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Predictive modelling of historical and recent land-use patterns

by Cord Peppler-Lisbach, Oldenburg

with 2 figures and 11 tables

Abstract. Land-use is constrained both by physical and socio-economic factors. The aim of this study is to evaluate how and to what extent physical factors control the land-use pattern in a Central European rural landscape. Moreover, it intends to compare different temporal situations in order to find out, whether the relations between physical features (geomorphology, geology) and the land-use pattern have changed during the last 150 years.

To achieve this, logistic regression was applied to model two temporal states (1850 and 2000) of the land-use pattern. The statistical models were implemented in a raster GIS to obtain spatially explicit prediction maps. The model performance was evaluated using the AUC value and the Kappa index. In a first step, models for the single land-use types were calculated including several physical parameters as independent variables. This was done for the recent situation as well as for the situation in 1850. In a second step historical land-use and usability parameters were added as predictors for the present land-use pattern.

The study area, located in northern Hesse, Germany, experienced several land-use transitions over the past 150 years. The most significant was the conversion of cropland into grassland or meadow orchards, respectively. Others were afforestation of common pastures and the expansion of residential, industrial and traffic route areas.

The modelling results show that the land use pattern of the study area is fundamentally determined by physical factors. The degree of determination is at present lower than it was 150 years ago. Models comprising the additional parameters, e. g. historical land-use, show improved prediction accuracy.

By comparing the single land-use type models valuable information is gained for a better understanding of land-use changes and the underlying processes.

Keywords: cultural landscape, land-use change, predictive modelling, logistic regression, geographical information system.

Introduction

The occurrence of plant species and communities depends on a variety of factors, among them the availability of resources as well as the disturbance regime. While the resources are to a great extent controlled by physical factors, disturbance in cultural landscapes is decidedly influenced by human activities. On the landscape scale, they can be described coarsely by certain land-use types. Land-use varies in space, resulting in a characteristic land-use pattern. It also varies in time, leading to temporal changes in the distri-

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bution of land-use types. Understanding the underlying relations and processes is one important step towards a reliable prediction of community or species distribution. The results presented in this paper are derived from a project mainly designed to create predictive models of plant communities and species, focussing on terrain parameters. Since land-use is a decisive factor in modelling community and species distribution (FISCHER 1994, ZIMMERMAN & KIENAST 1999), it has to be integrated in the modelling approach. This can simply be done by including land-use types as explanatory variables. Although possibly sufficient for a good predictive performance, this would ignore the fact that land-use types are partly depending on the same factors as communities and species. They are also highly associated with features of the landscape such as terrain attributes and, of course, with human activities. The following article presents results concerning predictive modelling of the land-use types themselves.

The cultural landscapes in Central Europe have experienced significant changes over the last decades (BASTIAN & BERNHARDT 1993). Though the rate of these changes may have increased in recent years, it is in the nature of cultural landscapes to undergo certain transformations. The landscape altered by man reflects the variable conditions under which a human society exists. The spatial pattern of human impact on the landscape is not arbitrary. There are socio-economic as well as physical factors constraining the management decisions of the users (FORMAN & GODRON 1986, ZONNEVELD & FORMAN 1990, BAUDRY 1993). Both interact, since changes in the economic context result in modified effects of physical parameters (BAUDRY 1993). The question is, how strong the particular influences of physical attributes and socio-economic circumstances are. There are different answers to that question in the literature. Some authors stress the importance of physical constraints (SIMPSON et al. 1994, HALL et al. 1995, PAN et al. 1999), others emphasise the dominance of socio-economic factors (IVERSON 1988, BAUDRY 1993). IVERSON (1988) describes a difference between historical land-use, which is moderately associated with physical attributes and the actual land-use pattern showing only weak relations. Opposite to this investigation in Illinois, PAN et al. (1999) report a reverse development from Quebec, where the physical constraints of land-use have increased since the 19^{th} century.

The aim of this study is to evaluate how and to what extent terrain factors control the land-use pattern in a Central European rural landscape. Moreover, it intends to compare different temporal situations in order to find out, whether the relations between physical features (geomorphology, geology) and the land-use pattern has changed during the last 150 years.

The approach of the present study is to model these relations by methods widely used for habitat distribution models (reviewed in FRANKLIN 1995, GUISAN & ZIMMERMANN 2000). Logistic regression (HOSMER & LEMESHOW 2000) was regarded to be suitable for this purpose. It is widely used in predictive modelling of vegetation types or single species, respectively (DAVIS & GOETZ 1990, OLDE VETERINK & WASSEN 1997, FRANKLIN 1998, ZIMMERMANN & KIENAST 1999, GUISAN & THEURILLAT 2000, CAIRNS

2001). A model obtained by logistic regression can be presented quite easily as a regression equation, moreover giving the opportunity to compare different models in a concise manner.

Different from most habitat models, the dependent variables in the models presented here are land-use types, not species or community types. They may, though not always, be congruent with widely defined vegetation types, e.g. "woodland" or "grassland". Treating land-use types like species or community types means to assign to them a characteristic "habitat", i.e. a certain pattern of site conditions that results in a realisation of this type. In species modelling, a parameter pattern that results in the occurrence of a species is referred to as the "realised niche" (Hutchinson 1957, Austin et al. 1990, Franklin 1995, Heglund 2002). Though perhaps slightly problematic, the term "niche" can be applied to land-use types as well. Land-use types, as opposed to organisms, do not primarily require resources themselves. They rather reflect the requirements of a human society under specific socio-economic conditions. Each type represents demands for certain resources needed. As there are several demands and only a limited area, this results in a potential "competition" between land-use types for the most suitable terrain conditions. Being aware of a competitive situation like this may be useful in understanding the underlying processes leading to spatial distribution and temporal changes of the land-use types.

Extensive modelling of the socio-economic part (Parks 1991, Irwin & Geoghegan 2001) is not the purpose of this study. In a first step, only terrain parameters are included in the models as explanatory variables. Thus, the background of traditions, society and economy will only contribute to stochasticity. In a second step, at least some socio-economic aspects are considered by including rather simple parameters reflecting land-use continuity and usability (see methods). Land-use types mostly tend to be conservative in their distribution and they do so to a variable extent. This characteristic may differ from landscape to landscape, type to type and time-step to time-step. Anyway, if there is any temporal continuity, the occurrence of a land-use type in the past will have a positive influence on the recent occurrence of that type at a given site. Land-use change analysis and models frequently use transition matrices and Markov chain models to deal with temporal dependencies (Turner 1987, Baker 1989, Aaviksoo 1993, Cousins 2001). In the models presented here, as an alternative approach, the historical land-use type is used as an additional explanatory variable in logistic regression.

It has been pointed out by several authors that spatial autocorrelation should be considered in spatially explicit modelling to achieve more accurate predictions (Smith 1994, Augustin et al. 1996, Wu & Huffer 1997). A short look at the land-use maps (Fig. 1) will confirm that the land-use types are more or less highly spatially autocorrelated. As far as this autocorrelation of the dependent variables is caused by an autocorrelation of the independent variables, it is implicitly integrated in the models presented in this paper. The models will presumably have a higher predictive power by including autocorrelation measures, if there is a spatial dependence which cannot be explained by the autocorrelation of independent variables. In the case of land-use types, without a biological background, e.g. dispersal strategies of plant species, spatial autocorrelation rather has a socio-economic aspect. It is quite obvious that nearly every land-use type demands a minimum plot size for economical reasons. This minimum size will be larger for woodland than for grassland or cropland. This is especially the case in the study area where, at least in parts, very small field sizes are common. Minimum sizes will change due to different socio-economical conditions. Common pastures, for instance, required larger areas in historic times than they do today, as they are merely relics managed for conservational purposes. Cropland, on the other side, demands greater field sizes today due to the usage of large agricultural engines. Anyway, spatial autocorrelation of land-use, where it is not the effect of autocorrelation of terrain attributes, represents primarily socio-economic aspects and thus is not considered in the models described in this paper.

Study area

The study area is located in the German low mountain range east of the city of Kassel (northern Hesse). The transect reaches from the eastern slope of the "Kaufunger Wald" in the west to the Werra valley in the east. With a size of 10 km × 2 km it covers an area of 2000 hectares. Elevation ranges from 137 to 570 m. Geology shows a great variety (sandstone, limestone, dolomite, clay, marl, loess, holocene floodplain sediments). The relief is mainly moderate except for some rugged valley slopes and ridges, while the valley bottoms are more or less plane.

The climate is characterised by a mean annual rainfall of approx. 650 mm in the lower parts and 900 mm at higher altitudes of the transect, with mean annual temperature ranging from approx. 8.5 °C to 5.5 °C (Klink 1969).

Several land-use types occur in the study area (see Tab. 1). The land-use pattern has considerably changed during the last 150 years (see results). Much of the vegetation changes does not become obvious when looking at the land-use types only. While 150 years ago there were only deciduous forests, coniferous forests cover approximately 35 % of the woodland area today. The woods in 1850 were mainly used as coppices with standards or pure coppices, respectively, while today most of them are high forests. On common pasture areas, in 1850 calcicolous grassland types as well as heaths or matgrass-communities were dominating. Today, only calcicolous grassland remains.

The region of northern Hesse is very much characterised by a fine-grained land-use pattern due to traditional gavelkind tenure and widespread part-time farming. Hence, the plot widths often do not exceed 10 or 20 metres.

Material and methods

Data collection and data set

Land-use data

The historical land-use data were derived from an ancient map of the region on 1:25,000 scale. The survey published in 1857 is called "Niveaukarte vom Kurfürstentum Hessen", available as a reprint from the land survey office of Hesse. Considering the time they were released, these triangulated maps show an impressive accuracy. For analysis the maps were georeferenced and digitised.

The recent land-use was mapped at 1:5,000 scale in the field between 1994 and 2001.

For the sake of comparability of the two surveys, five land-use types were distinguished for analysis as follows:

– woodland
– common pastures (extensively used)
– grassland (meadows, fertilised pastures, meadow orchards)
– cropland
– miscellaneous (settlements, roads, rivers, ponds etc.)

Terrain data

Terrain data can be divided into data derived from a Digital Elevation Model (DEM) and data on geology. The DEM was calculated on the basis of contour lines digitised from the 1:25,000 ordnance survey map. It was computed with SURFER v. 7, using the radial basis function. The following topographically derived parameters were used as explanatory variables for the statistical analysis: elevation [m], slope [°], slope position [0: drainage lines to 1: ridges] (cf. Skidmore 1990), annual solar radiation [kWh/(m^{2}*a)], topographic wetness index [TWI = catchment area * $(\tan(\text{slope angle}))^{-1}$] (cf. Wilson & Gallant 2000).

Slope and slope position were computed with IDRISI, annual solar radiation and topographic wetness index with DIGEM 2.0 (cf. Conrad 1998).

The geological information was obtained from a 1:25,000 map (Moesta & Beyschlag 1886a, b). The original units were reclassified in order to summarise similar dominating substrates in one category. The categories used in the analysis are siliceous massive rock, limestone, dolomite, clay/marl, loess and holocene floodplain sediments. Especially in grassland models the metric variable "distance to floodplain sediments" was used as a surrogate for data on inundation. In these models the categorical variable "floodplain sediments" was removed to minimise collinearity.

Data on usability

The suitability of a sample point (i. e. grid cell) for a certain land-use type is not only influenced by terrain attributes of that cell itself. There are also parameters influencing the suitability which rather depend on context parameters, e. g. attributes of neighbouring areas or distance parameters. It is often important for the realisation of a certain land-use type, how easily a plot can be reached by the user. Thus, a variable expressing the average accessibility is introduced as the "accessibility index". The accessibility index is derived by a cost surface analysis that generates a distance surface where distance is measured as the least cost in moving over a friction surface (Burrough & McDonnell 2000: 199). Here, the distance to the next settlement was measured with the slope data used as the friction surface. For this procedure, the roads were assigned a slope of zero degrees. A high index value stands for a restricted accessibility because the plot is far away from the next settlement and/or can only be reached by getting over more or less steep slopes. The index was calculated with the COST-module of IDRISI. The final accessibility-index is the square root of the output value.

The suitability of a plot for a land-use type is also influenced by the fact that some areas have been terraced in former times for agricultural use. Nowadays, this terracing strongly impedes the continuing usage as arable fields, because the plots become too small to be treated with agricultural machines. Therefore, a binary variable is used expressing whether the plot is located in a terraced area or not.

Both, accessibility and terracing are called "usability parameters" in contrast to the aforementioned "terrain parameters", as they rather reflect an economic background.

Data sets

The data are stored in a raster-based GIS (IDRISI). The grid size is 10 m × 10 m, resulting in a total of 200,000 grid cells for the study area. Each land-use type and each parameter represents a single raster layer.

For model calibration, a subset of 2000 randomly chosen grid cells was used, which is equivalent to 1 % of the total area. The data set for model validation consisted of all the other grid cells, except the grid cells assigned to the "Miscellaneous" land-use type, i. e. settlements, roads etc. Because these grid cells have no chance of a true prediction of any of the other types, they were omitted from the validation data set.

Statistical analysis

Model calibration

For each land-use type a single model was calculated both for the historical and the recent pattern. As the land-use types represent nominal data, logistic regression was applied for statistical analysis in order to assess the dependence of the land-use types on terrain and usability parameters. The dependent variable is presence/absence of a certain type. The terrain parameters were used as independent variables in all models. The variables with a metric scale were also included as second polynomials in order to allow for unimodal relationships between these variables and the response variables. The statistical analyses were performed with SPSS v. 10.

For the prediction of recent land-use pattern, additional models were calculated including not only terrain parameters as explanatory variables, but also usability parameters in order to consider economical aspects. The historical land-use was included in order to elucidate temporal dependencies. Accordingly, there are three models for each land-use type presented in this paper which are labelled as follows:

1850T	model 1850, terrain parameters only
2000T	model 2000, terrain parameters only
2000TU	model 2000, terrain parameters + usability parameters + land-use 1850

In the final models only parameters with a significant influence were included. The significance of each metric variable was tested by Wald-statistics. For the categorical variables the likelihood ratio test was regarded as decisive. The significance threshold in either case was 5 %.

In the tables, the dependence on a particular explanatory variable is expressed by the odds ratio. The odds ratio indicates the increase/decrease of odds (for the dependent variable) per unit increase of the independent variable. For better interpretation, the rightmost column of a table contains the respective unit.

The models obtained by logistic regression result in a formula giving the probability of occurrence (p_{pred}) as a function of a certain parameter pattern. For a spatially explicit prediction, the formula is applied to every grid cell of the data set, resulting in a map of predicted probabilities.

To get a classified map of predicted land-use types, their probabilities have to be compared for each grid cell. Instead of the predicted probability p_{pred} the difference

$$p_{diff} = p_{pred} - p_0$$

was used for classification, where p_0 is the prevalence of the type, i. e. the relative frequency in the whole data set. The type with the highest p_{diff} was considered as the predicted type of each grid cell, achieving a classified land-use prediction for the studied area. In cases where p_{diff} was negative for all types, the cell was assigned the maximum p_{pred} of all types. This classification rule allows for unbalanced prevalence in order to consider that prevalence has a decisive influence on the maximum probability achievable by a model. Otherwise, a rare land-use type would hardly have a chance to gain a higher probability than a frequent type, unless the model has a superb discriminatory power.

Model validation

The models were validated by applying them to the validation data set and assessing the performance by two measures:

The single models giving the probability of occurrence for a certain type were evaluated using the AUC-value. This measures the ability of the model to discriminate between variable patterns resulting in the presence of a predicted type and those leading to absence (Fielding & Bell 1997, Hosmer & Lemeshow 2000, Pontius & Schneider 2001, Schneider & Pontius 2001, Fielding 2002). The AUC is the area under a ROC (Receiver Operating Characteristic) curve. It plots the proportion of true positive predictions against the proportion of false positive predictions for a given number of different classification thresholds. Thus, it does not depend on a subsequent classification of the prediction. A null model which predicts the occurrence of a type not better than by chance, yields an AUC-value of 0.5, while a model with perfect discriminating power results in an AUC of 1. AUC values near zero indicate complementary responses. According to Hosmer & Lemeshow (2000: 162) an AUC exceeding 0.7 can be regarded as acceptable, an AUC beyond 0.8 is considered as excellent and > 0.9 as outstanding.

The classified maps of predicted land-use types are evaluated by using the Kappa index of agreement (Cohen 1960, Monserud & Leemanns 1992). This was done both for the single types and the overall map. The Kappa index is a probabilistic measure to assess the degree of agreement between a predicted map and a reference (observed) map considering the agreement by chance on the bases of the marginal distributions of an error matrix. It is calculated as

$$\varkappa = \frac{p_{obs} - p_{exp}}{1 - p_{exp}}$$

where p_{obs} is the observed proportion of agreement and p_{exp} is the expected proportion of agreement.

The Kappa index ranges from −1 to 1, with a value of 0 indicating no association. A value of 1 indicates perfect agreement, while −1 indicates a perfect negative association.

The grading of Kappa values follows Monserud & Leemanns (1992):

Kappa index	Degree of agreement
< 0.05	No
0.05–0.20	Very poor
0.20–0.40	Poor
0.40–0.55	Fair
0.55–0.70	Good
0.70–0.85	Very good
0.85–0.99	Excellent
0.99–1.00	Perfect

Additionally, the correct classification rate (CCR in the following, see Fielding 2002) of the validation data-set grid cells is given. Though the CCR is an intuitive measure for map accuracy, it is rather unsuitable when comparing land-use types with very different prevalence in the data set. The prediction of a rare category tends to yield a high CCR because the probability of absence is high at the outset. Hence, the CCR is only given to the overall models. The CCR is sometimes valuable for the sake of comparability to other studies using this accuracy measure.

Model transfer

In order to assess the validity of a model over space and time, it can be applied to spatially or temporally independent data sets (Schröder 2000). This model transfer method is also used to compare the niches of different species for testing an umbrella effect (Bonn & Schröder 2001). Model transfer in this study is used to evaluate changes in the realised niches of land-use types as well as niche overlaps.

Results

Situations and changes of land-use pattern

Between 1850 and 2000 the land-use pattern of the study area has changed considerably (see Tab. 1 and 2). Major changes can be stated referring to the proportion and distribution of grassland, common pastures and cropland. The proportion of grassland including meadow orchards has increased significantly, mainly on former cropland. Thus, the proportion of cropland was cut down to one half approximately.

The area covered by woodland has expanded significantly as well as the settlement areas. On the other hand there were considerable losses of common pastures, which were mostly converted into woodland. The transition matrix (Tab. 2) shows the probabilities of change between 1850 and 2000 for the single land-use types.

Table 1. Historical and recent proportion (%) of land-use types.

Land-use type	1850	2000
Woodland	35.7	46.1
Cropland	42.8	20.2
Common pastures	10.1	0.8
Meadows/fertilised pastures	8.1	13.3
Meadow orchards	1.0	11.2
Settlement areas	0.9	5.3
Roads	0.7	1.2
Rivers	0.7	0.5
Miscellaneous	0.0	1.3

Table 2. Transition matrix of land-use types.

	Probability of changing to (2000):				
1850:	Woodland	Cropland	C. pastures	Grassland	Misc.
Woodland	0.96	0.01	0.00	0.02	0.01
Cropland	0.10	0.41	0.00	0.40	0.08
Common pastures	0.59	0.10	0.07	0.19	0.06
Grassland	0.16	0.14	0.00	0.48	0.21
Miscellaneous	0.09	0.03	0.00	0.08	0.81

Predictive models of land-use pattern based only on terrain parameters

The most important predictor variables in the 1850 models are altitude, slope, slope position and geology. The significant categories of geology, however, differ between the single models (see Tab. 6 to 9).

The model performances in general are quite satisfactory with AUC values ranging from 0.82 to 0.91 (Tab. 3), whereas the resulting classification shows a more heterogeneous quality referring to the single land-use types (Tab. 4). While the distribution of woodland is predicted with a good accuracy, the classification for the common pastures yields a poor Kappa only.

With an overall Kappa of 0.55 the model matches the real situation quite well. Thus, the predictor variables can be regarded as suitable for explaining the basic land-use pattern in 1850.

Table 3. AUC values of the prediction models.

	Model 1850T	Model 2000T	Model 2000TU
Woodland	0.90	0.88	0.96
Cropland	0.86	0.89	0.91
Common pastures	0.82	0.91	0.93
Grassland	0.91	0.72	0.86

Table 4. Kappa indices and overall Correct Classification Rate (CCR) of the prediction models.

	Model 1850T	Model 2000T	Model 2000TU
Woodland	0.63	0.59	0.81
Cropland	0.53	0.52	0.62
Common pastures	0.38	0.24	0.51
Grassland	0.55	0.21	0.26
Overall Kappa	0.55	0.46	0.65
Overall CCR	0.70	0.66	0.78

In 2000, the performance of the woodland and cropland models is similar to the 1850 model, with Kappa values indicating a more or less good agreement with the observed distributions. In detail, the Kappa values for both types are slightly smaller, whereas the AUC of the cropland model is even a little higher. Significant differences can be stated for the grassland and common pasture models as they perform only poorly, indicated by small Kappa values. The overall Kappa is considerably below the 1850 value. Anyhow, a Kappa of 0.46 still stands for a fair agreement. Accordingly, the recent land-use pattern can be explained by terrain parameters to a certain extent. This can be verified as considering Figures 1 and 2.

Table 5. AUC values of transferred models (model 1850 – observed 2000).

	AUC
Woodland	0.87
Cropland	0.83
Common pastures	0.89
Grassland	0.58

The change in the relationships between terrain parameters and land-use types can be expressed by applying the models of 1850 to the recent situation. Provided that the relationships are constant, the models should perform with a similar accuracy. Table 5 shows that this is not true with the grassland model, as it yields a very poor AUC when being transferred. This is a hint that considerable changes in the terrain-dependent situation of grassland have taken place, while the other land-use types seem to have rather constant requirements. To analyse this in detail, the models have to be compared explicitly with respect to single parameters.

Comparison of the models 1850T vs. 2000T

To compare the models for the historical and the recent situation in detail, consider Tables 6 to 9. The line-up of the single explanatory parameters is done by specifying the odds ratios of the variables used in the multiple logistic regression model. The tables give information about the significant explanatory variables used in the models and about the strength of the correlation. Indeed, this has to be interpreted with care, as the level of the odds ratio of one single variable depends on the other variables in the model. Nevertheless there are certain conclusions that can be drawn.

Woodland

The woodland models both contain the same explanatory variables, but there is some shift in the odds ratios. Especially altitude has a weaker influence, while slope position and dolomite have higher odds ratios. This finding can be related to the afforestation of common pastures on ridges and upper slopes, particularly on dolomite and at lower altitudes.

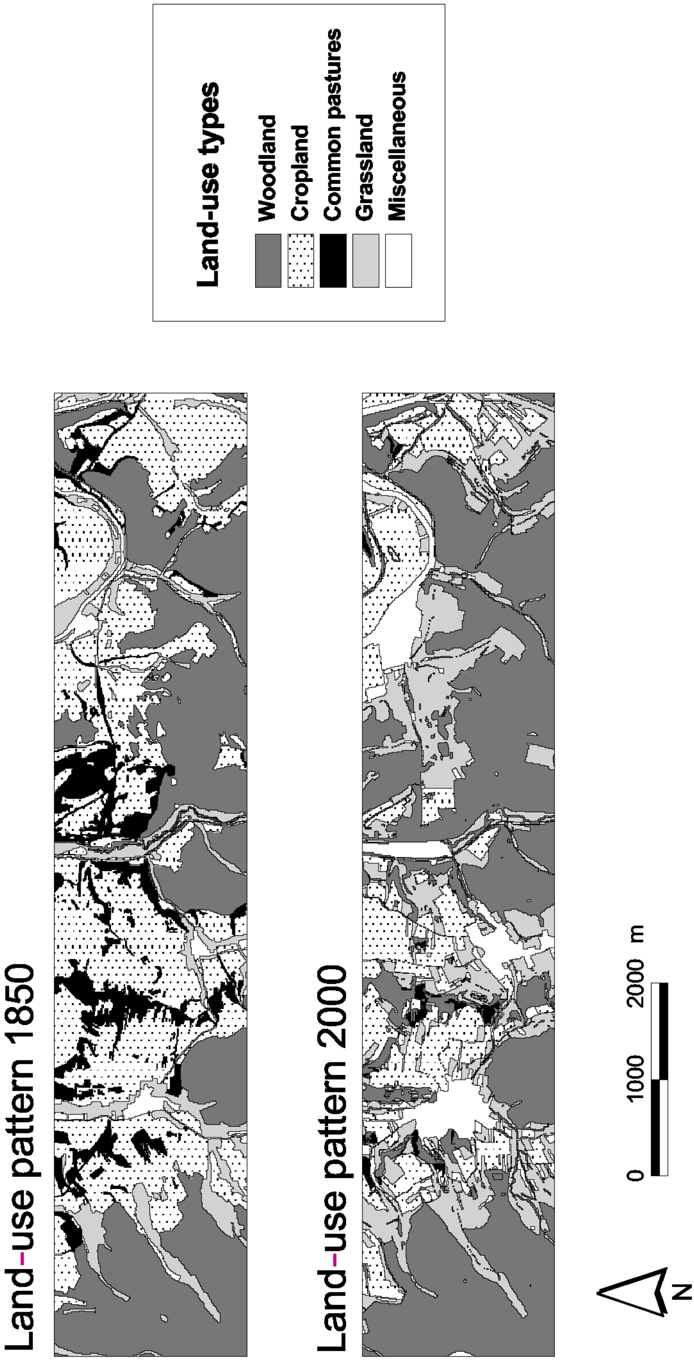
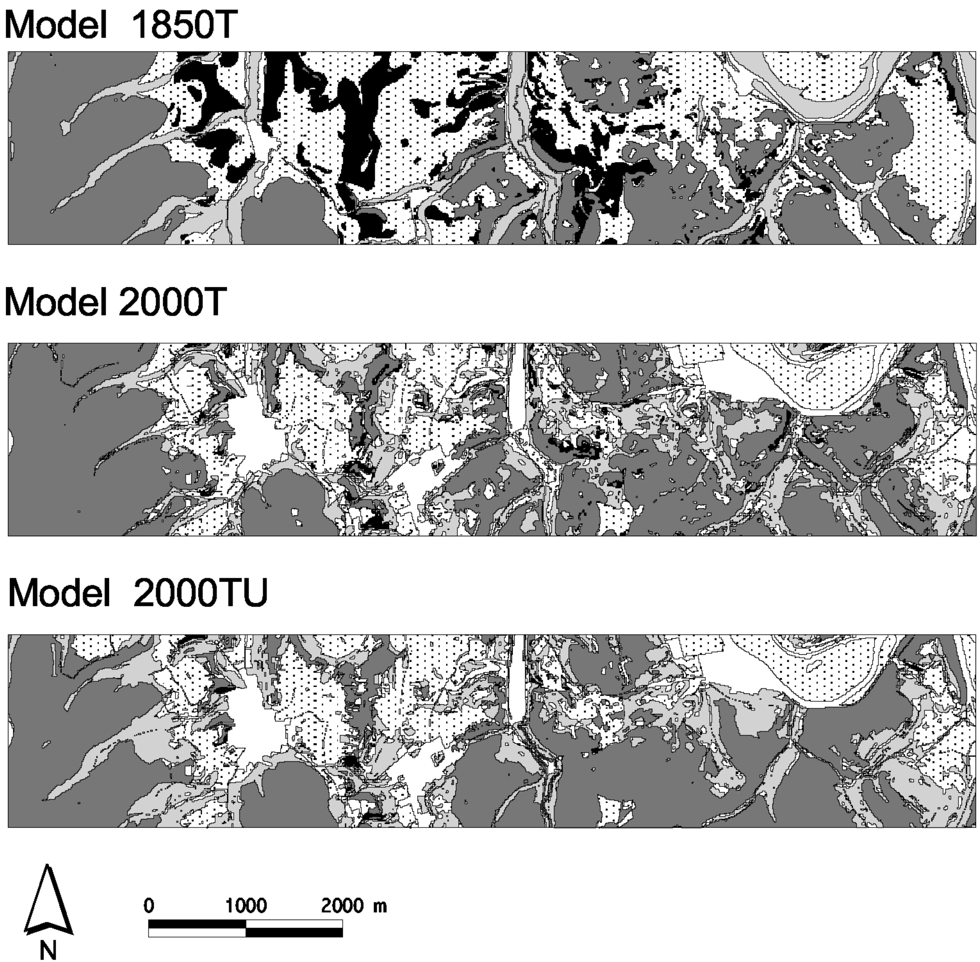


Fig. 1. Observed land-use patterns in 1850 and 2000.



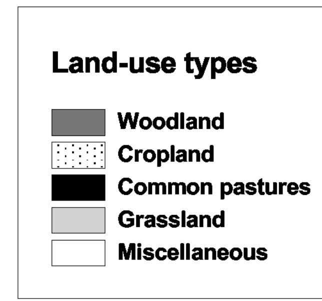


Fig. 2. Predicted land-use patterns.
1850T, 2000T: models of the historical and the recent land-use patterns, including only terrain parameters as explanatory variables.
2000TU: model of the recent land-use pattern, including terrain parameters as well as usability parameters and land-use in 1850 as explanatory variables.

Table 6. Woodland: odds ratios in multiple logistic regression model.

Parameter	**Model 1850T**	s.l.	Confid. Interval (95 %)		**Model 2000T**	s.l.	Confid. Interval (95 %)		Unit
Slope position	**3.34**	***	2.05	5.42	**5.09**	***	3.21	8.06	1
Altitude	**5.08**	***	3.99	6.46	**3.61**	***	2.89	4.51	100 m
Slope	**1.15**	***	1.13	1.18	**1.17**	***	1.14	1.19	1°
Solar radiation	**0.84**	***	0.79	0.90	**0.87**	***	0.82	0.93	100 kWh/(m^2*a)
Dolomite	**0.09**	***	0.06	0.13	**0.31**	***	0.22	0.43	1
Loess	**0.35**	***	0.19	0.64	**0.27**	***	0.16	0.47	1
Clay/marl	**0.13**	***	0.09	0.19	**0.14**	***	0.10	0.20	1

s.l.: significance-level according to Wald test-statistic. * 0.05, ** 0.01, *** 0.001.

Cropland

The cropland models differ with respect to loess and limestone, being not significant in the 2000 model. The positive correlation with clay/marl has become less strong as well as the negative correlation with floodplain sediments. With regard to slope position, there is a unimodal response in 1850 with an optimum of 0.38. In 2000 there is a significant negative correlation with the second polynomial which indicates a strong decrease of the likelihood of cropland to occur on higher slope positions. The correlation with slope has altered slightly towards a decrease of odds on steeper slopes.

These changes in the odds ratios reflect several processes leading to land-use change, i.e. conversion of meadows to cropland in the Werra-valley and conversion of cropland to grassland on marginal gain sites. This concerns mainly higher slope positions, steeper slopes and less suitable substrates like clay and limestone.

Table 7. Cropland: odds ratios in multiple logistic regression model.

Parameter	**Model 1850T**	s.l.	Confid. Interval (95 %)		**Model 2000T**	s.l.	Confid. Interval (95 %)		Unit
Altitude	**0.32**	***	0.25	0.41	**0.40**	***	0.31	0.51	100 m
Slope	**0.89**	***	0.87	0.91	**0.82**	***	0.79	0.84	1°
Slope position	**15.13**	***	3.40	67.42	**n.s.**				1
(Slope position)^2	**0.03**	***	0.01	0.14	**0.59**	*	0.35	0.99	1
Solar radiation	**1.07**	*	1.00	1.14	**1.17**	**	1.06	1.29	100 kWh/(m^2*a)
Limestone	**1.90**	***	1.30	2.78	**n.s.**				1
Dolomite	**2.26**	***	1.60	3.19	**2.63**	***	1.75	3.94	1
Floodplain sed.	**0.12**	***	0.07	0.21	**0.31**	***	0.19	0.50	1
Loess	**1.80**	**	1.16	2.80	**n.s.**				1
Clay/marl	**7.13**	***	5.17	9.82	**4.07**	***	3.01	5.49	1

s.l.: significance-level according to Wald test-statistic. * 0.05, ** 0.01, *** 0.001.

Common pastures

The two common pasture models differ markedly. In the 1850 model there is a significant unimodal response to altitude and slope, a positive correlation with slope position, solar radiation and dolomite. Limestone shows a significant negative correlation with common pastures in 1850. This can be regarded partly as a local effect of the study transect. In the neighbouring areas there were indeed more common pastures on limestone sites at this time, but, different from dolomite, it was not a predominant land-use type there. In 2000 common pastures are merely sparse, covering less than 1 % of the study area. With only 17 positive plots in the calibration model, the model can only be quite simple containing few parameters. Still, there is a significant positive correlation with solar radiation, slope, dolomite and clay/marl. The different odds ratios concerning the geological categories are due to the fact that in 2000 the remaining common pastures are found almost solely on dolomite and clay/marl sites whereas 150 years earlier they still covered large areas on sandstone and even on floodplain sediments.

Table 8. Common pastures: odds ratios in multiple logistic regression model.

Parameter	**Model 1850T**	s.l.	Confid. Interval (95 %)		**Model 2000T**	s.l.	Confid. Interval (95 %)		Unit
Altitude	**64.396**	**	3.56	11.63	**n.s.**				100 m
$(\text{Altitude})^2$	**0.377**	***	0.21	0.68	**n.s.**				
Slope	**1.141**	***	1.06	1.23	**1.105**	**	1.04	1.17	1°
$(\text{Slope})^2$	**0.997**	*	0.99	1.00	**n.s.**				
Slope position	**9.463**	***	5.10	17.55	**n.s.**				1
Solar radiation	**1.154**	***	1.06	1.25	**1.345**	**	1.08	1.67	100 kWh/(m^2*a)
Limestone	**0.226**	***	0.10	0.51	**n.s.**				1
Dolomite	**6.362**	***	4.41	9.17	**31.293**	***	6.73	1.46	1
Clay/marl	**n.s.**				**7.898**	*	1.39	44.72	1

s.l.: significance-level according to Wald test-statistic. * 0.05, ** 0.01, *** 0.001.

Grassland

The grassland models reflect an obvious change in the site conditions during the last 150 years. The 1850 model indicates negative association with slope, slope position, distance to floodplain sediments and dolomite and a rather weak positive association with altitude. Thus, the optimal parameter pattern for grassland in 1850 can be described as plain valleys filled with floodplain sediments, preferentially at higher altitudes. An extremely low likelihood for the occurrence of grassland was found on dolomite. In 2000 the situation has changed enormously. There is a unimodal response to altitude and slope with optima near 230 m and 13°, respectively. The negative correlation with slope position as well as distance to floodplain sediment has decreased, and the negative correlation with dolomite is no more significant. Instead, there is a positive correlation with clay/marl.

These findings reflect a considerable transformation of cropland to grassland in the last century. Grassland has lost its strict confinement to inundated valleys. Nowadays, it covers completely different parts of the landscape, especially those where cropping is no more profitable.

Table 9. Grassland: odds ratios in multiple logistic regression model.

Parameter	**Model 1850T**	s.l.	Confid. Interval (95 %)		**Model 2000T**	s.l.	Confid. Interval (95 %)		Unit
Altitude	**1.72**	***	1.28	2.30	**78.09**	***	16.8	362.9	100 m
$(\text{Altitude})^2$	**n.s.**				**0.39**	***	0.29	0.53	
Slope	**0.92**	***	0.89	0.95	**1.29**	***	1.21	1.38	1°
$(\text{Slope})^2$	**n.s**				**0.99**	***	0.986	0.992	
Slope position	**0.14**	***	0.06	0.34	**0.33**	***	0.21	0.51	1
Floodpl. sed. (dist.)	**0.85**	***	0.98	0.99	**0.99**	***	0.998	0.999	10 m
Clay/marl	**n.s**				**1.55**	***	1.19	2.01	1
Dolomite	**0.23**	**	0.07	0.76	**n.s**				1

s.l.: significance-level according to Wald test-statistic. * 0.05, ** 0.01, *** 0.001.

Predictive models of land-use pattern based on terrain parameters, usability parameters and historical land-use (2000TU)

The models described here differ from the models above in two respects. Firstly, they consider economical aspects by including usability variables. Secondly, they consider temporal dependencies by including the land-use in 1850 as an independent variable. Both the AUC values and the Kappa indices indicate a good accuracy of the models and a noticeable improvement compared to the models based solely on terrain parameters. Only the grassland model yields a poor Kappa, while especially the woodland model performs very good. This is to be discussed in detail later, but it is quite obvious that the models of those land-use types with the highest transition probabilities (i. e. the strongest temporal autocorrelation) show the best improvements.

With an overall Kappa of 0.65 (Tab. 4) the land-use pattern is predicted with a rather high accuracy. Fig. 2 illustrates this when compared to the observed situation displayed in Fig. 1.

Considering the individual model parameters (Tab. 10), one can assess the relative extent of association between the land-use 2000 and usability parameters and land-use 1850, respectively. The basic pattern of dependence between the land-use types and terrain parameters is very much the same as in the models disregarding economical and historical aspects. However, there are certain differences due to the fact that usability parameters and historical land-use show a collinearity with terrain parameters. Hence,

Table 10. Land-use 2000 models (2000TU) including usability parameters and historical land-use, odds ratios in multiple logistic regression model.

Parameter	Woodland	s.l.	Confid. Interv. (95 %)		Cropland	s.l.	Confid. Interv. (95 %)		Common pastures	s.l.	Confid. Interv. (95 %)		Grassland	s.l.	Confid. Interv. (95 %)	
Woodland 1850	100.4	***	63.6	158.50	n. s.				n. s.				0.06	***	0.03	0.10
Grassland 1850	3.044	***	1.75	5.28	4.986	***	2.06	12.08	n. s.				3.25	***	1.73	4.75
Cropland 1850	n. s.				29.205	***	13.29	64.18	n. s.				1.84	**	1.26	2.74
Common p. 1850	7.697	***	5.08	11.67	4.637	**	1.84	11.69	13.383	***	3.88	46.14	n. s.			
Terraced	n. s.				0.306	***	0.16	0.57	n. s.				2.84	***	1.88	4.46
Accesibility	1.051	***	1.03	1.07	1.246	***	1.17	1.33	n. s.				1.20	***	1.14	1.26
(Accesibility)^2	n. s.				0.993	***	0.991	0.995	n. s.				0.996	***	0.994	0.997
Altitude	n. s.				0.571	**	0.42	0.78	n. s.				n. s.			
(Altitude)^2	n. s.				n. s.				n. s.				n. s.			
Slope	1.093	***	1.06	1.12	0.808	***	0.78	0.84	1.097	**	1.03	1.17	1.25	***	1.16	1.35
(Slope)^2	n. s.				n. s.				n. s.				0.991	***	0.988	0.994
Slope position	3.591	***	1.87	6.91	n. s.				n. s.				n. s.			
Distance to floodpl. sed.	n. s.				n. s.				n. s.				0.983	***	0.977	0.989
Solar radiation	n. s.				1.163	*	1.03	1.31	1.307	*	1.06	1.62	0.90	**	0.83	0.97
Dolomite	n. s.				n. s.				4.747	**	1.51	14.97	0.59	**	0.40	0.86
Loess	0.419	*	0.20	0.88	n. s.				n. s.				n. s.			
Clay/marl	0.394	***	0.25	0.62	1.534	**	1.13	2.09	n. s.				n. s.			

s.l.: significance-level according to Wald test-statistic. * 0.05, ** 0.01, *** 0.001.

some of the terrain parameters do not appear in the final model, because their explanatory power is substituted by another parameter. Altitude, for instance, is correlated with accessibility as the higher areas tend to be more remote from settlements (ϱ = 0.66**). This parameter, although significant in all of the terrain-based models is no more significant in most of the models including usability and historical land-use.

Regarding the usability parameters and the extent of temporal autocorrelation, there are considerable differences between the land-use types.

Woodland is strongly temporally autocorrelated, i. e. it is conservative in its distribution, with a high odds ratio of the variable "woodland 1850". Its occurrence is positively correlated with the accessibility index, i. e. more likely in remote areas.

Cropland is less conservative in its distribution, being promoted also, but weaker, by a grassland or a common pasture background. Cropland is less likely to occur in terraced areas and shows a unimodal response to the accessibility index with an optimum of about 16.

Common pastures have a significant positive association with land-use continuity only, though the odds ratio is not very high, compared with the woodland or cropland models.

Grassland is, apart from a rather weak temporal autocorrelation, positively associated with a cropland background. It occurs preferentially in terraced areas and shows a unimodal distribution in relation to accessibility. The optimum is located at an accessibility index of about 22, i. e. in more remote areas than cropland.

Discussion

Before discussing some aspects arising from this study, I summarise the most important results in a short overview:

- at large, the 1850T models perform better than the 2000T models. There is evidence that the association between terrain parameters and land-use has become weaker during the last 150 years.
- the predictive abilities of the 2000TU models are better than the 2000T models. Especially the consideration of historical land-use information improves the accuracy.
- in general, the occurrence of woodland can be predicted best, followed by cropland. The environmental relationships of common pastures can be modelled quite satisfactorily, but the classification shows only a poor agreement of predicted and observed areas. The grassland models perform very differently. The 1850T model works quite well, but not the 2000T model, yielding only poor AUC and Kappa values. Hence, it can be assumed that there is but a weak association between terrain parameters and recent grassland distribution. Even the inclusion of usability parameters and land-use history does not lead to a good model performance.

Evaluation of the model performance

To rank the model accuracy of this study, it should be interesting to compare the validation results with other investigations on land-use or vegetation modelling. Problems may arise, though, with different scale levels of the studies.

In general, using the simple grading scheme of Hosmer & Lemeshow (2000), the AUC values indicate a good to mostly excellent performance. There are only a few published studies using the AUC in spatially explicit modelling. Compared with the values achieved by Pontius & Schneider (2001), the accuracy of the models of this study can be regarded as rather good.

According to Monserud & Leemanns (1992), the Kappa values indicate a fair to good agreement for most of the models. In the literature, there are other spatially explicit models on vegetation types and species, respectively, performing within this range of Kappa and CCR values (see e.g. Fischer 1994, Zimmermann & Kienast 1999, Guisan & Theurillat 2000, Cairns 2001). Better values are obtained especially by distribution models of alpine communities and species on sites with low anthropogenic influence (Zimmermann & Kienast 1999).

It is obvious that land-use depends very much on other factors than terrain parameters, such as socio-economic factors and cultural traditions. It is one purpose of this study to assess the degree to which land-use in fact depends on geomorphologic and geological attributes. The results show that about 70% of the raster cells can be predicted correctly on the basis of rather simple associations between terrain parameters and land-use types. The ability of the statistical models to predict land-use types correctly by terrain attributes has decreased within the last 150 years. Hence, it can be assumed that land-use nowadays is less dependent on the geomorphologic or geological situation than it was 150 years ago. The model performance can be optimised by including usability parameters and historical land-use. Yet, even some of these extended models yield only poor validation values. Therefore one should ask for the reasons for these deficiencies.

Reasons for deficiencies in the model performance

There are at least four reasons for model deficiencies: a) weak data quality (i.e. positional errors, classification errors, errors in deriving topographic parameters), b) inadequate selection of parameters, c) the model deficiency is due to factors that are beyond the purpose of the study, d) general stochastic errors.

Concerning data quality, there are several possible sources of inaccuracies. Positional errors may have emerged while georeferencing the historical land-use map as well as the geological map. The different scales of different data sources may also have led to positional errors. The quality of the DEM determines the quality of all other DEM-derived parameters, e.g. slope, slope position, solar radiation etc. Slope measurements for validation of the calculated values at 50 randomly selected locations showed a high correlation ($\varrho = 0.89^{**}$) between calculated and measured slope angles.

Classification errors referring to explanatory variables occur especially in the geological data. Most problematic here is the classification of loess sites, as the geological map classifies loess only with a given thickness of more than 2 metres.

The selection of explanatory variables is first of all constrained by the availability of data on terrain parameters or usability parameters, respectively. An adequate soil map, for instance, was not available for the study area. Thus, important factors like soil texture or soil depth could not be used. To a certain extent they were substituted in the models by other, indirect parameters like slope position or geology.

As this study focuses on the association of land-use types and terrain attributes, it does not attempt to model socio-economical processes. The usability parameters used in this study are actually context parameters depending on the terrain as well. As the terrain context is important for economic considerations of the land-user, they reflect economical aspects in a certain way. The integration of terrain independent factors like farm size, farm structure, individual distance between plot and corresponding farm etc., would certainly lead to better predictions (cf. Irwin & Geoghegan 2001). This is, however, beyond the purpose of this study and would rather be subject to socio-economic modelling, considering also other factors like producer prices or EU policy.

The weak performance of the 2000T grassland model can be attributed to the reason mentioned under c) above. The accuracy is weak because factors beyond terrain features are affecting the distribution (see below). The relatively low Kappa indices for the common pasture models can be interpreted in the same way, although the AUC values indicate rather good discriminatory abilities of the models. This discrepancy could also result from the classification process, as the classification rule (see methods) considers not only the individual response, but also those of the other land-use types. However, the optimum Kappa index of the common pasture 2000T model achievable by a direct classification yields not more than 0.22. Thus, the classification regarding "co-competitors", i. e. the other types, is even better than a classification with an optimal individual threshold. This gives evidence that the classification process is presumably not the cause for a weak agreement. Instead, the model seems to perform unsatisfactorily in spite of a high AUC.

Trends and processes of land-use change

The results given above reflect trends of land-use change which have been described from other parts of Central Europe in a similar way. Such trends are among others afforestation of common pastures (e.g. Ressel & Zimmerer 1989, Weller 1997) and conversion of cropland to grassland or orchard meadows (e.g. Hülbusch 1986, Ressel & Zimmerer 1989, Küpfer 1995, Weller 1996 and 1997, Röller & Peppler-Lisbach 1998). Afforestation of former common pastures is a well known process and has been perceived since the beginning of the last century. On the contrary, the constitution of large grassland areas on former arable fields has often not been realised, despite the publications mentioned above. This may be due to the fact that the reverse process, i.e. conversion of grassland to cropland, is a phenomenon which also can be observed frequently. As this transformation is normally resulting in a loss of valuable habitats and biodiversity, it is much more perceived in the field of nature conservation. In parts of the study area, especially in the Werra valley, there has been a change from grassland to cropland (cf. Tab. 2), but only on a relatively small area compared to the large proportion of new grassland. As the recent grassland of the study area mainly consists of Arrhenatheretum-type stands, it can be assumed that this community is now occurring mostly on former cropland. As far as can be derived from recent observations, the grassland patches of 1850 consisted mainly of Calthion-type meadows. The establishment of Arrhenatheretum-meadows on former arable fields has been observed in other parts of the German mountain range as well, e.g. the "Pfälzerwald" (Lisbach & Peppler-Lisbach 1996) or the "Lahn-Dill-Bergland" (Fuhr-Bossdorf et al. 1999).

The modelling approach used in this study provides the opportunity to assess whether a land-use type has a certain "niche", i.e. distinguished terrain conditions, under which the possibility of occurrence is significantly higher (see introduction). It gives evidence about temporal changes of definition of the niche. The AUC can be regarded as a measure indicating the sharpness of this niche definition. Tab. 11 contains the AUC values of a reciprocal model transfer between the terrain-based models presented in this paper. The transferred woodland and cropland models yield AUC values between 0.1 and 0.2, i.e. both types are antagonists with quite a distinct niche definition. On the other hand, grassland has lost its distinct niche under recent land-use conditions. The relatively high AUC values of the cropland 2000T model when transferred onto the observed grassland distribution indicates an increased overlap of the cropland and grassland niches in 2000. Thus, it can be stated that the occurrence of grassland is much more controlled by socio-economic conditions than it was 150 years ago. It is more likely that grassland occurs on sites rather typical for cropland, but it is hard to predict where. The 2000T and 2000TU models indicate a significant preference of marginal sites for the conversion of cropland to grassland (cf. Weller 1997), but this gives only a coarse frame. Which plot really is converted depends very much on the individual socio-economic situation.

The present occurrence of common pastures is also only poorly determined by terrain factors, although there are certain terrain situations significantly more suitable, like steep slopes, high solar radiation and dolomite substrate (see results). Since common pastures, unlike the other types, could acquire almost no new areas in the last 150 years, the present occurrence is highly associated with the historical distribution. Further reasons for the survival of this type at a certain plot have to be located in the socio-economic background or are simply a matter of chance. Today, most common pastures are managed as sheep pastures for conservation purposes. This management, initiated about 10 years ago, is concentrating on those areas, where extended stands of semi-natural calcicolous grassland has endured afforestation and secondary succession. While succession is presumably controlled by terrain attributes influencing nutrient and water supply, afforestation is linked to ownership pattern and therefore often arbitrary.

Table 11. AUC values of a reciprocal model tranfer. Model row applied to observed column.

1850T Model	Woodland	Cropland	Common pastures	Grassland
Woodland	**0.90**	0.19	0.44	0.37
Cropland	0.15	**0.86**	0.49	0.43
Common pastures	0.35	0.58	**0.82**	0.34
Grassland	0.47	0.45	0.34	**0.91**
2000T				
Woodland	**0.88**	0.13	0.51	0.35
Cropland	0.13	**0.89**	0.47	0.62
Common pastures	0.52	0.46	**0.91**	0.48
Grassland	0.27	0.59	0.43	**0.72**

Conclusions

The results allow several conclusions concerning the degree of determination of land-use pattern by terrain attributes.

– the main features of land-use pattern can be predicted by using terrain parameters as explanatory variables. Hence, land-use in the study area can be regarded as decidedly constrained by physical attributes of a landscape. As mentioned in the introduction, some investigations from other parts of the world show different results, while others confirm these findings. The degree of physical determination of land-use patterns is therefore obviously specific for particular landscapes. Regions which have experienced a strong intensification of land-use only show a weak determination (Iverson 1988). The differing results from northern Hesse are presumably due to the fact that the area represents a marginal region with a rather extensive land-use. Over the last 150 years, farming in this region has very much been characterised by a contraction process. On the one hand, this leads to an extensification on marginal gain sites, where afforestation, abandonment and conversion of cropland into grassland or meadow orchards, respectively, are the main phenomena. On the other hand, the land-use of productive sites has been intensified.

– the degree of determination has decreased in the last 150 years, but to a different extent referring to the particular land-use types. The temporal change in physical constraint is also characteristic for certain landscapes and their specific history. A lower degree of determination by physical attributes is not necessarily an indicator for intensification of land-use (cf. Iverson 1988). As is shown in this study, much of the uncertainties now occurring in predicting land-use types are mainly due to extensification. On the contrary, the Quebec landscape studied by Pan et al. (1999) showed an increased degree of determination, while the processes of land-use change since the 19th century are in many respects similar to those in our study area. This contradiction can be explained when taking into account that the constraint of physical attributes can be revealed best in a state of relative equilibrium. Landscapes undergoing rapid changes with driving processes not finished yet tend to elude reliable predictions based on equilibrium models. While the Central European study area was in a proximate balanced state in the mid 19th century, i. e. at the end of the pre-industrial period, it is now in the middle of a profound conversion process. In the 19th century, the Canadian landscape was at the beginning of cultivation, thus far from any equilibrium, with land-use mainly controlled by land availability (Pan et al. 1999). This corresponds to results of Paquette & Domon (1997), finding no determination of land-use by physical factors. The increase to the present state may be due to a certain consolidation of land-use converging into an equilibrium.

– there is a strong constraint of the actual land-use by the historical situation. Thus, integration of historical land-use into the models leads to better predictions.

– separate from direct terrain parameters there are context parameters affecting usability which can improve the models when included as explanatory variables.

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Address of the author:
Dr. Cord Peppler-Lisbach, Landscape Ecology Group, Institute for Biology, Earth and Environmental Sciences, University of Oldenburg, PO Box 2503, D-26111 Oldenburg, Germany. E-mail: cord.peppler.lisbach@uni-oldenburg.de