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Natural forest regrowth as a proxy variable for agricultural land abandonment in the Swiss mountains: a spatial statistical model based on geophysical and socio-economic variables

Mario Gellrich · Priska Baur · Niklaus E. Zimmermann

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Abstract In many European mountain regions, natural forest regrowth on abandoned agricultural land and the related consequences for the environment are issues of increasing concern. We developed a spatial statistical model based on multiple geophysical and socio-economic variables to investigate the pattern of natural forest regrowth in the Swiss mountain area between the 1980s and 1990s. Results show that forest regrowth occurred primarily in areas with low temperature sum, intermediate steepness and soil stoniness as well as close to forest edges and relatively close to roads. Model results suggest that regions with weak labor markets are favored in terms of land abandonment and forest regrowth. We could not find an effect of population change on land abandonment and forest regrowth. Therefore, we conclude that decision makers should consider non-linearities in the pattern of forest regrowth and the fact that labor markets have an effect on land abandonment and forest regrowth when designing measures to prevent agricultural land abandonment and natural forest regrowth in the Swiss mountains.

Keywords agriculture · land-use change · logistic regression · reforestation · spatial autocorrelation

1 Introduction

In contrast to the global trend of deforestation, particularly in non-industrialized countries, a continuous increase in forest cover can be observed in many industrialized countries [6, 10, 16, 22]. In these countries, the continuous increase in forest area in recent decades can be attributed in particular to natural forest regrowth [1, 7, 13, 24, 29]. It often occurs in agricultural areas below the treeline when cultivation is abandoned because it ceases to be viable under the changing economic conditions. This process is also known as agricultural “marginalization” [2]. The degree of this specific form of extensification is often determined by location-specific social, economic, political and environmental conditions [30].

Land abandonment and natural forest regrowth lead to a variety of consequences for the environment. Negative consequences are the irreversible loss of traditional cultivation forms such as alpine and mountain pasturing [11], the long-term loss of species-rich habitats [1] and the higher probability of wildfires [29]. Positive consequences are the stabilization of soils [36], carbon sequestration [10] and the temporary increase in biodiversity [15].

Available studies on the human-driven patterns and causes of agricultural land abandonment can safely be divided into studies with an agricultural economics perspective or social geographical perspective in social geography, land abandonment is considered to be the result of social and economic development, changes in values (e.g., migration, farm abandonment) and preferences (e.g., changing management practices) are identified as the relevant causes [14, 37, 39]. In agricultural economics, the ‘operators’ of agricultural land (normally farmers) are assumed to be profit maximizers, who allocate their labor to the land yielding the highest rent. Land abandonment is explained as the result of exogenous factors such as changing markets, technologies and infrastructure developments which affect the viability of agricultural cultivation [33]. In this study, we use an agricultural economics perspective to explain

M. Gellrich (✉) · P. Baur · N. E. Zimmermann
Swiss Federal Institute for Forest,
Snow and Landscape Research WSL,
Zürcherstrasse 111,
CH-8903 Birmensdorf, Switzerland
e-mail: mario.gellrich@wsl.ch

agricultural land abandonment and subsequent forest regrowth.

In Switzerland, empirical studies on land abandonment and forest regrowth have to date been carried out at the local level. Surber et al. [34] investigated the pattern and causes of agricultural land abandonment in selected municipalities. Their findings, which were also used to make nationwide predictions of future states of fallow land, suggest that land abandonment and forest regrowth mostly take place where the topographic and agroclimatic conditions are unfavorable for agricultural production and agricultural incomes are low. Walther [39] suggests that land abandonment is the result of a prevented modernization of land use. Pezzatti [26] found a direct relationship between road infrastructure developments and land-use intensity. However, as available studies in Switzerland are solely restricted to small case studies, the current knowledge about the patterns and processes is limited.

The objective of this study was to investigate which geophysical and socio-economic determinants contribute to the explanation of natural forest regrowth in the Swiss mountain area over a 12-year period between the 1980s and 1990s. We were also interested in the direction of the correlation between forest regrowth and each of the geophysical and socio-economic proxy variables in the statistical model. We used remote sensing data to investigate changes in land use and forest cover. As in similar studies based on remote sensing data [12, 21, 25], we used natural forest regrowth as a proxy variable for agricultural land abandonment. Thus, the correlations between natural forest regrowth and the selected geophysical and socio-economic variables found in the statistical model also allowed us to identify *where* agricultural land-use changes have occurred. This is typically referred to as the pattern of land-use change [27]. We hypothesized that the pattern of forest regrowth is linked to the cost/benefit-based management decision of landowners, i.e., that forest regrowth occurs in agricultural areas with high cultivation costs and low yield potential.

2 Methods

2.1 Study area

The study area (figure 1) was the Swiss mountain area as delineated by the “Act on Investment Aid for Mountain Regions” [38]. It covers 68% of the total area of Switzerland (2,813 km^2) and is inhabited by 24% of the Swiss population. The economic and agricultural structure within the study area differs widely, but in general, it follows a north–south gradient. In the southern parts of the study area, tourism is very important; agriculturally, a small-scale ownership structure dominates and part-time farming is common. In the Jura Mountains and in the northern parts of the study area, tourism is less important; however, the accessibility of urban centers is often better, and agriculture is characterized by larger farms and a higher proportion of full-time farms. Over a 12-year period between the 1980s and 1990s, the area covered by forest and bushes in the study area increased by 14,800 ha or 1.9% (source: own calculations based on Swiss land-use statistics data). Much of the new forest vegetation occurred on former agricultural lands [32]. Locations in the study area, where we observed abandoned and overgrown agricultural land, are shown in figure 1.

Within our study area, we aimed to compare abandoned and non-abandoned agricultural land. Since forest regrowth was our measure of abandonment, we delineated agricultural areas where forest cannot occur, i.e., above the climatological treeline. As an exact measure of the treeline was not available, it was estimated based on the potential treeline as delineated in the distribution atlas of vascular plants [35]. Our modification extended the treeline delineated by Sutter and Welten [35] by 300 m (vertical distance on the digital elevation model). This modification was used because a validation exercise revealed that some of the new forest areas occurred above this delineated treeline. The area above the newly demarcated treeline was subsequently excluded from our analysis.

2.2 Response variable

The binary response variable used in our statistical model (presence/absence of forest regrowth) was derived from two nationwide land-use statistics (called ASCH). The ASCH provides two comparable data sets for the years 1979/1985 and 1992/1997 (hereafter referred to as ASCH85 and ASCH97), where the years indicate the evaluation time span of the aerial photographs [32]. In both surveys, 74 land-use/land-cover categories were distinguished by overlaying aerial photographs with a regular 100-m lattice. A single land-use category was manually assigned to each lattice point, by evaluating a so-called ‘reference area’ (size, 50 × 50 m). Classifications were verified in the field where difficulties arose from the interpretation of aerial photographs. Changes in land use between both inventories can be analyzed through comparison of the land-use category assigned to lattice points in ASCH85 and ASCH97, respectively.

The ASCH comprises several land-use categories for ‘agriculture’ and ‘forest’. Other ASCH land-use categories represent transition states between agriculture and forest. Since preliminary investigations showed that many of the new forest areas between 1979/1985 and 1992/1997 have their origin in these transitional land-use categories, we extended the definition of ‘agriculture’ and ‘forest’ prede-

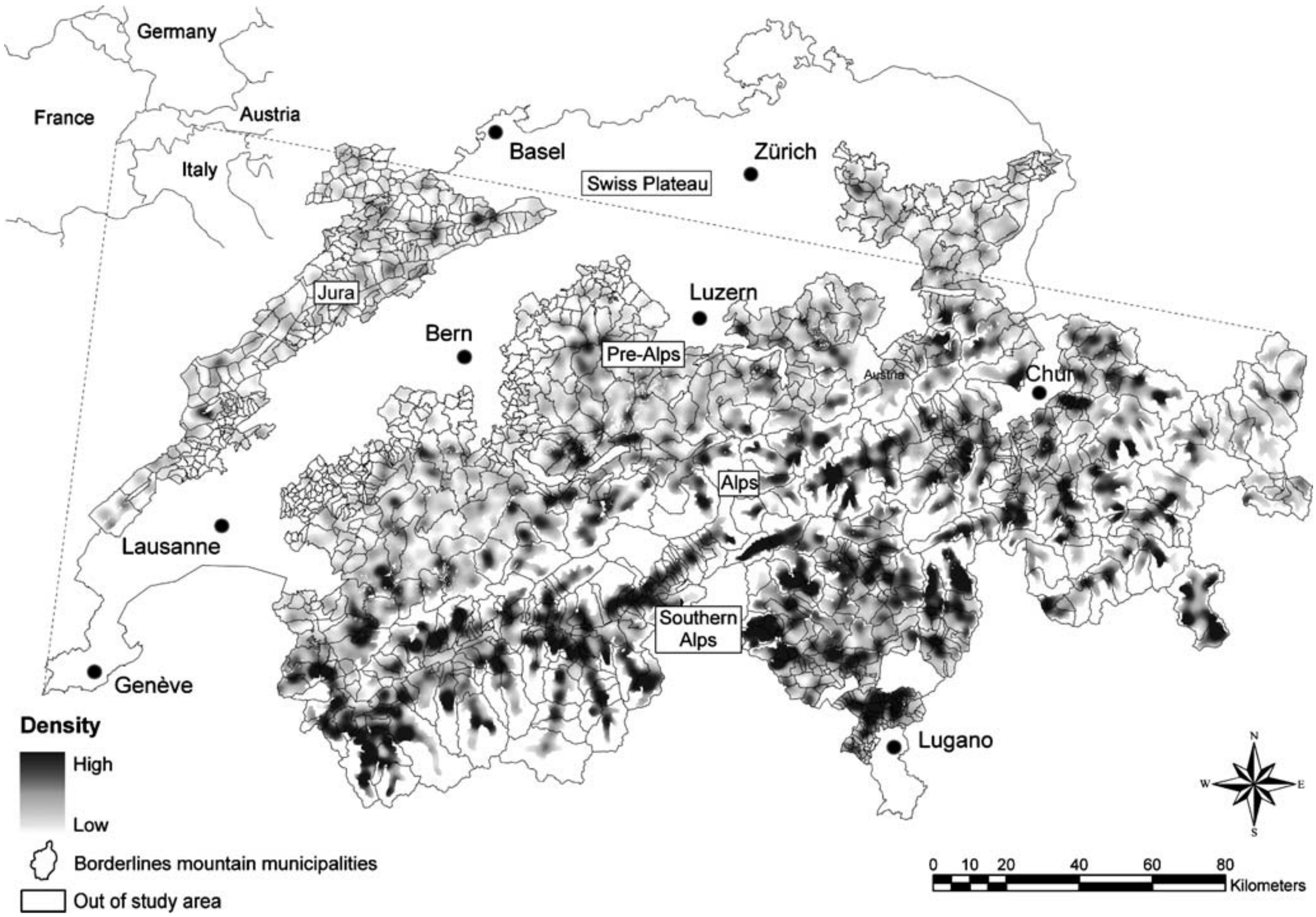

Figure 1 Swiss mountain area with the density of agricultural land (measured on a hectare lattice) that changed from agricultural use to forest. Data were taken from two nationwide land-use surveys carried out by the Swiss Federal Statistical Office in the years 1979/1985 and 1992/1997. The density was calculated by using a kernel-density function with radius of 3 km in ArcGis 8.3 (ESRI)

fined by the ASCH. Our definition of 'forest' includes all land-use categories, where the reference area is completely or partially covered by trees, bushes and scrub and that show no agricultural land use. This includes the following land-use categories: closed forest, open forest, bushes, groups of trees on areas without agricultural use, and bush and scrub vegetation. Our definition of 'agriculture' includes all land-use categories with high and low use intensity, i.e., vineyards, orchards, meadows and arable farm land, farm pastures, mountain pastures, alpine and Jura pastures. It additionally includes land-use categories that are partially covered by trees and scrubs, but show agricultural land use on the reference area. This includes the following: groups of trees on agricultural areas, hedges and groups of trees on cultivated land, and unproductive grassland and scrub vegetation. For detailed definitions of each ASCH land-use category, see BFS [4]. Changes in land use were analyzed by comparing ASCH lattice points of both years. Lattice points which changed from agricultural land use to forest are referred to as 'presence' observations. Likewise, lattice points which showed agricultural use in both ASCH surveys are referred to as 'absence' observations. Within the whole study area, we observed 21,630 presence and 932,561 absence observations.

To reduce the spatial autocorrelation in our presence/absence data, we used a random sample of 1,000 observations for presence and 1,000 observations for absence (i.e., 2,000 observations in total for spatial modeling). Random sampling involves 'declustering' of observations – which means that within each group of the presence/absence observations (i.e., ASCH lattice points that are 100 m apart), we randomly sampled only one observation. This approach was undertaken to avoid sampling two or more observations from the same agricultural area, i.e., ensuring that the sampled observations were independent from another.

2.3 Explanatory variables

The explanatory variables used in our model (table 1) reflect the suitability of agricultural land for cultivation as

Table 1 Potential explanatory variables.

Variable description	Unit	Spatial resolution (m)	Exp. sign[a]	Source[b]
Degree days[c]	(day °C)	100	−	CSD/DEM25
Potential direct shortwave radiation[c]	(kJ/day)	100	?	CSD/DEM25
Mean precipitation sum[c]	(1/10 mm/month)	100	?	CSD/DEM25
Distance to forest edges	(m)	100	−	ASCH
Soil depth	(cm)	100	−	BEK200
Soil stoniness	(%)	100	+	BEK200
Slope	(°)	100	+	DEM25
Distance to roads[d]	(m)	100	+	Vector 25©
Distance to settlements[d]	(m)	100	+	ASCH
Dummy for alpine pastures	(0/1)	Alpine zone	+	SFSO
Dummy for population change	(0/1)	Municipality	+	SFSO
Dummy for labor markets	(0/1)	Municipality	+	Bätzing et al. [3]
Coordinate in *x*-direction	(m)	100	?	–
Coordinate in *y*-direction	(m)	100	?	–

The spatial resolution indicates the level of spatial detail given to the variable. The expected sign indicates the assumed nature of the relationship between each explanatory variable and forest re-growth. The source describes the origin of the data.

[a] The expected sign refers to the relationship between each of the explanatory variables and the response variable: (−) negative (+) positive, (?) undetermined.

[b] The following sources were used: CSD, climate station data (Normals 1961–1990); DEM25, digital elevation model at 25 m resolution; ASCH, Swiss land-use statistics; SFSO, Swiss Federal Statistical Office; BEK200, Bodeneignungskarte der Schweiz – soil suitability map; Vector 25, Mapped Vector25 data© 2003 SwissTopo (DV033594); SwissTopo, Federal Office of Topography.

[c] The variable was calculated as average per growing season (May to September). For details of variable calculation, see Zimmermann and Kienast [40].

[d] The distance was calculated as the Euclidian distance.

well as the opportunity costs (i.e., the value of the alternative use) of agricultural labor. Under the assumption that farmers are profit maximizers, we expected to find positive or negative relationships between the explanatory variables and the response variable. Our hypothesized relationships between each of the explanatory variables and the response variable are expressed through the 'expected sign' in table 1.

We used the variables *degree days*, *potential direct shortwave radiation*, *mean precipitation sum* and *soil depth* as proxies for the yield potential of agricultural land. The effect of *radiation* and *precipitation* was not *a priori* determined because the yield potential can be low at locations with both high and low values for these variables, resulting in non-linear relationships. We additionally used *distance to forest edges* as a proxy for yield potential. Land close to forest edges in general has less favorable cultivation conditions than land remote from forest edges (due to shade, woody plant seed rain, etc.). Thus, we expected to find a negative relationship between the distance to forest edges and forest regrowth.

We used the variables *slope*, *soil stoniness*, *distance to roads* and *distance to settlements* as proxy variables for cultivation costs. These variables reflect the degree of mechanization possible in an agricultural area as well as the accessibility of agricultural land by vehicles and on foot. We expected to find forest regrowth primarily in areas where the cultivation and accessibility costs were high, i.e., where slopes are steep, soils are stony and where land is remote from roads and settlements.

In Switzerland, farmers receive lower subsidies for alpine pasturing than for mowing, which led us to the expectation that the different subsidy regimes have an influence on forest regrowth. We used a digital map of the Swiss agricultural production zones (Landwirtschaftliche Zonengrenzen) to calculate a binary dummy variable which contained the value of 1 for alpine pastures and a value of zero for all other agricultural land.

Rural depopulation [16] and immigration [13] have been linked to land abandonment and forest regrowth in European mountain regions. Mather and Fairbairn [18] assume complex relationships between migration, land abandonment and forest regrowth in Switzerland. To test a possible long-term influence of population change on forest regrowth, we calculated a binary dummy variable based on population censuses taken in the years 1930 and 1990 at the municipality level. In detail, we assigned a value of 1 to all municipalities in which the population had increased between both points in time and a value of zero to all other municipalities.

Off-farm employment is often related to land abandonment because farmers who work elsewhere generally have better paid jobs, and therefore do not rely on the cultivation of their marginal land [2]. The differences between their agricultural and off-farm incomes forces farmers to invest their labor outside the agricultural sector. In economic terms, one would say farmers abandon their land because they have high opportunity costs of agricultural labor [33]. We used a binary dummy variable which reflects strong and weak labor markets to test a possible effect of the opportunity costs of agricultural labor on land abandonment and forest regrowth. The variable was calculated based on a classification of mountain municipalities by Bätzing et al. [3]. Bätzing et al. [3] defined 11 economic municipality types based on the proportion of employees in the primary, secondary and tertiary sectors (primary = agriculture, secondary = industry, tertiary = service including tourism) and the proportion of employees that are commuters. To calculate our binary dummy variable, we assigned a value of 1 to all municipalities in which the majority of employees work in the secondary and tertiary sectors and a value of zero to all other municipalities. We expected to find land abandonment and forest regrowth primarily in municipalities in which the majority of employees work in the secondary and tertiary sectors, i.e., where labor markets are strong.

To account for potential spatial autocorrelation in model residuals from determinants of forest regrowth for which suitable proxy variables could not be included in the model, we followed the suggestions of Müller and Zeller [21] and included the *x*- and *y*-coordinates of the sample observations as additional explanatory variables.

To visualize our data extraction process, imagine that we stacked all thematic maps representing the potential explanatory variables. A pin pierces the stack of the thematic maps at each presence/absence observation (sampled lattice point), and the mapped information for the point – slope, soil depth, distance to roads, population change, etc. – was recorded and stored in a database.

2.4 Statistical model

Logistic regression, which was chosen as the modeling approach in our study, is designed to estimate the parameters of a multivariate statistical model where the response variable is binary and the explanatory variables are continuous or categorical. Logistic regression yields coefficients and associated confidence intervals for each explanatory variable. The equation of a logistic regression function is given by Hosmer and Lemeshow [9]:

$$P(Y=1)=\frac{\exp(\alpha+\beta_1X_1+\beta_2X_2+\cdots+\beta_nX_n)}{1+\exp(\alpha+\beta_1X_1+\beta_2X_2+\cdots+\beta_nX_n)} \quad (1)$$

where $X_1 ... X_n$ are explanatory variables, $\beta_1 ... \beta_n$ are the corresponding parameter estimates and α is the constant term. To assess the overall goodness of model fit, we used a pseudo R^2 measure [8]:

$$\text{pseudo } R^2=(D_0-D_R)/D_0 \quad (2)$$

where D_0 is the deviance of the model with the intercept only and the D_R is the deviance that remains unexplained by the model after all explanatory variables have been included.

The linearity of the bivariate relationship between each of the explanatory variables and the response variable were tested [9]. For explanatory variables that showed non-linear relationships to the response variable, we followed the suggestions by Serneels and Lambin [31] and added quadratic terms of the respective explanatory variables to the model.

For model validation, we calculated the area under the receiver operating characteristics (ROC) curve (= AUC, [20]) applied to an independent data set. In an ROC plot, the fraction of observed presence correctly predicted (true positives) is plotted on the *y*-axis; the fraction of observed presence incorrectly predicted (false positives) 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 based on different 'probability' thresholds. 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.

Since unequal sampling rates do not influence the parameter estimates, but impact the model intercept, we followed the suggestions of Maddala [17] and adjusted the intercept for unequal sampling proportions when producing model predictions. Therefore, we decreased the model intercept by ($\ln p_1 - \ln p_0$), where p_1 and p_0 are the proportions of observations chosen from the two groups for which the response variable takes the values of 1 (presence) and 0 (absence), respectively. The model was built using a generalized linear model (GLM) in the R-statistics software version 2.1.1 [28].

3 Results

Low levels of collinearity between the explanatory variables were found in preliminary statistical analyses. The coefficients of determination (R^2) of the multivariate relationships between one of the independent variables against all the others ranged from 0.11 to 0.57. These R^2 values are below the critical R^2 value of 0.80 as proposed by Menard [19]. Thus, all explanatory variables (table 1) were used in the logistic regression model.

Results of the logistic regression model are illustrated in table 2. As indicated by the pseudo R^2 value of 0.10, the

Table 2 Results of the logistic regression model.

Variables	Parameter estimate	Standard error	*z* - Statistic	*Pr* (>|*z*|)
Intercept	−1.58e+00	0.7469	−2.110	0.0348
Degree days	−3.86e−04	0.0001	−2.907	0.0037
Potential direct shortwave radiation	−2.57e−06	0.0000	−0.183	0.8551
Mean precipitation sum	−1.14e−04	0.0002	−0.663	0.5072
Distance to forest edges	−1.22e−03	0.0006	−1.997	0.0458
Soil depth	2.44e−03	0.0028	0.868	0.3851
Soil stoniness	5.61e−02	0.0098	5.729	0.0000
Soil stoniness^2	−6.12e−04	0.0001	−4.906	0.0000
Slope	1.25e−01	0.0201	6.185	0.0000
Slope^2	−2.51e−03	0.0004	−6.599	0.0000
Distance to roads	−4.19e−04	0.0001	−4.006	0.0001
Distance to settlements	9.80e−05	0.0001	0.666	0.5056
Distance to settlements^2	−3.45e−08	0.0000	−1.215	0.2244
Dummy for population change	1.18e−01	0.1060	1.112	0.2663
Dummy for alpine pastures	2.20e−01	0.1448	1.520	0.1285
Dummy for labor markets	−3.17e−01	0.1057	−2.999	0.0027
Coordinate in *X*-direction	2.03e−06	0.0000	2.677	0.0074
Coordinate in *Y*-direction	−6.47e−06	0.0000	−4.126	0.0000
N (presence/absence)	1,000/1,000			
Pseudo R^2	0.10			
AUC (independent data set)	0.68			

overall explanatory power of the model was rather low. This suggests high spatial heterogeneity of the causes of land abandonment and forest regrowth throughout the study area. The prediction accuracy measured by the area under the ROC curve (AUC) measured on the basis of an independent data set was 0.68. According to DeLeo [5], the AUC value can be translated as the probability that the model will correctly distinguish between two cases (presence and absence of forest regrowth in this study).

The variables *degree days*, *slope*, *soil stoniness*, *distance to forest edges*, *distance to roads* and the binary dummy variable for strong and weak labor markets contributed significantly ($p < 0.05$) to the explanation of the response variable. The variable *degree days* showed the expected negative relationship to the response variable which indicates that forest regrowth occurred primarily where the temperature sum was low. The statistical significance of the squared terms of the variables *slope* and *soil stoniness* suggests that the probability of forest regrowth peaked at locations that showed neither very steep slopes and stony soils nor comparably shallow slopes and low degrees of soil stoniness. The variable *distance to roads* showed an unexpected negative relationship to the response. It suggests that forest regrowth occurred more frequently in areas close to roads than in areas remote from roads. The variables *mean precipitation sum, potential direct shortwave radiation* and *distance to settlements* showed no significant relationship to the response variable in the model ($p < 0.05$).

The binary dummy variable for strong and weak labor markets showed an unexpected negative relationship to the response. It indicates that forest regrowth occurred more frequently where labor markets were weak. The binary dummy variables for population growth and alpine pastures were not statistically significant in the model ($p < 0.05$).

The *x*- and *y*-coordinates of sample observations were statistically significant ($p < 0.05$). The positive sign of the *x*-coordinate indicates that forest regrowth occurred more frequently in the eastward direction of the study area. Likewise, the negative sign of the *y*-coordinate indicates that forest regrowth occurred more frequently in the southward direction of the study area. This suggests that there were geophysical and/or socio-economic determinants of forest regrowth in the southern and eastern parts of the study area for which suitable explanatory variables were absent from the model.

Model estimates were used to calculate the probability of forest regrowth for an independent sample of observations representing agricultural land use in the Swiss land-use survey taken in 1979/1985 (figure 2). When adjusting the model intercept for unequal sampling rates following the suggestions of Maddala [17], the predicted probabilities (which originally ranged from zero to 0.82) decreased to values between zero and 0.08. Model predictions for an independent data set showed that agricultural areas with low use intensity, such as bushy and stony alpine and Jura pastures, had the highest probabilities of conversion from agricultural land use to forest, which is as expected.

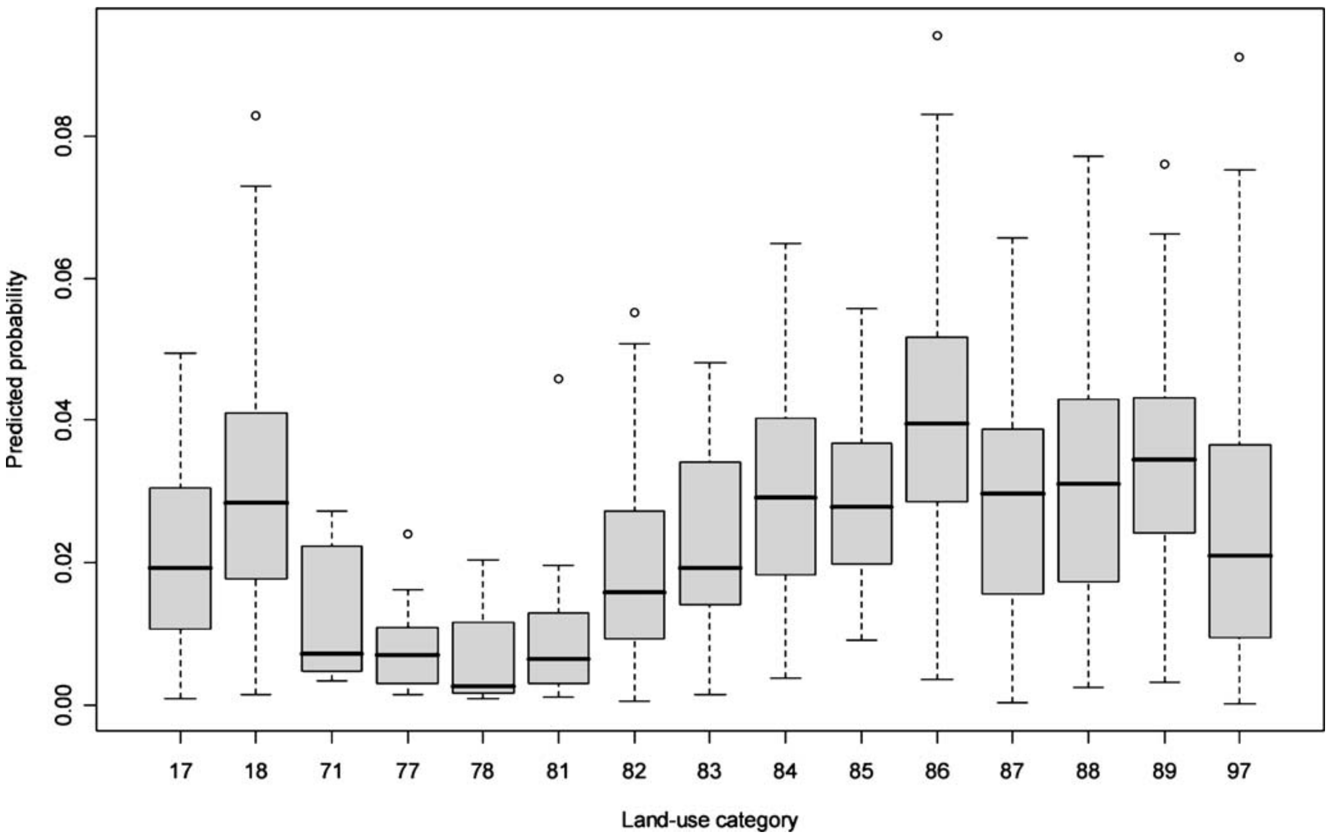

Figure 2 Predicted probabilities of conversion from agricultural land use to forest. The probabilities were calculated for an independent sample of observations representing agricultural use in the Swiss land-use survey taken in 1979/1985. Each box plot represents the median, 25% and 75% quantiles and extreme values of the predicted probabilities per land-use category. The land-use categories are coded according to the Swiss land-use statistics: (17) hedges and groups of trees on cultivated land, (18) groups of trees on agricultural areas, (71) vineyards, (77) orchards, (78) horticultural areas, (81) favorable meadows and arable farmland, (82) other meadows and arable farmland, (83) farm pastures, (84) bushy meadows and farm pastures, (85) mountain pastures and meadows, (86) bushy alpine and Jura pastures, (87) sheep pastures, (88) favorable Alpine and Jura pastures, (89) stony alpine and Jura pastures and (97) unproductive grassland and scrub vegetation

4 Discussion

Our model results describe the pattern of forest regrowth in the Swiss mountains over a 12-year period between the 1980s and 1990s. Results show that forest regrowth was mostly restricted to former alpine and Jura pastures with steep slopes, stony soils and low temperature sums. Many of the new forest areas occurred close to forest edges and relatively near to roads. Forest regrowth was a regional phenomenon, largely restricted to regions showing weak labor markets. Model results generally confirm our study hypothesis in that they suggest that land abandonment took place where the cultivation costs were high and the yield potential low.

Our model results confirm findings from case studies in neighboring Alpine regions, such as the French Alps, northern Italy, as well as parts of Austria and Slovenia, where forest regrowth has mostly been found on abandoned pastureland and low intensively used hay meadows [7, 12, 30, 36]. In Western Europe, the abandonment of pastureland in favor of forest is not restricted to Alpine regions, but has also been observed in Sweden, Poland, Denmark, Latvia and Spain [11, 13, 14, 24, 29].

Our model shows that forest regrowth occurred more frequently on lands with intermediate measures of steepness and soil stoniness. This may be explained as follows: On less steep and stony land, cultivation has been maintained due to the suitability of land for agricultural production. On the other hand, very steep and stony land is generally used for pasturing [32]. Pasturing is related to low costs because these areas are extensively grazed by cattle, sheep and goats [23]. Also, in very steep and stony areas, forest regrowth is limited due to the unfavorable growing conditions for trees and shrubs (snow avalanches, lower water holding capacity). The combination of pasturing and limited growing conditions slows down forest regrowth in very steep and stony areas. The non-linear relationships found for these variables reflect the specific characteristics of agriculture in the Alps, where farmers cultivate the more favorable land in the valleys and the steep and stony land above the treeline [23]. Non-linear patterns of forest regrowth have also been found in the Carpathians, where forests expanded to higher and lower altitudes compared to the existing forest [13].

Our model shows that the frequency of forest regrowth decreases with increasing distance from roads. This is contrary to our expectations and to the findings of previous case studies. Pezzatti [26] found, for example, that the land-use intensity decreases with the distance from roads. A closer examination of the data, however, revealed that a small number of observations at very large distances from roads (above 2 km) was responsible for the negative linear relationship. By excluding these observations, the distance to roads shows a squared relationship to the response. This would indicate that the frequency of forest regrowth 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 is high, where parcels are remote from roads. On alpine pastures, the remoteness has only minor effects on land abandonment because the accessibility of these areas for agricultural vehicles is often not necessary [23]. Nevertheless, eliminating extreme values of single variables would violate our quest for generality. Thus, we retained these observations in the model, but this means the negative relationship of the variable ‘distance to roads’ to forest regrowth should be interpreted with caution.

We included the binary dummy variable for alpine pastures/other agricultural land in the model in order to investigate the influence of the different degree of subsidization of pasturelands compared to other agricultural land. This variable was not significant in the model, which suggests that the different degree of subsidization of pastureland compared to other agricultural land had no affect on the decision of farmers to abandon their land. The explanation may be found in the fact that much of both the abandoned and cultivated land is found in areas designated as alpine pastures. Mountain farmers in the Alps rely on the mixed cultivation of meadows and alpine pastures [23]. This explains why they maintain the cultivation of alpine pastures although the cultivation conditions of these areas differ largely from the cultivation conditions of the meadows in valleys.

Our variable for population change did not show a significant relationship to the response variable in the statistical model. This is interesting as it suggests that migration had no effect on land abandonment in our study area. This is contrary to findings in other European mountain regions, where rural depopulation as well as population growth has been linked to land abandonment [13, 16]. Rather, our result confirms that complex relationships exist between migration, land abandonment and forest regrowth in the Swiss mountains, as hypothesized by Mather and Fairbairn [18]. They explain this complexity by the industrialization of parts of the Swiss mountains, which prevented rural depopulation in spite of declining agriculture. The development of the tourism sector from the 1960s onwards might have had a similar effect as it prevented many rural regions from depopulation.

Our results show that forest regrowth was largely restricted to municipalities showing weak labor markets. This finding is unexpected as it suggests that regions where off-farm job opportunities were scarce were favored in terms of land abandonment and forest regrowth. One possible explanation is that the demand for agricultural land was higher in economically strong municipalities than in economically weak municipalities. The higher demand for agricultural land could have slowed down land abandonment and forest regrowth in economically strong municipalities. Another explanation might be that farmers in economically weak municipalities tended to manage their farms more efficiently than farmers in economically strong municipalities because of their dependence on income from agriculture. Land is abandoned where cultivation is not easily possible. In the European context, however, the relationships between land abandonment and off-farm job opportunities seem to be more complex, because land abandonment and forest regrowth has been documented for both economically weak and strong regions. Land abandonment and forest regrowth is documented for economically weak regions in central Spain, the French Southern Alps and the Baltic countries [6, 7, 29]. On the other hand, land abandonment and forest regrowth is also documented for economically strong regions in northern Italy and Austria [16, 30].

The statistically significant *x*- and *y*-coordinates of the model sample of observations indicate that part of the spatial pattern in forest regrowth could not be explained by the geophysical and socio-economic variables included in our model. The direction of the correlation between the *x*- and *y*-coordinates and response variable suggests that proxy variables for the determinants of forest regrowth in the southern and eastern parts of our study area were absent from the model. Our study, therefore, does not enable us to make such precise statements regarding which determinants influence forest regrowth in these parts of the study area.

The relative poor overall model fit suggests that the causes of agricultural land abandonment and forest regrowth were very heterogeneous within our study area. Much of this heterogeneity might be explained by unrevealed local characteristics such as poor water availability or small-scale topographic peculiarities (old stonewalls, small trenches, soil damage by cattle). Another important factor that could not directly be considered in our study is the motive behind the decision of an individual landowner to abandon or maintain cultivation.

5 Conclusions

In many European mountain regions, natural forest regrowth on abandoned agricultural land and the related consequences for the environment are issues of increasing concern. In this study, we investigated the pattern of forest regrowth in the Swiss mountains based on land-use change (1980s to 1990s), geophysical and socio-economic data as well as the use of a spatial statistical model. Model results suggest that agricultural land was abandoned and became overgrown where the cultivation costs were high and yield potential low, thus confirming our study hypothesis.

The results extend the current knowledge about the pattern of forest regrowth and agricultural land abandonment in the Swiss mountain area. We found, for instance, non-linear relationships between steepness and soil stoniness, and forest regrowth. This result suggests that forest regrowth occurred in the 'in-between' areas where the labor costs were low, e.g., mechanically mown meadows in the valleys and labor-extensive pastures close to the treeline. Decision makers should consider these non-linearities in the pattern of forest regrowth when designing adequate measures to prevent or support agricultural land abandonment and forest regrowth in the Swiss mountains.

A new finding from this study is that forest regrowth occurred more frequently in regions which showed weak labor markets. We explain this by the lower demand for marginal agricultural land and the more profit-oriented management practices of farmers in regions with weak labor markets compared to regions with strong labor markets. Although this result is unexpected, it implies that labor markets have an influence on land abandonment and forest regrowth in the Swiss mountain area.

Results showed high heterogeneity in the pattern of forest regrowth which we relate to unrevealed small-scale local characteristics of agricultural land and the motives of individual landowners to maintain or abandon cultivation; both these areas require further study. The motives of individual landowners to maintain or abandon cultivation, however, is currently being investigated in selected case studies, where we combine results from spatial statistical models with findings from landowner interviews.

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