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ScienceDirect
Landscape and Urban Planning 79 (2007) 65–76
LANDSCAPE AND URBAN PLANNING
This article is also available online at:
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Investigating the regional-scale pattern of agricultural land abandonment in the Swiss mountains: A spatial statistical modelling approach

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Received 8 April 2005; received in revised form 14 March 2006; accepted 14 March 2006
Available online 23 May 2006

Abstract

In many European mountain regions, agricultural land abandonment and the related consequences for the environment are issues of increasing concern. During the last few decades, natural forest re-growth has steadily replaced 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. The aim of this study was to investigate the recent regional-scale pattern of agricultural land abandonment, as indicated by forest re-growth, in the Swiss mountains. For this, we developed multivariate spatial statistical models on the basis of mountain-wide land-use change data, evaluated between the 1980s and 1990s, and selected geo-physical and socio-economic variables. Results show that regions with shallow soils, steep slopes and under-developed road infrastructure were favoured in terms of land abandonment and forest re-growth. These regions were also characterised by low proportions of full-time farms. In some regions, strong labour markets were related to higher abandonment rates, but this is not a general trend in Swiss mountainous regions. We found no relationship between land abandonment and migration, which contrasts with findings in other European mountain regions. One model suggests a spatial 'spillover' effect, causing similar abandonment rates in adjacent regions, although this could not be proven in this study. We conclude that decision-makers should consider non-linearity in the pattern of land abandonment and the fact that part-time farming is related to land abandonment when designing measures to react to land abandonment and its consequences.

Keywords: Land-use change; Forest re-growth; Spatial regression; Neighbourhood effects

1. Introduction

Agricultural land abandonment reflects a decline in traditional agricultural practices that can be observed worldwide (Rudel et al., 2000; MacDonald et al., 2000; Perz and Skole, 2003; DLG, 2005). In many European countries, this trend is not new. Considerable land abandonment 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; Mather and Fairbairn, 2000). In many of the new Member States of the EU, such as the Baltic countries, considerable land abandonment rates occurred only recently as the result of the economic development in the post-socialist era from the beginning of the 1990s on (DLG, 2005).

In Western Europe it is in particular mountain regions which are affected by land abandonment (MacDonald et al., 2000). As a consequence, natural forest re-growth is increasingly replacing agricultural land in European mountains (Douguédroit, 1981; Anthelme et al., 2001; Romero-Calcerrada and Perry, 2004; Nikodemus et al., 2005).

Agricultural land abandonment and forest re-growth lead to a variety of ecological and economic consequences. 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 irreversible loss of traditional cultivation forms, such as alpine and mountain pasturing (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 is

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doi:10.1016/j.landurbplan.2006.03.004

of importance in the recent political discussion (Baldock et al., 1996; MacDonald et al., 2000; DLG, 2005) and have attracted interest among researchers.

Baldock et al. (1996), for example, studied land abandonment in different European countries and identified areas with "physical and socio-economic obstacles to modern agriculture", such as steep and terraced slopes, wet areas without drainage and areas remote from roads and settlements as the most vulnerable to land abandonment. Changing labour markets, relative prices for agricultural products, agricultural structures and policies, and migration and infrastructure developments have been identified as important drivers of land abandonment in European case studies (Baldock et al., 1996; MacDonald et al., 2000; DLG, 2005).

In Switzerland, agricultural land abandonment has been observed for more than 150 years (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 land abandonment in earlier case studies (Surber et al., 1973; Walther, 1986; Pezzatti, 2001). Land abandonment is of increasing concern in the Swiss mountains because traditional agricultural cultivation forms have preserved unique landscapes and habitats of high ecological value, which are threatened by changes due to recent economic development (Hunziker, 1995). With the support of the Alpine Convention (http://www.alpenkonvention.org), Swiss politicians have been sending a signal for international co-operation regarding the preservation of Alpine landscapes. Agricultural land abandonment is an issue related to most of the 12 sectors for which contracting parties of the Alpine Convention were requested to find measures, including nature conservation, mountain farming and forests, soil conservation, water management and culture and tourism.

1.1. Problem analysis and objective

To date, empirical studies on agricultural land abandonment in Switzerland are rare and exist solely in the form of smaller case studies (see studies by Surber et al., 1973; Walther, 1986; Pezzatti, 2001). Thus, knowledge about the human driven patterns and processes of land abandonment is limited. There is urgent need for research, in particular on the administrative scale, which is the scale for which policy measures are designed and implemented.

Land-use change studies can be used to: (i) investigate the quantity of land-use change, (ii) investigate the underlying causes of land-use change, which are often changing economic and/or policy factors and (iii) characterise the locations of these changes (Lambin, 1997). The objective of this study was the latter, i.e. we aimed to investigate where land abandonment has occurred. This is typically referred to as the 'pattern' of land-use change (Pontius et al., 2001).

In this study, we used an economic framework to explain the pattern of agricultural land-abandonment in the Swiss mountains for which natural forest re-growth was used as an indicator (see text below). Our main hypothesis was that regions where the cultivation costs of agricultural areas may not be covered by the yields were favoured in terms of land abandonment and forest re-growth. To answer the study question and prove the hypothesis, we developed multivariate spatial statistical models on the basis of mountain-wide land-use change data and selected geophysical and socio-economic variables.

2. Materials and methods

2.1. Study area

The study area (Fig. 1) covers 68% of the total area of Switzerland (2813 km^2) and is inhabited by 24% of the Swiss population. It includes all 54 regions of the Swiss mountain area as defined by the "Act on Investment Aid for Mountain Regions" (=IHG, Wachter, 2002). In this study, the municipality of Davos and eleven municipalities of Oberengadin (Eastern Central Alps) were combined and added as an additional (i.e. 55th) region.

Approximately, 33% of the study area is used for agriculture, at altitudes between 200 and 2800 m. Agriculture consists mostly of cultivation of hay meadows and alpine pastures (Netting, 1972). Over the summer local livestock (i.e. cattle, sheep and goats from the municipalities to which the alpine pastures belong) and non-local livestock (from regions outside these municipalities) graze on the alpine pastures. These 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 Central Alps (Körner, 1998).

The agricultural structure mostly takes on the form of small family farms: 37% of the farms are smaller than 10 ha. The farms in the canton of Jura and in the Northern Alps are generally larger and dairy farming is common there. In the Central Alps, there are a higher proportion of part-time farms than in the canton of Jura and the Northern Alps. In those areas, less intense cultivation forms, such as sheep pasturing, are common. 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 (*data source*: agricultural censuses provided by the Swiss Federal Statistical Office).

In the period between the 1950s and 1990s, Swiss agricultural policy was mainly product-related and the agricultural commodity market was characterised by high protectionism (Rieder, 1996). Since the beginning of the 1990s, agricultural policy has undergone radical changes. The agriculture law was completely revised, so that it now focuses on direct payments instead of being product-related (SAEFL—Swiss Agency for the Environment, Forests and Landscapes).

Over a 12-year period between the 1980s and 1990s, forest re-growth has on average replaced 2.3% of the agricultural areas within each region (*source*: own calculations based on the Swiss land-use statistics). In the IHG-regions of the Central Alps, there has generally been a higher percentage of agricultural land that has been abandoned and replaced by trees, scrub and bushes than in the IHG-regions of the canton of Jura and Northern Alps (Fig. 1).

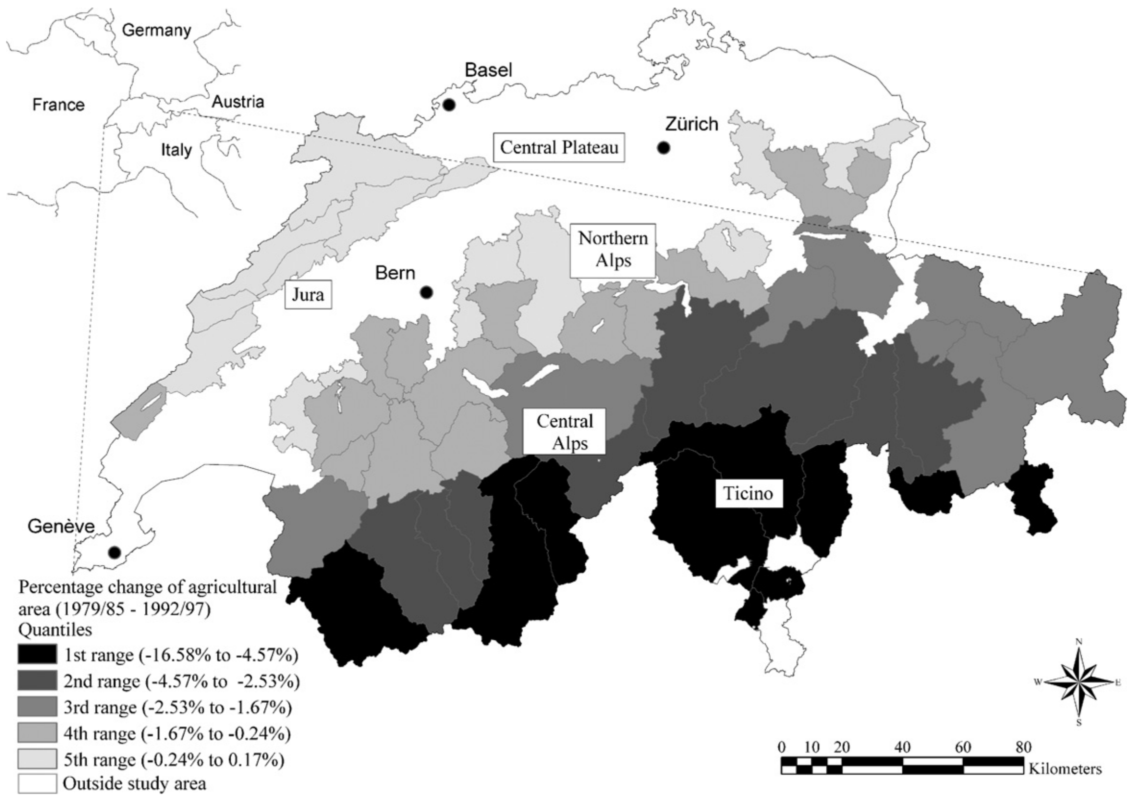

Fig. 1. Study area with the IHG-regions and the extent of abandonment of agricultural areas. The percentage change of agricultural area in each region was calculated on the basis of two Swiss land-use surveys carried out over a 12-year period in the 1980s and 1990s (see Eqs. (1) and (1a) for details of variable calculation).

2.2. Scale and response variable

All analyses were carried out on a regional scale, using the 55 mountain regions as a basis. The regional scale is used for three reasons. Firstly, it is farmers who make land-use decisions and they are affected by their wider environment. Farm incomes, for instance, often depend on off-farm job opportunities within each farmer's wider economic environment (e.g. on a regional scale). Secondly, institutional settings are often made for and affect land-use change within administrative units. The canton of Grisons, for example, has begun to support the removal of scrub from the pastures, whereas the neighbouring cantons have not. An effect of this measure on the land-use change pattern in our study period could not be investigated because it was recently introduced, although we expect to observe effects in the future. Thirdly, policy makers usually make decisions for administrative units and seek general solutions for problems occurring on these levels.

The response variable used in the statistical models (y_{agri}) is a $(n \times 1)$ vector of percentage change of agricultural areas (illustrated in Fig. 1) multiplied by a constant of -1 (thus positive values reflect abandonment). More formally, it is defined as:

$$y_{\text{agri}} = \left[\frac{y_t - y_{t-1}}{y_{t-1}}\right] \times -100 \quad (1)$$

$$y_t = y_{t-1} + y_{\text{net}}, \quad (1a)$$

where y_{t-1} is a $(n \times 1)$ vector of agricultural areas within the IHG-regions measured in the Swiss land-use survey (ASCH) carried out in the 1980s (referred to as ASCH85) and y_t is a $(n \times 1)$ vector of agricultural areas measured in the survey of the 1990s (referred to as ASCH97). The y_{net} is a $(n \times 1)$ vector of the net decrease/increase in agricultural areas as measured by forest re-growth/clearing between both surveys.

In both surveys, 74 land-use categories were distinguished by overlaying aerial photographs with a regular 100 m lattice (SFSO, 2001). Changes in land-use at a single lattice point can be estimated by comparing the land-use category assigned to it in ASCH85 with that in ASCH97.

In this study, a single ASCH observation is defined as 'abandoned' if the categorisation has been altered from 'agriculture' to 'forest'. Likewise it is defined as 're-used' if it has been altered from 'forest' to 'agriculture'. The predefined land-use categories provided by ASCH allow for individual definitions of 'agriculture' and 'forest'. Our definition of 'agriculture' includes all ASCH land-use categories that refer to total or partial agricultural land-use (Table 1). Likewise, our definition of 'forest' includes all ASCH land-use categories that are totally or partially covered by trees and/or scrub, with no agricultural land-use.

Land abandonment is defined via forest re-growth in this study, but this cannot be observed above the climatological treeline. Thus, all agricultural areas, which are located above that treeline were excluded from this study. Since an exact measure of the climatological treeline was not available, we used the poten-

Table 1
The ASCH land-use categories were grouped into *agriculture* and *forest* in this study

ASCH-code	Description
Defined as *agriculture* in this study	
17, 18	Hedges and groups of trees on agricultural areas
71, 72, 73	Vineyards
75, 76, 77	Orchards
78	Horticultural areas
81, 82	Meadows and arable farmland
83, 84	Home pastures
85	Mountain pastures
86, 87, 88, 89	Alpine and Jura pastures
97	Grass and scrub vegetation
Defined as *forest* in this study	
10, 11, 14	Closed forest
12, 13	Open forest
15	Scrub
16	Bushes/shrubs
19	Groups of trees

ASCH-code refers to the coding used by the Swiss Federal Statistical Office. For detailed definitions of each ASCH land-use categories see BFS (1992a).

tial treeline as delineated in the distribution atlas of vascular plants (Sutter and Welten, 1982). A validation exercise revealed that considerable areas of new forest have grown above this line. Therefore, we modified it by using a 300 m buffer (vertical on a digital elevation model). Above the buffered delineation, only a very small fraction of new forest areas developed, which we consequently excluded from our analyses.

ASCH-based estimates of agricultural areas and their changes are associated with an estimation error that specifies the maximum deviation (a positive or negative percentage) of the estimated from the (unknown) 'true' agricultural areas and their changes. The estimation error can be calculated for a 95% confidence interval by means of Eq. (2) (BFS, 1992b):

$$\text{estimation error}\,(\%) = \frac{196}{\sqrt{n}} \tag{2}$$

where n represents the number of lattice points showing agricultural land-use and agricultural land-use change, respectively. The ASCH-based estimates of the agricultural areas, as well as their increases, decreases and relative estimation errors are listed in Appendix A.

2.3. Potential explanatory variables

The choice of the explanatory variables (Table 2) is based on von Thünen's and Ricardo's land rent theories (Von Thünen, 1990; Ricardo, 2002). These theories state that landowners are profit maximisers, allocating their land to the use yielding the highest rent. The distance of a land parcel to markets (von Thünian ideas) and its 'quality' of land, in terms of geo-physical characteristics (Ricardian ideas), determine the land-use decision of each landowner.

The relationships hypothesised between each of the explanatory variables and the response variable are expressed in Table 2. In order to obtain a resolution suitable for comparing the response and explanatory variables, all variables were aggregated to the IHG-region level. There is an (unknown) time lag between the socio-economic determinants of land abandonment, effective land abandonment and 'observable' land abandonment, i.e. forest re-growth, in our study. Similar time lags have been identified in a study by Perz and Skole (2003). To account for this time lag in our data, we followed the latter authors and only included the socio-economic variables evaluated in the period before and up to the evaluation year of the first Swiss land-use statistics. All GIS operations were performed using ArcInfo©procedures. Below is a brief description of the potential explanatory variables.

Table 2
Variables used in this study to explain the pattern of land abandonment with units, data collection year(s), expected relationship and sources

Variable	Evaluation year(s)	Expected relationship[a]	Source[b]
Average degree days[c,d] (day × C°)	1961–1990	–	CSD, DEM25
Average summer precipitation[c,d] (1/10 mm)	1961–1990	–	CSD, DEM25
Average soil depth[d] (cm)	–	–	BEK200
Average slope[d] (°)	–	+	DEM25
Average distance to roads[d] (m)	1984–1996	+	Vektor25©
Commuters (%)	1980	(U-shaped)	SFSO
Employees in sectors II and III (%)	1980	+	SFSO
Land used as alpine pasture[d] (%)	1979–1985	+	ASCH85
Full-time farms (%)	1985	?	SFSO
Population change[e] (%)	1950–1980	?	SFSO
Dummy for Davos and Oberengadin (0/1)	–	?	–

[a] The expected relationship (−, negative; +, positive) refers to the relationship hypothesised between each of the explanatory variables and the response variable.
[b] DEM25: digital elevation model with 25 m cell size provided by the Federal Office of Topography (SwissTopo); CSD: Swiss climate station data; BEK200: soil suitability map at 1: 200,000; Vektor25©: Mapped Vector25 data provided by the Federal Office of Topography (DV033594); ASCH85: Swiss land-use statistics 1979/85; SFSO: Population and agricultural censuses carried out by the Swiss Federal Statistical Office.
[c] For details of variable calculation see Zimmermann and Kienast (1999).
[d] Aggregations are based on intersections of ASCH lattice points showing agricultural land-use in ASCH85 with raster maps of these variables.
[e] This variable has been calculated as the average annual rate of change.

Average degree days: Is equivalent to the daily heat sum above a threshold of 3 °C, integrated over the whole year and based on normalised monthly temperatures between 1961 and 1990. The values were calculated (Zimmermann and Kienast, 1999) using temperature data from Swiss climate stations and a digital elevation model at 25 m resolution (DEM25). It was used as a proxy for the yield potential of agricultural areas. Since physical yields are in general higher for areas with higher heat sums and lower for areas with lower heat sums, we expected a negative relationship to the response.

Average summer precipitation: The values were calculated (Zimmermann and Kienast, 1999) as monthly mean precipitation sums for the growing season (May–September), using precipitation data (1961–1990) from Swiss climate stations and the DEM25. It was used as a proxy for the yield potential of agricultural areas. Physical yields are generally higher at locations with higher precipitation sums and lower at locations with a shortage of precipitation. The latter might also be related to higher cultivation costs because areas with a shortage of precipitation often require irrigation. We thus expected a negative relationship to the response.

Average soil depth: Was used as a proxy for the yield potential of agricultural areas. Higher values of the average soil depth are generally related to higher nutrient and water holding capacities and thus higher yield potentials. Thus, we expected a negative relationship to the response.

Average slope: Was used as a proxy for cultivation and accessibility costs of agricultural areas. Steepness affects the accessibility of land for agricultural vehicles and on foot (e.g. for herdsmen). Higher values of this variable are generally related to higher cultivation and accessibility costs. Thus, we expected a positive relationship to the response.

Average distance to roads: Is based on a digital 1:25,000 map of the Swiss road network. It was calculated as the average of the pixel-wise Euclidian distance from all roads that are accessible by agricultural vehicles. Since higher values of this variable are generally related to higher accessibility costs, we expected a positive relationship to the response. A possible influence of road network changes on land abandonment can be neglected within our 12-year study period because infrastructure developments have mostly been carried out in the period prior to 1980.

Land used as alpine pasture: Was calculated based on the Swiss land-use statistics carried out in the 1980s (ASCH85). It represents the proportion of agricultural land used as alpine pasture below the estimated treeline. The delineation is based on the Swiss Agricultural Production Zones ("Landwirtschaftliche Zonengrenzen"). For areas outside the alpine pastures, subsidies are paid for both agricultural areas and livestock, while on alpine pastures subsidies are only paid for livestock. The latter provides lower income per unit (alpine) pasture. Thus, we expected a positive relationship to the response.

Economic theory suggests that the opportunity costs (the value of the alternative use) of agricultural labour are an important driver of land abandonment: if opportunity costs are high, then marginal land is more often abandoned (Strijker, 2005). Two proxy variables were used to assess the influence of opportunity costs of farm labour on land abandonment: the proportion of commuters and the proportion of employees in sectors II and III (abbreviated: *commuters* and *employees* in sectors II and III). Both variables where calculated as proportions of the total number of employees per region. Lower values for commuters reflect strong labour markets within a region and thus higher opportunity costs of farm labour. Higher values for commuters reflect weak labour markets within regions. However, easily accessible strong labour markets outside the region, means higher opportunity costs of farm labour. Therefore, we expected a U-shaped relationship to the response. Higher values for employees in sectors II and III reflect strong labour markets inside the regions, i.e. high opportunity costs of farm labour. Thus, we expected a positive relationship to the response.

Full-time farms: The proportion of full-time farms is a proxy for off-farm employment. The relationship between off-farm employment and land abandonment can be complex (Baldock et al., 1996). Therefore, we included this variable to test this relationship.

Population change: Rural emigration and immigration has been linked to land abandonment in European mountain regions (MacDonald et al., 2000). Mather and Fairbairn (2000) assume complex relationships between migration, land abandonment and forest re-growth in Switzerland. As there is no mountain-wide spatially explicit study related to this topic, we included this variable to test this relationship.

Dummy variable for Davos and Oberengadin: To account for possible effects of our additional region, we included a binary dummy variable, coded as one for this region and zero for all other regions.

2.4. Statistical tests and models

Prior to statistical modelling, all variables were tested for spatial autocorrelation using Moran's *I* statistic (Anselin, 1988). It is similar to a correlation coefficient with a range of −1 to 1, provided that the required spatial weights matrix is row-standardised (Anselin, 1988). Whether data show spatial autocorrelation is of interest for two reasons. Firstly, it affects the assumption of data independence in standard statistical tests, resulting in incorrect test statistics. Secondly, despite the methodological disadvantages, it provides useful information about structures and patterns of data (Anselin, 1988).

We used a maximum-likelihood (ML) based spatial lag model (MLLAG) and a spatial error model (MLERR) to explore and describe the multivariate relationship between our response and the potential explanatory variables. These modelling techniques take into account possible spatial effects when dealing with spatially autocorrelated data (Anselin, 1988). The latter is of importance to obtain efficient parameter estimates, i.e. ones that lead to correct interpretation of the significance of variables in explaining the response variable. The MLLAG model can be expressed through Eq. (3) (Anselin, 1988):

$$y_{\text{agri}} = \rho W y_{\text{agri}} + \beta X + \varepsilon, \tag{3}$$

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

$$y_{\text{agri}} = \beta X + u \quad \text{with } u = \lambda Wu + \varepsilon, \tag{4}$$

where u is an $(n \times 1)$ vector of spatially autocorrelated errors, Wu a $(n \times 1)$ vector of spatially lagged errors, λ a coefficient and ε is a $(n \times 1)$ vector of iid errors.

A significant spatially lagged error term indicates that the residuals of a standard regression model would be correlated among neighbouring regions. Specifying a spatial autoregressive process for the error term by means of the MLERR model is equivalent to carrying out a standard regression model on 'spatially filtered' explanatory 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 change is generated by processes that do not match the boundaries of the study regions (Perz and Skole, 2003).

Model fit was measured using a pseudo R^2 measure recommended by Anselin (1992):

$$\text{pseudo } R^2 = \frac{\sigma^2_{\text{pred}}}{\sigma^2_{\text{obs}}} \tag{5}$$

where σ^2_{pred} is the variance of the predicted response variable and σ^2_{obs} is the variance of the observed response variable. For model comparison, we used the Akaike Information Criterion (AIC, Bozdogan, 1987). Higher values of pseudo R^2 and lower values of AIC indicate a better model fit.

Spatial statistical tests and models require a spatial weights matrix, which determines the strength of the correlation between neighbouring regions (Anselin, 1988). In this study, the spatial weights matrix was calculated based on first-order contiguity of IHG-regions (i.e. only adjacent regions were defined as neighbours). To improve the comparability between parameter estimations of our models, we followed suggestions made by Anselin (2002) and row-standardised the weights matrix.

Models were checked for heteroscedasticity, spatially autocorrelated errors and multicollinearity. Non-linear relationships between the response and explanatory variables were tested in preliminary univariate models. For explanatory variables that did not show linear relationships to the response, we added squared terms of the respective variable to the statistical models. All models were calculated following the recommendations by Anselin (1988, 1992), using the R statistics software, Version 2.0.1 (R Development Core Team, 2005).

3. Results

3.1. Descriptive statistics

Except for population change, all variables had significant ($p < 0.001$) positive spatial autocorrelation (Table 3). It shows that adjacent regions tend to have similar abandonment rates as well as similar climatic, topographic, infrastructural and socio-economic conditions, but that regions with similar population changes are randomly distributed throughout the study area.

The scatterplots (Fig. 2) show the bivariate relationships between the geo-physical and socio-economic variables and response variable. It shows that land abandonment occurred more frequently where the heat sums are low, soils are shallow, slopes are steep and road infrastructure is less developed. The relationship between summer precipitation and the response variable is less distinct, i.e. a clear trend cannot be observed. Scatterplots additionally show that land abandonment occurs more frequently where the proportion of commuters is low and high and where the proportion of employees in the secondary and tertiary sectors is high, but that this result is influenced by a small number of regions. Regions where the proportion of alpine pastures is low generally have lower abandonment rates than regions where the proportion of alpine pastures is high. A clear negative relationship is distinguishable between the response variable and the proportion of full-time farms, i.e. regions with

Table 3
Descriptive statistics of the variables across the 55 IHG regions analysed; Shapiro-Wilk test (SW) for normality and Moran's I test (MC) for spatial autocorrelation (under the randomisation assumption)

	Min	Max	Mean	Median	S.D.	SW[a]	MC[b]
Response variable							
(Percentages change of agricultural areas) × −1	−1.72	16.58	2.33	1.19	3.12	0.735***	0.69 (7.34)***
Explanatory variables							
Average degree days (day × C°)	701.40	2764.30	1691.30	1747.00	419.78	0.981	0.69 (6.78)***
Average summer precipitation (1/10 mm/month)	797.00	2051.00	1395.00	1351.00	280.51	0.967	0.73 (7.15)***
Average soil depth (cm)	25.88	98.87	52.76	41.85	21.02	0.891***	0.70 (6.84)***
Average slope (°)	6.09	28.65	17.67	19.82	6.59	0.931**	0.77 (7.51)***
Average distance to roads (m)	44.49	1320.88	274.42	212.54	256.37	0.781***	0.46 (4.86)***
Commuters (%)	9.19	69.53	36.37	37.40	11.82	0.987	0.37 (3.74)***
Employees in sectors II and III (%)	55.98	93.95	77.38	79.51	9.20	0.968	0.19 (2.06)*
Land used as alpine pasture (%)	0.00	74.24	41.65	52.12	26.00	0.859***	0.67 (6.50)***
Full-time farms (%)	5.31	87.72	57.82	64.95	22.44	0.871***	0.60 (5.94)***
Population change (%)	−0.92	2.14	0.04	−0.01	0.58	0.922**	−0.03 (−0.15)

[a] The significance is indicated with ***, ** and * for $p < 0.001$, $p < 0.01$ and $p < 0.05$, respectively.
[b] The first value is the Moran's I coefficient. The test statistics are enclosed in brackets. The significance is indicated as in footnote (a).

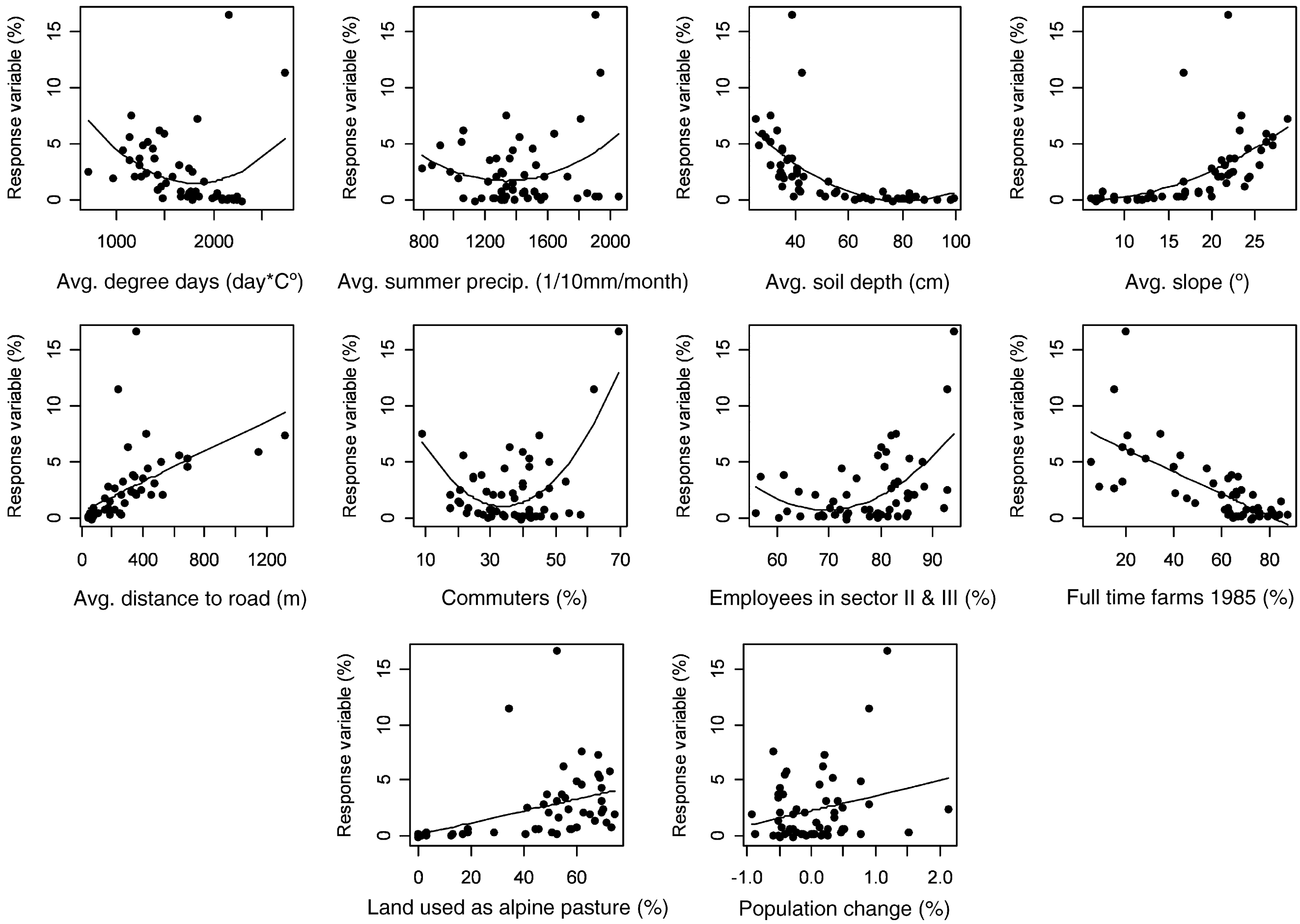

Fig. 2. Scatterplots showing the bivariate relationships between the geo-physical and socio-economic variables and the response variable (percentage change of agricultural areas multiplied by a constant of −1). Except for the variables population change and avg. summer precipitation, fitted linear and squared curves illustrated in the scatterplots are statistically significant ($p < 0.05$). Significance must be interpreted with caution due to the spatial autocorrelation in data (Table 3).

higher proportions of part-time farms are favoured in terms of land abandonment and forest re-growth. The variable population change shows no relation to the response in the scatterplots.

Two regions in the southern canton of Ticino (called Malcantone and Valli di Lugano) differ from other regions in several respects. They show, for example, the highest abandonment rates of all regions, but intermediate steepness and comparatively high heat sums (Fig. 2).

The preliminary model diagnostics revealed a high level of collinearity between the explanatory variables. The R^2-values of the models, where each of the explanatory variables was treated in turn as the dependent variable in a model with all other explanatory variables as predictors showed a maximum of 0.92. This value is more than the 'critical' value of 0.80 as proposed by Menard (2002). In order to reduce multicollinearity, we followed the suggestions by Maddala (2001) and removed some variables from the statistical models. In detail, we removed the variables average soil depth, average distance to roads and full-time farms. The variables average soil depth and average distance to roads were removed from the models because they were highly correlated with the variable average slope ($R^2 = 0.88$ and 0.83, $p < 0.001$). The variable average slope was retained in the models because we regard the steepness of slopes as a key factor in the process of land abandonment. The variable full-time farms was removed from the models because it was highly correlated with all other explanatory variables ($R^2 = 0.83$, $p < 0.001$). By removing these variables from the statistical models, we reduced the level of multicollinearity to obtain an R^2 value of 0.82. This value is only slightly in excess of the 'critical' R^2 value, but is accepted in order to avoid bias in the statistical models, due to the omission of variables (Menard, 2002).

3.2. Model results

The models were fitted in order to investigate the multivariate relationships between the geo-physical and socio-economic variables and response (percentage change of agricultural areas multiplied by a constant of −1). Both models (Table 4) show a very good overall fit, with pseudo R^2-values of 0.85 (MLLAG model) and 0.76 (MLERR model). This indicates that land abandonment is, at least partially, a reaction to the geo-physical and socio-economic conditions within a region. The higher pseudo R^2 and lower AIC values indicate that the MLLAG model fits better than the MLERR model. The spatial Breusch–Pagan test for the MLLAG model ($p = 0.658$) and MLERR model ($p = 0.296$) and the LM-test for the MLLAG model ($p = 0.391$)

Table 4
Results of the spatial lag model (MLLAG) and the spatial error model (MLERR)

Estimation results[a,b]		
	MLLAG	MLERR
Intercept	2.64E+01 (2.466)*	3.07E+01 (2.753)**
Average degree days	−2.30E−04 (−0.064)	−1.98E−03 (−0.526)
Average degree days (squared)	−5.66E−08 (−0.057)	7.93E−07 (0.800)
Average summer precipitation	−1.38E−03 (−0.304)	−2.15E−03 (−0.374)
Average summer precipitation (squared)	5.79E−07 (0.367)	9.19E−07 (0.456)
Average slope (squared)	5.74E−03 (3.292)**	7.82E−03 (4.086)***
Commuters	−3.74E−01 (−5.510)***	−3.82E−01 (−4.922)***
Commuters (squared)	5.61E−03 (6.149)***	5.99E−03 (5.824)***
Employees in sectors II and III	−5.72E−01 (−2.202)*	−6.60E−01 (−2.437)*
Employees in sectors II and III (squared)	4.07E−03 (2.327)*	4.47E−03 (2.467)*
Land used as alpine pasture	−1.89E−02 (−1.382)	3.66E−03 (0.210)
Population change	−4.88E−01 (−1.211)	−2.32E−01 (−0.529)
Dummy for Davos and Oberengadin	−1.84E+00 (−0.905)	−2.20E+00 (−1.070)
Wyagri (spatially lagged response)	0.482 (4.937)***	–
Wu (spatially lagged error term)	–	0.506 (4.429)***
Goodness-of-fit and assumption violation tests		
Pseudo R^2	0.856	0.769
AIC	198.83	207.83
LM-test (residual autocorrelation)	0.733 ($p = 0.391$)	–
Spatial Breusch–Pagan (heteroscedasticity)	9.514 ($p = 0.658$)	14.066 ($p = 0.296$)
LR-test (test on null hypothesis ρ and $\lambda = 0$)	15.67 ($p < 0.001$)	6.67 ($p = 0.009$)

[a] The z-values for the MLLAG and MLERR model are given in brackets. Significance is indicated with ***, ** and * for $p < 0.001$, $p < 0.01$ and $p < 0.05$, respectively. Fields marked "–" indicate that variables or tests are not foreseen for these models. AIC: Akaike Information Criterion; LM-test: Lagrange Multiplier test; LR-test: Likelihood Ratio test.

[b] Response variable: (percentage change of agricultural areas × −1), $N = 55$, spatial weights matrix: row standardised based on first order contiguity.

show that heteroscedasticity and spatial autocorrelation of model residuals were accounted for.

The variables average slope, commuters and employees in sectors II and III contribute significantly ($p < 0.05$) to explaining land abandonment in the statistical models. However, we found that the regions Malcantone and Valli di Lugano strongly influenced our model results. By excluding these regions, the variables commuters and employees in sectors II and III are insignificant. Nevertheless, eliminating observations displaying extreme values would violate our quest for generality concerning the statistical models. Therefore, we did not remove these regions from the models.

Both the spatially lagged response variable and the spatially lagged error variable contribute significantly ($p < 0.001$) to explaining land abandonment in the models. This indicates that part of the observed pattern of land abandonment could not be effectively modelled by the geo-physical and socio-economic variables included in the models.

4. Discussion

4.1. General findings

Our models show the regional-scale pattern of agricultural land abandonment (as measured by forest re-growth) in the Swiss mountains over a 12-year period between the 1980s and 1990s. This pattern can be summarised as follows: land abandonment occurred more frequently where slopes are steep, the proportion of commuters and the proportion of employees in the secondary and tertiary sectors were high or low, and where land abandonment occurred in neighbouring regions. The bivariate scatterplots illustrate the pattern of land abandonment, based on all geo-physical and socio-economic variables (Fig. 2). With regard to the variables which were removed from the models to reduce multicollinearity, it shows that land is more frequently abandoned where soils are shallow, road infrastructure is less developed and the proportion of full-time farms is low.

That farmers abandon their land more frequently where soils are shallow, slopes are steep and road infrastructure is less developed is in keeping with findings from other European countries (Baldock et al., 1996) and earlier Swiss case studies (Surber et al., 1973; Walther, 1986; Pezzatti, 2001). It confirms our study hypothesis, that land has been abandoned where the cultivation costs were high and yield potential low, i.e. cultivation costs were not covered by yields.

The variables proportion of commuters and proportion of employees in the secondary and tertiary sectors were used as proxies to test a possible effect of the opportunity costs of farm labour on land abandonment as discussed by Strijker (2005). The models show a significant U-shaped relationship between the proportion of commuters and the response variable. This would suggest that land abandonment occurred primarily where strong labour markets were present or easily accessible (i.e. where the opportunity costs of farm labour are high) which is as expected. For the variable employees in the secondary and tertiary sectors, the models also suggest a U-shaped relationship to the response. However, as shown by the scatterplots (Fig. 2), this relationship is rather hook-shaped. It shows that land abandonment occurred more frequently where the proportion of employees in the secondary and tertiary sectors was high which is as expected. However, we found a strong influence of a small number of regions (including Malcantone and Valli di Lugano) on this result. By excluding these regions, the proportion of commuters and the proportion of employees in the secondary and tertiary sectors are insignificant. Overall, this result suggests a local influence of strong labour markets (and opportunity costs of farm labour) on land abandonment. However, in the mountain area as a whole, an effect of labour markets on land abandonment seems to be less distinct.

The proportion of alpine pastures was used as a variable to test the influence of agricultural income differences, which arise from the different subsidy regime for alpine pastures, compared to agricultural areas outside alpine pastures. This variable is not significant in the models, which suggests no influence of subsidy differences on land abandonment. The corresponding scatterplot (Fig. 2) shows that forest re-growth was generally lower where the proportion of alpine areas was lower. With increasing proportions of alpine pastures, both high and low abandonment rates can be observed. This indicates that in some regions the cultivation of alpine pastures did not change although the proportion of alpine pastures is comparatively high. These regions are mostly located in the Northern Alps, where alpine pastures are generally less steep and more accessible than in the other parts of the study area (Surber et al., 1973). The unchanged maintenance of alpine pasturing in the Northern Alps might explain the insignificant relationship of this variable in the statistical models.

We could not foresee the relationship between the proportion of full-time farms and land abandonment. Scatterplots (Fig. 2) show that the abandonment rate is higher where the proportion of full-time farms is lower (i.e. off-farm employment is common). We interpret this relationship as follows: unfavourable cultivation conditions lead not only to the abandonment of marginal land, but also to the abandonment of full-time farms. Low proportions of full-time farms indicate farm abandonment in the past. The abandonment of farms and land are strongly correlated because they are caused by the same factors. Thus, off-farm employment is related to land abandonment, although it is not necessarily its cause. A positive relationship between off-farm employment and land abandonment has also be found in northern Italy (Petretti, 1996), central Spain (Romero-Calcerrada and Perry, 2004) and parts of Germany (Baldock et al., 1996). However, other studies show that the relationship between off-farm employment and land abandonment is more complex. Hetland (1986) describes regions in rural Norway where off-farm employment has slowed down the abandonment of farms and cultivation. Daniels (1986) showed for the U.S.A. that hobby farming can be an incentive to maintain cultivation.

Model results and scatterplots show that migration had no effect on land abandonment in our study area and on the regional scale. This suggests differences between the Swiss mountains and other European mountain regions, such as the French Alps and north-western Spain, where rural emigration has been linked to land abandonment (Douguédroit, 1981; MacDonald et al., 2000). Our result confirms the complex relationships between migration, land abandonment and forest re-growth in the Swiss mountains, as hypothesised by Mather and Fairbairn (2000). They explain this complexity by the industrialisation of parts of the Swiss mountains, which prevented rural depopulation in spite of declining agriculture.

Land abandonment does not occur until a certain threshold of steepness and soil stoniness has been reached (Fig. 2). Above this threshold, the abandonment rate increases progressively. Close to it, almost no land is abandoned although slopes are relatively steep and soils comparatively shallow. These regions can mostly be found in the Northern Alps and in the canton of Jura, where the majority of farms are managed on a full-time basis. Farmers in these regions are often older (Surber et al., 1973). Older farmers often have little education and therefore few opportunities to work off the farm, which forces them to maintain the cultivation of marginal land. Another explanation for the maintenance of cultivation is that dairy farming (which is common in the Northern Alps and the canton of Jura) is 'attractive' for farmers because milk quotas secure regular farm income. Farmers in these regions might also maintain the cultivation because they lack alternatives for their land, buildings and machines. These 'locked investments' make the abandonment of cultivation difficult and can force farmers to maintain the cultivation of marginal land (Strijker, 2005).

What is the reason for the particularly high abandonment rates in Malcantone and Valli di Lugano, compared to other regions? A specific characteristic of these regions is the Mediterranean-like climate. It might lead to faster forest growth, thus resulting in higher clearing costs (particularly on pastures) than in all other regions. Both regions are also in the vicinity of the cities of Bellinzona and Lugano, which are important centres for industry and tourism. This closeness to job centres is related to higher opportunity costs of farm labour, which might be another reason for land abandonment in both regions. In summary, we interpret the particular high abandonment rates in Malcantone and Valli di Lugano as the result of comparably high cultivation costs and opportunity costs of agricultural labour, which is in keeping with economic theory.

4.2. Methodological considerations

Much has been written about the influence of the spatial scale on the results of spatial statistical analyses. The "modifiable area unit problem" (MAUP) is often mentioned in this context (Green and Flowerdew, 1996). It describes how statistical results, based on the same dataset, change if the spatial scale and/or zoning (e.g. region boundaries) change. Our estimates are likely to be scale-dependent because much of the intrinsic variation in the original data has been masked through aggregation. The high collinearity between our explanatory variables and the good model fits are most likely the result of this aggregation. Overall, our results are only valid for the regional scale. Thus, further analyses are necessary to investigate the scale dependency of our findings.

Neighbourhood effects are an important part of land-use change models. For cell-based modelling approaches, such as cellular automata, neighbourhood interactions even provide the basis to better understand the rules leading to the observed changes (Verburg et al., 2004). In spatial statistical models, neighbourhood effects are often regarded as a nuisance. One exception is given by Pfaff (1999), who found an influence (theory-founded) of the spatially lagged population and road density on deforestation. Anselin and Bera (1998) interpret a significant spatial lagged response as a measure of “the extent of spatial spillovers, copycatting or diffusion” between neighbouring regions.

The significant influence of our lagged response suggests that land abandonment is generated by processes that do not match the boundaries of our regions (Perz and Skole, 2003). The question must be raised as to whether there is an ‘exchange’ between farmers in neighbouring regions, causing similar abandonment rates within these regions. However, we cannot answer this question, because we could not separate possible human driven ‘spillover’ effects, as suggested by Anselin and Bera (1998), from other factors causing a significant spatially lagged response variable. The aggregation of variables, non-detected non-linear relationships or omitted geo-physical and socio-economic variables can cause similar effects (Anselin, 2002).

4.3. Practical relevance

We found no relationship between migration and land abandonment. This finding is important because rural depopulation is regarded as one of the main reasons for agricultural abandonment in European mountain regions (e.g. MacDonald et al., 2000). This result shows that understanding the processes leading to land abandonment requires a more holistic view.

The steeper the agricultural area, the higher the cultivation costs. Therefore, the Swiss agricultural policy has introduced progressive graded subsidies for the cultivation of steep slopes. These subsidies have been paid for over 25 years (Rieder, 1996). Our results still show a progressive relationship between steepness and land abandonment. It indicates that agricultural subsidies could not compensate all the regional disadvantages related to the cultivation of steep slopes.

Agricultural land is primarily abandoned and overgrown in the southern regions of the Swiss mountains. These regions are predestined for the ‘encouragement’ of land abandonment, e.g. through the establishment of “new wilderness areas” as in northern Italy (Höchtl et al., 2005). Such measures can help to save on agricultural subsidies and might offer opportunities for an alternative use of marginal land, e.g. in form of wildlife reserves.

5. Conclusion

This study showed the regional-scale pattern of agricultural land abandonment, measured via forest re-growth in the Swiss mountains. Results confirmed the expected pattern and showed that land abandoned takes place where cultivation costs are high and yields low. They also extended the knowledge about the pattern of land abandonment in the Swiss mountains. We found, for instance, non-linear relationships between steepness and soil depth and land abandonment. It showed that the progressively graded agricultural subsidies could not compensate all the regional disadvantages related to the cultivation of marginal land. This non-linearity and the negative relationship in the influence of part-time farming on land abandonment should be considered by decision-makers when designing policy measures to react to land abandonment and its consequences. A new finding from this study is that land abandonment occurred independently from migration. This is contrary to what has been found in other European countries. We conclude that political measures require a more holistic view of the processes of land abandonment, which this study provides. Further research is necessary regarding possible scale dependency of our findings and neighbourhood effects.

Acknowledgements

This study is part of the Swiss National Research Programme 48 (NRP48) “Landscapes and habitats of the Alps” (contract number 4048-064360) and is financed by the Swiss National Science Foundation (SNF). Additional funding came from the 6th Framework Programme of the European Union (contract number GOCE-CT-2003-505376). We would like to thank Dr. Priska Baur and Dr. Gillian Rutherford for fruitful discussions and Sarah Galea Keating for proofreading the manuscript. We also wish to thank four anonymous referees for their constructive suggestions and improvements.

Appendix A

The table lists our estimates of agricultural areas (Agriculture 1985), their decrease measured by forest re-growth (Abandoned) and increase measured by forest clearing (Re-used) for each region. The estimates are based on two Swiss land-use surveys and refer to areas below an estimated climatic treeline (see text). The corresponding estimation errors (in %) were calculated by means of Eq. (2).

IHG-region	Agriculture 1985 (ha) ±%	Abandoned (ha) ±%	Re-used (ha) ±%
Zürcher Berggebiet	13776 ± 1.7	23 ± 40.9	18 ± 46.2
Oberes Emmental	18222 ± 1.5	98 ± 19.8	40 ± 31.0
Jura-Bienne	17650 ± 1.5	126 ± 17.5	125 ± 17.5
Oberland-Ost	29804 ± 1.1	778 ± 7.0	137 ± 16.7
Kandertal	16115 ± 1.5	264 ± 12.1	71 ± 23.3
Thun-Innertport	32052 ± 1.1	266 ± 12.0	67 ± 23.9
Obersimmental-Saanenland	28684 ± 1.2	337 ± 10.7	98 ± 19.8
Kiesental	8360 ± 2.1	4 ± 98.0	2 ± 138.6
Schwarzwasser	15095 ± 1.6	97 ± 19.9	14 ± 52.4
Trachselwald	18627 ± 1.4	17 ± 47.5	25 ± 39.2
RegioHER	46703 ± 0.9	213 ± 13.4	153 ± 15.8
Uri	25070 ± 1.2	890 ± 6.6	117 ± 18.1
Einsiedeln	14565 ± 1.6	90 ± 20.7	60 ± 25.3
Rigi-Mythen	20437 ± 1.4	225 ± 13.1	102 ± 19.4
Sarneraatal	17131 ± 1.5	173 ± 14.9	54 ± 26.7
Nidwalden	13739 ± 1.7	100 ± 19.6	56 ± 26.2
Glarner Hinterland-Sernftal	12607 ± 1.7	311 ± 11.1	60 ± 25.3
Sense	18041 ± 1.5	86 ± 21.1	25 ± 39.2
Gruyère	28296 ± 1.2	238 ± 12.7	51 ± 27.4
Glâne-Veveyse	18465 ± 1.4	15 ± 50.6	13 ± 54.4
Haute-Sarine	4806 ± 2.8	9 ± 65.3	1 ± 196.0
Thal	6239 ± 2.5	33 ± 34.1	25 ± 39.2
Appenzell A.Rh.	15974 ± 1.6	37 ± 32.2	15 ± 50.6
Appenzell I.Rh.	9576 ± 2.0	33 ± 34.1	10 ± 62.0
Toggenburg	25416 ± 1.2	115 ± 18.3	38 ± 31.8

IHG-region	Agriculture 1985 (ha) ±%	Abandoned (ha) ±%	Re-used (ha) ±%
Sarganserland-Walensee	23264 ± 1.3	565 ± 8.2	92 ± 20.4
Surselva	41368 ± 1.0	1709 ± 4.7	169 ± 15.1
Moesano	8113 ± 2.2	562 ± 8.3	88 ± 20.9
Viamala	20290 ± 1.4	833 ± 6.8	86 ± 21.1
Prättigau	22430 ± 1.3	574 ± 8.2	48 ± 28.3
Schanfigg	6699 ± 2.4	163 ± 15.4	27 ± 37.7
Mittelbünden	22799 ± 1.3	901 ± 6.5	105 ± 19.1
Bregaglia	4101 ± 3.1	247 ± 12.5	20 ± 43.8
Poschiavo	5750 ± 2.6	463 ± 9.1	30 ± 35.8
Unterengadin-Münstertal	26016 ± 1.2	597 ± 8.0	91 ± 20.5
Locarnese e Vallemaggia	18729 ± 1.4	1541 ± 5.0	182 ± 14.5
Tre Valli	20874 ± 1.4	1243 ± 5.6	290 ± 11.5
Malcantone	1762 ± 4.7	243 ± 12.6	42 ± 30.2
Valli di Lugano	3727 ± 3.2	682 ± 7.5	64 ± 24.5
Pays-d'Enhaut	9863 ± 2.0	171 ± 15.0	33 ± 34.1
Nord Vaudois	23393 ± 1.3	82 ± 21.6	35 ± 33.1
Vallée de Joux	4292 ± 3.0	49 ± 28.0	16 ± 49.0
Goms	12699 ± 1.7	594 ± 8.0	41 ± 30.6
Brig-Aletsch	13171 ± 1.7	729 ± 7.3	42 ± 30.2
Visp/Westlich Raron	20285 ± 1.4	1102 ± 5.9	102 ± 19.4
Leuk	7726 ± 2.2	282 ± 11.7	39 ± 31.4
Sierre	9147 ± 2.0	343 ± 10.6	87 ± 21.0
Sion	22161 ± 1.3	674 ± 7.5	114 ± 18.4
Martigny	24279 ± 1.3	1622 ± 4.9	110 ± 18.7
Chablais	27548 ± 1.2	640 ± 7.7	181 ± 14.6
Centre-Jura	22811 ± 1.3	72 ± 23.1	67 ± 23.9
Val-de-Travers	8071 ± 2.2	38 ± 31.8	22 ± 41.8
Val-de-Ruz	9213 ± 2.0	38 ± 31.8	24 ± 40.0
Jura	44647 ± 0.9	206 ± 13.7	283 ± 11.7
Davos and Oberengadin	21502 ± 1.3	561 ± 8.3	30 ± 35.8

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