparably large but few farms. Most of these farms are managed on a full-time basis, and off-farm activities are uncommon as tourism and industry are less developed. As many farms have reached their maximum size and farm labour is scarce, it is likely that farmers in these municipalities restrict their activities to the more favourable land. This may explain why land abandonment and forest re-growth are common in these municipalities.

Results show that forest re-growth is a regional phenomenon largely restricted to municipalities showing higher proportions of part-time farms as opposed to full-time farms and higher farm abandonment rates. High proportions of part-time farms can generally be found in the southern part of Switzerland where farms are smaller, cultivation is less optimised and land is often fragmented due to hereditary customs, i.e. where cultivation is still labour intensive (Surber et al., 1973; Walther, 1986). At the same time, part-time farmers often have less time to work on their farms (which is equivalent to saying opportunity costs of farm labour are high). This could explain why land abandonment and forest re-growth are more likely to be found in municipalities showing a high proportion of part-time farms. The situation for full-time farmers is the opposite; they often have invested in buildings, machines and rational cultivation methods and labour is therefore less scarce than on part-time farms (which is equivalent to saying opportunity costs of farm labour are low). Thus, they are more inclined to invest their time in the cultivation of marginal lands. This could explain why land abandonment and forest re-growth are less likely to be found in municipalities showing a high proportion of full-time farms.

The structural change in agriculture is influenced by the cultivation costs and benefits from agricultural land as well as by off-farm job opportunities (Balduck et al., 1996; Strijker, 2005). Thus, the positive relationship between farm abandonment and forest re-growth confirms the hypothesis that forest re-growth occurred more frequently where growing conditions were unfavourable and the opportunity costs of farm labour were high. Positive relationships between farm abandonment, land abandonment and forest re-growth are also documented for other regions with unfavourable cultivation conditions, such as the French Alps (Douguédroit, 1981), northern Italy (Petretti, 1996), central Spain (Romero-Calcerrada and Perry, 2004), parts of Sweden (Ihse, 1995), Denmark (Kristensen et al., 2004) and Slovenia (Kobler et al., 2005) and the Baltic countries (DLG, 2005).

Accounting for spatial effects through the inclusion of a neighbourhood term resulted in better model fits. It shows that whether the cultivation will be abandoned or continued depends on whether the cultivation of neighbouring land will be abandoned or continued. One explanation for this finding can be found in the design of the Swiss land-use statistics, where areas larger than 2 ha are represented as a group of observations (i.e. sampled grid-points). Within such groups, some observations were modelled well by the ordinary logistic model, while others were not. Possibly some observations within such groups have better cultivation conditions than other. On larger 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 re-growth at neighbouring parcels is a way to account for this lack of information, because it indicates higher probabilities of land abandonment where nearby land has been abandoned.

6.2. Methodological considerations

The models provide the general pattern of forest re-growth in the Swiss mountains but (despite a large set of covariates) show comparatively poor explanatory power.
Much of the residual deviance may come from omitted variables related to undetected local characteristics, such as the poor water availability or small-scaled topographic peculiarities (e.g. small trenches, stonewalls, soil damages by cattle). Another important factor that could not be considered in this study is the motivation of individual farmers to abandon or maintain cultivation. The municipality-level covariates took account for the local demand and supply of land and labour, but did not consider other factors for which it is likely that they have affected land abandonment and forest re-growth. As showed in similar studies, the age and education of farmers, farm income, farm size or the degree of mechanisation are important factors of land-use change (Baldock et al., 1996; Selby et al., 1996; MacDonald et al., 2000; Kristensen et al., 2004). These factors could not be considered in our models because individual-level and farm-level data were not available for this study. Collecting individual-level and farm-level information (e.g. by means of questionnaires) and linking this information to the locations where land-use changes have been observed could help to improve the understanding of the processes of land-use change (see contributions in Walsh and Crews-Meyer, 2002).

Model fit could also be improved by dividing the study area into smaller (more homogenous) spatial entities but, as pointed out by Serneels and Lambin (2001), ‘... subdividing a region in many small homogenous spatial entities and calibrating different models for every entity is not compatible with the quest for generality behind any modelling activity ...’. Aggregation could be another way to decrease the heterogeneity (and provide further insights) in the data of this study. Unfortunately, our land-use data do not allow additional modelling at the municipality-level. This is because the Swiss land-use statistics are based on a sample of grid points, not on area-wide estimates, such as satellite images. Area-wide estimates of land-use change based on these grid points are related to an estimation error (BFS, 1992). The municipality is not the adequate observation unit because it is too small to obtain precise estimates of land-use change, i.e. those with small estimation errors. Studies on the aggregated level also have some disadvantages compared to studies on the disaggregated level. Verburg et al. (2004) point out that: ‘aggregation of detailed scale processes does not straightforwardly lead to a proper representation of the higher-level process. Non-linearity, emergence and collective behaviour cause this scale dependency.’

In this study cluster-adjustment was used to take the group structure in the data into account. An alternative modelling approach for grouped data is multilevel modelling (Snijders and Bosker, 1999). Multilevel models, also referred to as hierarchical models or mixed effects models, include covariates (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 is expressed as ‘random effects’ (Snijders and Bosker, 1999). Hoshino (2001), Polsky and Easterling (2001), Pan and Bilsborrow (2005) and Overmars and Verburg (2006) used multilevel models in land-use research. Given the data in this study, the use of multilevel models would have several disadvantages compared to the use of cluster-adjusted models. Multilevel models require, for example, “a proper hierarchical structure” of data (Pan and Bilsborrow, 2005). In this study, data at the grid-point level and municipality-level existed, but no data at the farm-level. Therefore, the data lacks a proper hierarchical structure. It is a fact that researchers often plan the collection of data for use in multilevel models rather than using existing data in these models. Overmars and Verburg (2006) write: “Datasets that were not designed for multilevel modelling often appear to be inadequate. This is a serious constraint for applying multilevel modelling in land use studies, because many studies use available datasets. In studies with levels other than farmers and fields, for example, including country and sub-country level, the data structure can be more favourable to multilevel modelling.”

Another disadvantage of multilevel models compared to cluster-adjusted models is that a variety of strong statistical assumptions must be made (Snijders and Bosker, 1999). To the extent that these model assumptions are inaccurate, these inaccuracies will influence the entire analysis. In contrast, cluster-adjustment has no affect on the estimated coefficients (Froot, 1989; Williams, 2000; Primo et al., 2006). The disadvantage of cluster-adjusted models compared to multilevel models is that they do not enable the researcher to state what portion of the variance in the response variable is attributable to higher level versus individual level variation. The price of this information is a model with more (possibly inaccurate) assumptions. A disadvantage of both approaches is that they assume that the clustering being accounted for is the primary source of non-independence in the observations. If there are other forms of dependencies, inference may be affected. In summary, given our data cluster-adjustment was regarded as a suitable approach to take the group aspect in our data into account, but other modelling techniques, such as multilevel models are available for this purpose.

7. Conclusions

Understanding the processes of land-use change in mountain regions is of importance because land-use changes are related to a variety of environmental consequences. Results mostly confirmed the expected pattern of forest re-growth as they show that forest re-growth took place where the cultivation costs were high and yield potential was low. The results of this study extend the current knowledge about the pattern of forest re-growth in the Swiss mountains. For instance, it was found that non-linear relationships between steepness and soil stoniness and forest re-growth exist. This suggests that forest re-growth occurred in the ‘in-between’
areas where the labour costs were low, e.g. mechanically mowed meadows in the valleys and labour-extensive pastures close to the treeline.

A new finding from this study is that forest re-growth occurred alongside part-time farming, farm abandonment and immigration. From this, the conclusion was made that immigration per se is not a driving factor of land abandonment and forest re-growth. Land abandonment and forest re-growth seem rather to be the result of the relative decline of the agricultural income from marginal land. Results show high heterogeneity in the pattern of forest re-growth. We related this heterogeneity to the undetected local characteristics, such as poor water availability, small-scaled topographic peculiarities and individuals’ motivations to abandon or maintain cultivation. The conclusion was made that general policy measures for the whole mountain area (the current practise) are not suitable for the prevention of land abandonment and forest re-growth, and that policy measures must pay more attention to local characteristics and needs. Further research is necessary regarding the possible scale dependency of these findings, neighbourhood effects and local characteristics and peculiarities including the motivations of individual landowners. The latter is part of ongoing research in selected case studies, where it is planned to extend the time horizon (1950–2000) and combine results from local spatial statistical models with findings from landowner interviews.

Acknowledgements

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Appendix A. Descriptive statistics for the model sample of observations

<table>
<thead>
<tr>
<th>Variable</th>
<th>Presence observations N = 1000</th>
<th>Absence observations N = 1000</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Median</td>
</tr>
<tr>
<td>Degree days (days × degrees)</td>
<td>1458</td>
<td>1372</td>
</tr>
<tr>
<td>Potential direct short-wave radiation (kJ/day)</td>
<td>21618</td>
<td>22162</td>
</tr>
<tr>
<td>Mean precipitation sum (1/10 mm/month)</td>
<td>1358</td>
<td>1310</td>
</tr>
<tr>
<td>Distance to forest edge (m)</td>
<td>119.2</td>
<td>100.0</td>
</tr>
<tr>
<td>Soil depth (cm)</td>
<td>32.04</td>
<td>21.00</td>
</tr>
<tr>
<td>Proportion of employees in the primary sector</td>
<td>21.11</td>
<td>17.50</td>
</tr>
<tr>
<td>Distance to roads (m)</td>
<td>433.7</td>
<td>282.8</td>
</tr>
<tr>
<td>Average number of parcels per farm (number/farm)</td>
<td>10.11</td>
<td>6.00</td>
</tr>
<tr>
<td>Proportion of full-time farms (%)</td>
<td>48.20</td>
<td>50.00</td>
</tr>
<tr>
<td>Rate of change of agriculture area per farm</td>
<td>8.27</td>
<td>7.16</td>
</tr>
<tr>
<td>Rate of change of farms (%/year)</td>
<td>1.847</td>
<td>1.699</td>
</tr>
</tbody>
</table>

References


DeLeo, J., 1993. Receiver operating characteristic laboratory ROCLAB: software for developing decision strategies that account for uncertainty.


Van Hoof, T.B., Bunnik, F.P.M., W aucromont, J.G.M., Kärschner, W.M., Visscher, H. Forest re-growth on medieval farmland after the Black
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