Predicting land cover changes and their impact on the sediment influx in the Lake Balaton catchment

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Abstract The land cover pattern in the Lake Balaton catchment (Hungary) has been changing since decollectivization in the 1990s. These land cover changes significantly impact the landscape connectivity, controlling the influx of sediments into the lake. A comparison of high resolution land cover maps from 1981, 2000 and 2005 showed a significant extensification of the agriculture with land cover conversions from arable land and vineyards to grassland and forest. For each land unit transition probabilities were assessed using logistic regression techniques to evaluate to which extent land cover changes are controlled by physical or socio-economic parameters. A stochastic land cover allocation algorithm was applied to generate future land cover patterns. The landscape connectivity for each of the simulated land cover patterns was assessed by means of a distributed routing algorithm. The simulations suggest that further land abandonment in the upslope parts of the catchment will cause a non-linear reduction of average soil erosion rates. The changes, however, have a relatively low impact on the

sediment volume entering the lake because of the land unit's poor connectivity with permanent river channels. The major contributors to the lakes sediment load are the vineyards near the lakeshore. They are likely to be maintained because of their touristic value. A significant reduction of the total sediment input in the lake can be expected only if soil conservation measures in the vineyards near the shorelines are undertaken.

Keywords Lake Balaton · Hungary · Land cover change · Logistic regression · Landscape connectivity

Introduction

Lake Balaton is the largest freshwater lake in Central Europe with an area of 595 km² and a contributing drainage basin of 5,775 km². The average depth of the lake is only 3.25 m (Polyák and Hlavay 2005) which makes the aquatic ecosystem very susceptible to pollution by incoming nutrients and soil particles (Rátz 2003). Lake Balaton is a recreational area of international significance, which makes the protection of the lake's water quality an important point on the Hungarian economic agenda (Szilassi 2002; Rátz 2003). Land cover and land cover change in the contributing area largely control the amount of incoming soil particles and nutrients because (1) land cover is strongly correlated with average soil erosion rate in the catchment and (2) the land cover

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pattern determines which fraction of the produced sediment is delivered to the lake.

Pan-European soil erosion assessments (Gobin et al. 2004) suggest that the mean annual soil loss rates on arable parcels and vineyards in the Balaton watershed is in the order of $5\text{--}10 \text{ Mg ha}^{-1} \text{ year}^{-1}$. The yearly sediment volume delivered to the lake depends on the erosion rates in the contributing catchments and the sediment deposition. Measured sediment concentrations at the mouth of contributing rivers indicate that the area specific sediment yield of the hilly northern side of the Lake Balaton catchment is in the magnitude of $0.02 \text{ Mg ha}^{-1} \text{ year}^{-1}$ (Jordan et al. 2005). This indicates that the majority of the eroded soil material is stored within the contributing catchment and agrees with well established general geomorphic understanding on sediment delivery to fluvial systems and the role of partial area contribution (e.g. Trimble 1999; Walling 1999). This implies that the mean annual input of sediment and attached agro-chemicals is largely controlled by both topographic characteristics and the spatial configuration of land cover in the contributing area of the lake.

Szilassi et al. (2006) analysed historical land cover changes in a small tributary catchment on the northern shore of Lake Balaton over the last 220 years. They concluded that the average yearly volume of soil erosion in the catchment decreased 40% over the studied time span, yet the average yearly volume of soil material delivered to the lake increased 10%. The authors explain these at first sight contradictory findings by changes in landscape connectivity. Increasing landscape fragmentation opened corridors for sediment transport to the receiving drainage network in the studied catchment. The latter finding implies that the spatial pattern of possible future land cover change in the contributing area of Lake Balaton will control to a large extent future lake water quality. Strategic lake protection plans should therefore incorporate spatially explicit land cover scenarios.

Rural landscapes in countries under former communist regimes are undergoing major changes due to the political and economic changes in 1989. Since 1990, the original landowners or their successors can claim their original property. Therefore the large parcels of cooperatives and state farms are being split up resulting in a relatively fragmented land ownership (van Dijk and Kopeva 2006). New landowners

are often temporary residents coming for tourism, particularly in the scenic historic vine growing hillsides (Jordan et al. 2005). In some cases, land is not claimed and is abandoned or converted to extensive rangeland. At a later stage the rangeland may be converted into forest. Van Rompaey et al. (2003, 2007) showed that the sudden abandonment of collective farms in southern Bohemia resulted in a spectacular decrease of the sediment supply to rivers and retention ponds.

According to CORINE land cover maps (CEC 1994) the total area of arable land (i.e. the cropland excluding pasture and vineyards) in the contributing area of Lake Balaton decreased 9.7% between 1990 and 2000. The total area of vineyards increased 59.7%. Abandoned parcels naturally evolved into fallow and grassland (14.4%) or forest (4.3%). These numbers should be interpreted as a rough approximation as CORINE change maps have proven to be rather unreliable for area estimates of change at the regional scale (Feranec et al. 2007).

In 2004, Hungary joined the European Union which opened Hungarian agriculture to direct competition with other EU member states. The increased competition will act as a catalyst for future land cover change (Verburg et al. 2006). Possible future land cover trends for the Lake Balaton catchment area are: (1) an increase of the built-up area along the lake shores and a denser road network resulting from expansion of tourism, (2) a fragmentation of rural landscapes resulting from the decollectivization process, (3) an accelerated abandonment of arable lands and vineyards evolving into extensive rangelands and forests.

It is at present not clear to what extent these expected changes will impact on the sediment delivery ratio of Lake Balaton and its water quality. A direct coupling of European scale land use change scenario's such as presented by Rounsevell et al. (2006) and Verburg et al. (2006) with sediment flux algorithms is not possible because of a mismatch in scale levels. Most land cover change models operate with gridcells of $1\text{--}100 \text{ km}^2$ while typical flow algorithms require land cover data with a resolution of $100 \text{ m} \times 100 \text{ m}$ or less. In this paper a method is proposed to downscale regional land cover scenarios to the landscape scale by means of stochastic allocation algorithms. Next, the possible impact of the expected changes on the mean annual sediment

delivery to the lake is assessed by means of flow algorithms that evaluate the sediment connectivity between sediment sources on the one hand and the lake shore or contributing rivers on the other hand. Aerial photographs from 1981, 2000 and 2005 were used to reconstruct the landscape in a small but representative watershed in the northern part of the Lake Balaton catchment.

Materials and methods

Study area

The Lake Balaton catchment in Hungary, Europe, is situated in the centre of the Pannonian Basin, ringed by the Carpathian Mountains. The average lake level is 105 m above sea level. The northern part of the drainage basin has a hilly topography with hill tops above 400 m, while the southern part is relatively flat with maximum relief of 50 m. The southeastern part is slightly higher with the highest point reaching 300 m (Fig. 1). Although the northern parts of the catchment are characterized by a higher percentage of forest cover, most of the incoming sediments are delivered by northern tributaries (Jordan et al. 2005).

Landscapes in the Lake Balaton drainage basin are characterised by mosaics of arable land (43%), forests (26%), grasslands (11%) and vineyards (3%).

Distinct differences exist between the northern and the southern shore. Arable land, the dominant land cover category on the southern shore, covers 49% of the total area (25% on the northern shore), while the northern part of the Balaton catchment consists mainly of forest (37%), grassland (17%) and vineyard (12%) (on the southern shore these are 25%, 11% and 4% respectively).

The original settlement pattern consisted of small rural villages with mixed farmsteads. Since 1990, Lake Balaton became an increasingly popular holiday destination for mass tourism. This resulted in a spectacular increase of the built-up area along the lake shores while the more remote rural villages were abandoned. A significant number of farmers ceased farming activities and since 1990 many fields have naturally regenerated from grassland into forest.

Jordan et al. (2005) showed that soil erosion rates on arable land in the northern part are relatively high ($>20 \text{ Mg ha}^{-1} \text{ year}^{-1}$) but a large fraction of this eroded soil material is deposited in sediment sinks. The spatial pattern of these sediment sinks is controlled by topography and land cover.

To get a deeper insight in the land cover change patterns, three detailed land cover maps of a relatively small subcatchment were compiled. The selected subcatchment, situated on the northern shore (Fig. 1) has an area of 24.6 km^2 drained by the Örvényesi Séd. The villages of Péscely and Vászoly, with 548 and 177

Fig. 1 Topography of the Balaton Catchment and location of Lake Balaton in Hungary (upper left) and the subcatchment drained by the Örvényesi Séd

permanent inhabitants in 2000 respectively, are situated in the centre of the catchment. The catchment consists of a northern part with relatively steep slopes ($>10\%$) and a flatter central part surrounded by a hilly topography. The northern part of the catchment is part of the Balaton Highland National Park.

Digital aerial orthophotos from 1981, 2000 and 2005 (1:10,000) from the National Hungarian Mapping Agency were used to delineate individual parcels with five different land cover types: built-up area, arable land, vineyard, grassland and forest (Fig. 2). The cover type 'grassland' includes both permanent and temporary grassland as it cannot be distinguished on the aerial photographs.

The land cover pattern in the catchment consisted in 1981 of 36% forest, 30% grassland, 21% arable land and 10% vineyards. Only 1% of the total area was occupied by built up area. In the year 2000 forest cover increased to 42%, grassland was almost the same while arable land and vineyards decreased (19% and 7% respectively). A comparison of the land cover in 2000 with 2005 land cover suggests a persistence of the 1981–2000 trend with an increase of forest area (+0.1%) and grassland (+4.8%) and a decrease of arable land (−7.8%) and vineyards (−1.4%). The total number of parcels converted in the period 2000–2005 was too small to detect any significant changes in the 1981–2000 trend. The 2005 map was only used to verify the persistence of the observed trend and will not be used in the further analyses.

Mapping land cover change

The vector land cover maps of 1981 and 2000 were converted to integer raster images with a resolution of 5 m. Next, a crosstab procedure was carried out to map the spatial pattern of land cover conversions between 1981 and 2000, which resulted in a 5×5 crosstabulation matrix (Table 1).

The major 1981–2000 land cover conversions are arable land to grassland (AG), vineyard to arable land (VA), vineyard to grassland (VG) and grassland to forest (GF). Twenty-four percent of the 1981 arable land was converted to grassland by the year 2000. Abandoned vineyards were mainly occupied by arable land and grassland (both 25% of the initial vineyards) while 20% of the grassland evolved into forest. In general an extensification of the land use is observed reflecting the depopulation of rural villages. The villages in the centre of the catchment were abandoned because income from small scale farming is relatively low while tourist employment in the vicinity of the shoreline is more lucrative.

Spatial analysis

To predict land cover patterns, it is important to get a deeper insight in the variables that are correlated with the spatial pattern of the observed extensification. If no correlating variables can be found, the land cover change should be modelled as a random process. Van

Fig. 2 Land cover in the Örvényesi Séd basin on the northern shore of Lake Balaton: left situation—1981; right situation—2000

Table 1 Crosstabulation matrix of observed land cover changes between 1981 and 2000

	Land cover 1981 (%)	Land cover 2000 (%)						Total (ha)
		Built-up	Arable	Vineyard	Grassland	Forest	Total (%)	
Built-up	100.0	0.0	0.0	0.0	0.0	0.0	100	36
Arable	0.4	66.7	4.9	24.0	4.0	100	537	
Vineyard	0.0	24.7	47.5	24.6	3.1	100	247	
Grassland	0.1	6.2	2.8	70.8	20.2	100	762	
Forest	0.0	0.1	0.1	2.0	97.8	100	875	
The total area of each land cover category in the year 1981 represents 100%	Total (%)	108.2	86.9	67.0	98.1	118.7	100	
	Total (ha)	39	467	166	747	1,039	2,458	

Rompaey et al. (2002) showed that the spatial pattern of land abandonment in Central Belgium is strongly correlated with topographic and soil parameters while Bakker et al. (2005) linked land abandonment in Greece with soil erosion processes. Mottet et al. (2006) pointed out that agricultural land use change is to a large degree dependent on the distance of the parcels from the farmstead and the accessibility of individual parcels.

In order to test which variables control the spatial pattern of change, a logistic regression analysis was carried out for each of the four major land cover conversions in the selected subcatchment. For each individual parcel the following variables were quantified: slope gradient (SG), elevation (EV), distance to shoreline of the lake (DS), distance to village (DV), soil texture (ST) and distance to roads (DR).

Slope gradient and elevation were derived from a raster digital elevation model with a resolution of 5 m. The elevation of each grid cell was assessed via Delaunay triangulation based on digitized contour-lines with a contour interval of 2.5 m. Soil texture was mapped in four classes: clay, heavy clay, silt-loam and sandy gravel. These soil texture classes

account soil augerings and field experience. For each parcel the distance to the shoreline of the lake and distance to the nearest village was calculated. The roadmap is based on the 1:10,000 scale military maps of 1981, no significant change have occurred during the last decades.

Next, a logistic regression analysis was carried out to assess land cover transition probabilities of each individual parcel. A transition probability expresses the likelihood that land cover of a parcel will change over a considered time period. As five different land cover types were mapped, the probabilities of 25 different land cover conversions are possible. Because a logistic regression procedure requires minimal numbers of observations only four major land cover conversions (AG, VA, VG, GF) could be evaluated. Probabilities for each of these conversions were assessed using a standard logistic regression equation:

$$\text{Logit } (P(\text{AG})) = a + b * \text{SG} + c * \text{EV} + e * \text{DV} + f * \text{ST} + g * \text{DR}$$

or

$$P(\text{AG}) = \frac{\text{EXP}[a + b * \text{SG} + c * \text{EV} + d * \text{DS} + e * \text{DV} + f * \text{ST} + g * \text{DR}]}{1 + \text{EXP}[a + b * \text{SG} + c * \text{EV} + d * \text{DS} + e * \text{DV} + f * \text{ST} + g * \text{DR}]}$$

were derived from the digital geological map of Hungary at a scale 1:50,000 (Geological Institute of Hungary) and a database with soil augerings compiled by the Hungarian Plant Protection and Soil Conservation Service. For each geological formation a typical soil texture was determined taking into

with $P(\text{AG})$, the probability that an arable parcel will be converted to grassland; SG, slope gradient (in degrees); EV, elevation (in meters); DS, distance to shoreline (in meters); DV, distance to nearby village (in meters); ST, soil texture (qualitative variable represented by dummy variables); DR, distance to

roads (in meters); a, b, c, d, e, f, g, regression coefficients.

The regression coefficients of the equation described above were parameterized using the Multiple Logistic Regression procedure (MLR) of the SAS Software. This MLR-procedure takes into account the possible multicollinearity between the predicting variables. If such multicollinearity occurs, redundant variables are omitted from the equation and the coefficients of the remaining parameters are recalibrated.

Positive values for the coefficients b, c, d, e, f, g imply that an increase of SG, EV, DS, DV, ST and DR respectively, results in an increase of the probability that the land cover conversion in consideration will occur.

Next, the regression equations were used to map the probabilities for AG-, GF-, VA- and VG-conversions at a parcel scale. Variables not significant at a 95% confidence level were not included.

For each MLR-model (for AG-, GF-, VA- and VG-conversions) the goodness of fit was evaluated using a ROC procedure (Pontius and Schneider 2001). This procedure compares for each transition probability class assessed land cover probabilities with the observed number land cover transitions, taking into account agreement by chance. An area under the ROC-curve of more than 0.5 indicates that the model performs better than a random model.

In this study the ROC procedure was used to compare the assessed transition probabilities that were derived from the change pattern 1981–2000, with the observed changes in the same time period. This analysis was carried out to evaluate whether the MLR-models describe the observed land use change patterns better than random models.

Land cover change simulation

The calibrated MLR-models were used to map land use transition probabilities for each parcel. These maps were used to simulate possible future land cover patterns for the years 2010, 2020 and 2030. In order to assess the future area of vineyard, arable land, grassland and forest in the catchment, the following assumptions were made: (1) there will be no or very limited interventions by regional, national or European authorities to support non-productive farming activities in the area, (2) the tourist industry around Lake Balaton will continue to grow, and (3) the

protection of traditional landscapes around holiday resorts and agro-tourism farmsteads will be encouraged. These assumptions imply a persistence of the existing trend. Therefore the future areas of vineyard, arable land, grassland and forest were assessed by means of a linear extrapolation of the observed 1981–2000 trend. When this trend persists till 2030, the amount of forest will increase from 36% of the total area to 52%. Arable land will decrease from 22% land cover in 2000 to 15% in year 2030 while vineyards will decrease from 10% to 3%. In the proposed scenario the amount of grassland remained relatively constant but the spatial distribution will change over time.

For each land cover type the required number of parcels was spatially allocated following a procedure proposed by Van Rompaey et al. (2001a, 2002). This procedure selects on average the parcels with the highest transition probability but simulates the random behavior. Firstly, a parcel on the map was selected randomly, without replacement. Next, a random number between 0 and 1 was generated using the stochastic number generator of Borland Delphi. The land cover of a parcel is converted if the random number is lower than the transition probability of that parcel. This procedure was reiterated until the necessary areas of vineyard, arable land, forest and grassland were reached. The major advantage of this approach is that it allows generating a set of possible future land cover maps, which can be used as the input for a Monte Carlo analysis. The stochastic allocation procedure described above was used to produce a set of 10 possible land cover maps for each time period (2010, 2020 and 2030).

Impact on the sediment influx

Finally, the land cover scenarios were used to assess future levels of sediment input into Lake Balaton using the WaTEM/SEDEM model structure proposed by Van Oost et al. (2000) and Van Rompaey et al. (2001b). The procedure requires an assessment of the mean annual sediment production (SP in Mg year^{-1}) and a mean annual transport capacity (TC in Mg year^{-1}) for each gridcell. SP is dependent on the slope length, the slope gradient, the soil erodibility, the rainfall erosivity and the land cover type. TC is dependent on the slope length, the slope gradient and the land cover type. A topographical flow-algorithm is

used to link all gridcells with the outlet of the catchment. Sediment loads are accumulated along these flowpaths. If at a certain location in the landscape the sediment load is higher than the transport capacity, sedimentation occurs. Otherwise the sediment load is transported to the next gridcell. The sediment delivery (SD in Mg year^{-1}) is the total mass of the sediment that reaches the permanent river channels of the catchment. The sediment delivery ratio (SDR) of the catchment is the fraction of the eroded sediment that is delivered to the outlet of the catchment and can be calculated as follows: $\text{SDR} = \text{SD}/\text{SP}$.

In this study SP-levels and TC-levels were assessed using parameters proposed by Jordan et al. (2005). Slope length and slope gradient were derived from a 5 m resolution DEM. Rainfall erosivity was assessed from monthly rainfall records using a formula proposed by Renard and Freimund (1994). Soil erodibility values were derived from a 1:50,000 soil texture map using a formula proposed by Römken et al. (1986). The routing algorithms of the sediment delivery model WaTEM/SEDEM were used to link the sediment sources with the permanent river channels of the catchment. At parcel boundaries TC-values were decreased by 30%. For a detailed description of these procedures see Jordan et al. (2005) and Van Rompaey et al. (2001b).

The model described above was applied to assess mean annual sediment production and sediment delivery levels for 2000, 2010, 2020 and 2030. For 2000 the observed land cover pattern was used as an input. For 2010, 2020 and 2030 10 model runs were carried out based on the generated land cover predictions.

Results

Table 2 gives an overview of all assessed MLR model parameters for the four major conversions in the selected subcatchment.

The MLR-models were used to map conversion probabilities for the different conversion types (Fig. 3).

Using ROC-indicators, the goodness of fit of this modelling approach was evaluated. The results for the four major conversion types are shown in Fig. 4.

For all analysed conversion types, the MLR model described the observed transitions better than a random model (area under curve (AUC) >0.5). The highest AUC-values were found for GF conversions (AUC = 0.65). Lower ROC-values were found for VA (0.59), VG (0.53) and AG (0.55).

Using the spatial allocation procedure described above, new land cover maps were constructed for the years 2010, 2020 and 2030 whereby the existing trend between 1981 and 2000 was extrapolated. Figure 5 shows the predicted land cover maps for the years 2010, 2020 and 2030 for one model run and the cumulative pattern of simulated changes in 2010, 2020 and 2030.

Figure 5 shows that although the overall land cover pattern persists according to the extrapolation, gradually the forest cover increases in the central and upper part of the catchment. In the neighbourhood of villages an increase in grassland and a decrease of the arable land can be observed.

Table 3 shows for each simulated year the modelled sediment production (SP in Mg year^{-1}), the modelled sediment delivery (SD in Mg year^{-1}) and the sediment delivery ratio (SDR). The predictions for 2000 are based on the observed land cover

Table 2 Coefficients of the logistic regression equation where a = intercept, b(SG) = coefficient of slope gradient, c(EV) = coefficient of elevation, d(DS) = coefficient of

distance to shoreline of the lake, e(DV) = coefficient of distance to village, f(ST) = coefficient of soil texture and g(DR) = coefficient of distance to roads

	a	b(SG)	c(EV)	d(DS)	e(DV)	f(ST)	g(DR)
AG (n = 248)	−0.3598	NS	NS	NS	−0.0032	NS	NS
VA (n = 170)	−1.9358	−0.0571	NS	NS	0.0008	NS	NS
VG (n = 356)	−0.6757	NS	NS	0.0001	−0.0003	NS	NS
GF (n = 333)	−2.8580	NS	0.0064	NS	0.0003	NS	NS

AG, arable to grassland conversion; VA, vineyard to arable conversion; VG, vineyard to grassland conversion; GF, grassland forest conversion

NS: not significant at a 5% confidence interval

n: number of converted parcels

Fig. 3 Logistic regression results. Probability maps for (a) AG conversions (b) GF conversions (c) VA conversions and (d) VG conversions

pattern. The predictions for 2010, 2020 and 2030 are based on a set of 10 simulated land cover maps. The model was run for each simulated land cover map which allowed calculating average SP- and SD-values and standard deviations.

The model simulations show that the present mean annual sediment production is expected to decrease more than 60% over the coming three decades because of expanding forest and grassland. The mean annual sediment delivery is expected to decrease 20%. Two types of errors are involved in these assessments: (1) errors caused by the land use change model and (2) errors due to the erosion and sediment delivery model. The errors caused by the land use change model were assessed by means of a Monte

Carlo Analysis to produce a set of 10 possible land cover maps for each time point (2010, 2020 and 2030). Next, the erosion and sediment delivery model was run with each of these land cover maps as an input. The standard deviation on the produced assessments for one period is in the order of 10% which shows that the detected geomorphic response and its evolution over time are significant (P -value < 0.05) (Table 4).

Discussion

The results show that AG- and VG-conversions typically occur on parcels near the main villages in

Fig. 4 ROC curves. Goodness of fit of the MLR-model based on the suitability maps for AG (diamonds), GF (rectangles), VA (triangles) and VG (crosses). The dotted line at the bottom shows the results for a random location

the centre of the study area, where commercial farming is probably no longer profitable. This may be explained by the fact that the villages in the centre of the catchment depopulate because of the low profit associated with the small scale farming. Many of the remaining farmers receive additional income from agro-tourism. Vineyards near the shoreline, on the other hand, have a much lower probability of being converted into grassland because of their attractiveness for tourists. During the last decades many new holiday resorts with lake views were constructed. To maintain the landscape attractive for tourists, a lot of resort managers decided to maintain the old vineyards. They are cultivating the vineyards both for own consumption as for the market, where they sell the grapes to the vine companies. In some cases new vineyards were developed. Therefore distance to shoreline is positively correlated with VG-conversions.

In some cases vineyards are converted into arable land. These VA-conversions occur mainly on parcels with low slopes and relatively far away from the villages where parcels are larger and intensification is still possible. GF-conversions occur on parcels with a high elevation and relatively far away from the villages. The variables 'Soil texture' and the 'distance to road' were not significant in the MLR-models.

Lower ROC-values for VA, VG and AG conversions can be explained by the fact that forest is in

most cases the end phase of land cover change: once a land unit is under forest it will not easily be deforested. Although a net decrease of arable land and vineyard is observed, the spatial change pattern is much more difficult to describe by means of MLR-models since these patterns can fluctuate significantly on a short time span. Farmers decide on a yearly basis which parts of the arable land are cultivated and which are set aside, which results in frequent conversions from arable land to pasture and vice versa. On decadal scale, existing vineyards may be renewed and new plantations may be started on former grassland or arable land.

Jordan et al. (2005) validated the WaTEM/SE-DEM model in a similar catchment using observed sediment export data. They reported a model error of $\pm 40\%$ on the predicted sediment delivery mainly due to an incorrect representation of the topography. This study focuses, however, on the relative change in sediment production (SP) and sediment delivery (SD) due to land cover changes. Because, apart from the land cover maps, all other input data (digital elevation model, soil map, rainfall data) are identical in all simulations, the error on the relative changes in SP and SD is expected to be much lower.

A closer look at the predicted mean annual erosion rates shows that the decreasing trend is not linear. This can be explained by the fact that conversions to grassland and forest take place on land units with steep slopes according to the extrapolation. This implies that the first 10% of converted arable parcels and vineyards will on average have a higher slope gradient than the second 10%. This will lead to a gradually stronger decline of the average erosion rate.

The predicted land cover changes, however, do not have the same impact on the sediment volume that enters the lake because of the poor connectivity of these land units with the permanent river channels. Only a small fraction of the eroded soil material on these parcels reaches the lakeshore. The conversions of arable land and grasslands at distant locations have a very limited impact on the total sediment delivery of the catchment. The major contributors to the lake sediment load are vineyards near the lakeshore which are likely to be maintained because of their touristic value. As a consequence, the relative importance of these vineyards in the total sediment budget of the catchment will increase. This explains why the model simulations show an increasing sediment delivery ratio. In the future, the

Fig. 5 Land cover maps for the years 2010, 2020 and 2030 respectively

Table 3 Simulated proportions of different land cover types

Year	Arable land (%)	Vineyard (%)	Grassland (%)	Forest (%)
1981	22	10	30	36
2000	19	7	30	42
2010	17	5	30	46
2020	16	4	30	49
2030	15	3	28	52

mean annual soil erosion rate in the catchment is expected to be lower by a continuous decrease of the area of arable land, but a higher percentage of the eroded material will be delivered to the rivers.

Conclusions

A detailed land cover change analysis of a catchment in the Balaton uplands showed an extensification of land use during the last 25 years. The major land cover changes in this period were conversions from arable land and vineyards to grassland and from grassland to forest.

The extensification of the land use is related to the collapse of the collective farming system and a depopulation of the rural villages. The decollectivization opened the Hungarian agriculture to competition with European Union (EU-) states and North America, which is leading to a more intensive

Table 4 Possible impact of land cover change on the levels of soil erosion (SP = sediment production), sediment delivery (SD) and sediment delivery ratio (SDR) in the subcatchment based on 10 land cover change simulations

Year	Sediment production (Mg year ⁻¹)		Sediment delivery (Mg year ⁻¹)		SDR	
	Average	Std. dev.	Average	Std. dev.	Average	Std. dev.
2000	1,490	n.a.	120	n.a.	0.08	n.a.
2010	1,090	75	107	3	0.10	0.01
2020	784	94	107	4	0.14	0.01
2030	564	67	94	4	0.17	0.02

use of fertile land in the Hungarian plains and a gradual conversion of less fertile soils into permanent grassland or forest in remote areas such as the Balaton uplands. The accession of Hungary to the EU since 2004 will probably enforce the current trend.

A second and equally important driver of land use and land cover change in the area is the tourist industry around Lake Balaton. The increasing number of tourists that visit the area led to (1) a spectacular increase of the built-up area around the villages at the lake shore and (2) a conservation of the “traditional” rural landscapes near the lake. In some cases holiday resort managers and agro-tourism farmers decided to continue vineyard farming or even install new vineyards near the shore in order to increase the attractiveness of the landscape for tourists.

The observed change patterns were described by means of multiple logistic regression models. A ROC-analysis showed that MLR-models describe the observed land cover change patterns better than a random model. By means of a stochastic land cover change allocation model based on the observed changes in the period 1981–2000, land cover scenarios for 2010, 2020 and 2030 were generated at the scale level of individual parcels assuming that the 1981–2000 trend will persist. An impact analysis showed that the increase of forest and grassland in the area will lead to a further decrease of the average soil erosion rate. Assessed standard deviations show that this trend is significant. The sediment delivery ratio to the lake on the other hand is expected to increase because of the relation between sediment sources and sinks in the catchment. The majority of the parcels where future land cover change will lower the average erosion rate are not contributing to the sediment influx in the lake. Most of the soil material eroded at these parcels is deposited within the

catchment before it reaches a river channel or the lake. The major contributors to the lake sediment influx are the vineyards near the lake shore. According to the developed scenario these will decrease but not disappear in the near future. To protect the water quality of Lake Balaton, land managers and environmental policy makers should emphasize the adoption of soil conservation measures on parcels near the shore.

This analysis shows that the spatial pattern of change seems to be more important than the percentage of change, which emphasizes the importance of the development and application of spatially explicit land cover change models. Moreover, the results suggest that the spatial scale of the model application needs to be sufficiently detailed. Land cover change models such as e.g. CLUE (Verburg et al. 2006) or ACCELERATES (Rounsevell et al. 2006) are often applied at spatial resolutions of 1–100 km² which is very useful to reproduce regional scale land cover change trends. However, in this case such models are of limited use because the topology of sediment sources and sinks between the different parcels is lost due to the aggregation of pixels.

The major drawback of a parcel-scale land cover model, on the other hand, is the volume of detailed input data needed, which limits its applicability at larger areas. Further research should therefore explore the potential of nested modelling approaches in which coarse scale land cover change models are downscaled to the level of micro-landscapes and parcel structures.

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