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Analysis of land cover changes in the past and the future as contribution to landslide risk scenarios

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ABSTRACT

Various factors influence the spatial and temporal pattern of landslide risk. Land cover change is one of the crucial factors influencing not only the natural process "landslide" and thus the hazard, but also the spatial distribution of elements at risk. Therefore the assessment of past and future landslide risk at regional scales implies the analysis of past and future land cover development. In this study, the first step in the analysis of landslide risk development over time is approached by analysing past land cover, as well as modelling potential future scenarios. The applied methods include analysis of orthophotographs and landcover scenario modelling with the Dyna-CLUE model. The timespan of the analysis covers 138 years from 1962 to 2100. The study area is located in Waidhofen/Ybbs (Austria) in the alpine foreland. A high number of landslides are recorded in the district. The predominant land cover types are grassland and forest. Buildings and residential areas are located in the valley bottoms and scattered on the hilltops. The results show clear changes in the land cover development of the past and in the future including spatial changes in the distribution of elements at risk. The trends show an increase in forest on the expense of grassland. The spatial evolution of the surfaces of arable land is rather high whereas the surfaces of residential zones increase steadily. The spatial analysis indicates also the development of new building areas and consequently potentially new landslide risk hotspots.

Introduction

The change in temporal and spatial patterns of landslide risk is attributed to several factors of global change. The changing climate is not only influencing intensity and frequency of extreme weather events, but also their extent, duration and occurrence time (IPCC, 2012). Alternating land use and land cover respectively may act as predisposing factors of landslide occurrence (Glade, 2003; Beguería, 2006), but may also control the spatial distribution of landslide consequences. The fact that not only the natural processes but also the elements at risk change continuously, leads to the assumption that risk assessment cannot be a static process (van Westen, 2010). To address the spatio-temporal variability of landslide risk, one aspect is to analyse past land cover changes, as well as future development of the land use and land cover using scenario-based approaches.

According to Slaymaker, Spencer, and Embleton-Hamann (2009), human activity, especially as far as land use and land cover patterns are concerned, is the most rapid driver of global change. Rindfuss, Walsh, Turner, Fox, and Mishra (2004) refer to the interaction of human and natural subsystems that lead to alterations in land use and land cover. New land cover patterns may occur not only due to natural factors but also as a result of a number of anthropogenic activities such as economic developments, population growth or land abandonment. The scenario based analysis serves as a tool to determine *what could happen* assuming different pre-conditions (Verburg, Eickhout, & Meijl, 2008). These pre-conditions mostly imply the interaction of factors of the subsystems as mentioned above (e.g. demographic or climate change). Modelling these scenarios and their uncertainties is an explorative analysis that helps to delineate the margins of the possible and conceivable (Verburg et al., 2008). Moreover, the analysis of the past and future land cover is significant to thoroughly investigate two of the major research questions dealing with land cover processes: 1) understanding in which locations land cover change occurs, and 2) assessing the rates of change (Lambin, 1997). The spatially explicit analysis enables to

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understand and delineate better the interactions of the two subsystems (Rindfuss et al., 2004).

The analysis of the possible future land cover development is especially important due to the fact that decision-makers are interested not only in the future hazard potential but also in the information on potential loss as input to a range of decisions (e.g. hazard mitigation plans; Downton & Pielke, 2005; Frazier, Walker, Kumari, & Thompson, 2013). Modelling and monitoring of land cover development on a regional scale has been conducted in many different regions around the world (Rembold, Carnicelli, Nori, & Ferrari, 2000; Ruelland, Levavasseur, & Tribotté, 2010; Teferi, Bewket, Uhlenbrook, & Wenninger, 2013). Many authors focus on ecosystems or more specific on deforestation (Etter, Mc Alpine, Wilson, Phinn & Possingham, 2006; Lambin, 1997). Regarding landslides and land cover change there are numerous studies available e.g. Alcántara-Ayala, Esteban-Chávez, & Parrot, 2006; Beguería, 2006; Glade, 2003 or Van Beek and Van Ash, 2004. Moreover, land cover change and consequent changes in the impact of natural hazards is an emerging topic within the research community e.g. Wood (2009) studying tsunami exposure, Alcántara-Ayala et al. (2006) assessing the distribution of landsliding in the context of vegetation fragmentation or Papathoma-Köhle and Glade (2012) also dealing with vegetation cover and landslide hazard and risk. In this study we apply a land cover analysis for the past, as well as, approximating future land cover in order to allow a first attempt towards the potential evolution of landslide risk.

The analysis of the spatio-temporal patterns of land cover will be the base for investigating the development of potential landslide risk. The focus of the paper is on the location explicit temporal analysis and the non-location specific quantitative analysis of land cover changes, based on implemented scenarios. First, the methodology used for the spatio-temporal land cover analysis is explained. Second, a short description of the study area detailed in order to demonstrate the relevance of the study's objectives on a regional scale. Finally, the results are discussed and some perspectives for further analysis are proposed.

Method

The approach for land cover analysis as a basis for the subsequent risk assessment requires the combination of different sets of methods. To analyse the land cover change, the applied methodology contains four steps:

1. setting the time scale of analysis,
2. analysing the spatial land cover changes,
3. adapting and modelling future land cover scenarios,
4. performing a quantitative and qualitative (spatially explicit) analysis.

Hereby, spatially explicit refers to a location based analysis of the different land cover types. Regarding the future land cover development, scenarios are envisaged in order to run the model for scenario-based approximation of possible future developments.

Time scale of the analysis

There are two considerations related to setting the time span of the land cover change analysis: a) which mapping documents are available for the past and b) what time span is reasonable concerning future scenarios.

In order to compare results, the time periods should be chosen in accordance to existing future scenarios regarding development plans or climate change models (Hiess et al., 2009; ÖROK, 2011; Schoener, Boehm, & Haslinger, 2011; Smiatek, Kunstmann, Knoche, & Marx, 2009). For this reason three future time steps are used in this analysis: 2030, 2050, and 2100. The year 2030 is selected due to the horizon of the spatial development plans and scenarios. 2100 is the horizon of various climate models and 2050 seemed reasonable in order to have periods with an adequate number of years for land cover analysis.

Spatial analysis of land cover changes

Analysis of past land cover changes

Available aerial photographs of past spatial land cover patterns are mapped in order to be used for the analysis of the land cover change over time. This is achieved by ortho-rectifying the available aerial photographs. To ensure reasonable results, certain rules and restrictions (Promper & Glade, 2012) were set for carrying out the visual interpretation in a GIS environment. If the data quality did not allow visual interpretation, a comparison with other orthophotographs was required.

Future land cover scenarios

Scenarios can be considered as alternative images on how the future might unfold (Nakićenović et al., 2000). Regarding land cover, this implies not only climate-driven changes but also direct anthropogenic impacts. Spatial and regional development scenarios available by authorities or previous projects may serve as a basis for land cover modelling. To serve as spatially explicit analysis, input parameters have to be defined. Further the assumptions need to be stated clearly in order to ensure transparency within the analysis.

The model Dyna-CLUE 2.0 (Verburg & Overmars, 2009) was selected to simulate the land use scenarios because it includes a spatial and a non-spatial module (Verburg et al., 2002). The model combines statistical analyses and decision rules that determine the sequence of land cover types (Schaldach & Priess, 2008). For the spatial analysis, the relationships between the different land cover classes and the main driving factors are evaluated by stepwise logistic regression (Verburg et al., 2002). Moreover, location specific restrictions (e.g. natural reserves) need to be included. The demand represents the non-spatial model input and is based on the scenarios used. These values are implemented in the model as a top-down factor. By an interactive process, the model tries to implement all these changes for one year before it proceeds to the next. This ensures that, for example in the map of 2030, all changes from 2005 onwards are already included.

The basis for the spatial distribution of the different land cover classes in the scenarios depends mainly on topographic factors like slope and aspect. However, some general spatial planning assumptions are also incorporated to limit certain factors (e.g. development in completely remote areas). Applying assumptions in scenario building enables implementation of possible societal and economic developments in order to simulate what might happen in the future (Rounsevell, Ewert, Reginster, Leemans, & Carter, 2005). The assumptions applied are explained in more detail in the following paragraph.

On one hand, an assumption that the demand for the years 2005–2030 will not change until 2100 had to be made, meaning that this was extrapolated, adopting at the same time some general trends in spatial planning. On the other hand, the second assumption is that no new building area outside a 100 m buffer of existing building area/street area is allowed. Further, a minimum distance (200 m) between farms is applied. Finally, street areas do not develop for the reason that Dyna-CLUE 2.0 does not integrate options for linear development. Another assumption was the fact that water surfaces do not change within the modelling process.

Additionally, the past development of land cover is not yet implemented into the future modelling. The hypothesis supporting this decision is that changes in the planning system and changes in the needs of the population overrule the importance of past developments. This is strongly supported by the fact that human activity is regarded as the most rapid and a very important factor regarding land cover change (Briassoulis, 2003; Meyer & Turner, 1994; Slaymaker et al., 2009).

Study area and datasets

Regional setting

Waidhofen/Ybbs is located in the Province of Lower Austria in the alpine foreland (Fig. 1). The administrative unit is a district as well as municipality and covers approximately 130 km^2. Due to data availability, the study area focuses to 112 km^2 of the district. The topography is characterized partly by steep slopes and partly by gentle hilltops.

Land cover and land use types are strongly linked to relief characteristics such as slope height, slope angle and slope exposition. It is composed mainly by cultivated grassland as well as by forest (Fig. 3). The acreage areas are scarce and depend on the exposition, as well as the location on the hill slope.

Waidhofen/Ybbs has approximately 11.500 inhabitants leading to a population density of about 90 inhabitants per km^2. Due to the relief, population is mainly concentrated in the valley bottoms and scattered settlements and farmhouses at the hilltops (Fig. 2). Furthermore, public buildings, as well as industrial areas, are concentrated in the valley along the Ybbs river.

The main soil type in Waidhofen/Ybbs is brown earth; however, patches of relict soils such as Rendsina, Gley and Pseudogley can also be found. The lithology is composed of Limestone, Flysch, the "Klippenzone" and Dolomite (Wessely, 2006). The Northern part is characterized by gentle hillslopes underlayed by Flysch.

The majority of landslides occur in the Flysch and the Klippenzone (Schwenk, 1992). Moreover, the district Waidhofen/Ybbs has one of the highest amounts of landslides in the province of Lower Austria (Petschko, Glade, Bell, Schwaigl & Pomaroli, 2010). In more detail, the landslide inventory of Waidhofen/Ybbs (Petschko et al., 2010) indicates a total of 691 landslides, mapped from the ALS (Airborne Laser Scanning). The landslide types have been classified by visual interpretation and include 522 distinct slides, 141 areas with slides, 25 with flows and 3 with complex landslides (Petschko et al., 2010). Therefore, the predominant landslide process for the study area of Waidhofen/Ybbs is sliding. The analysis of the reported damage in the landslide inventory (extracted from the building ground register provided by the Provincial Government of Lower Austria), includes estimations with respect to the depth and the size of the landslides. The depth of most of the landslides has been estimated in the range one to three meters. The reported

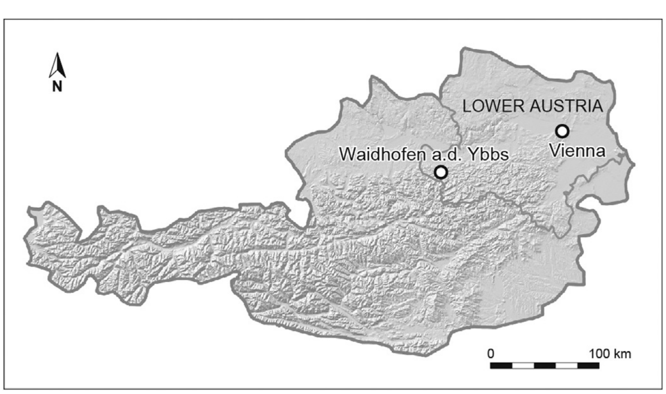

Fig. 1. Location of the study area Waidhofen/Ybbs in Austria (Promper & Glade, 2012).

damages are mostly related to infrastructures and agricultural areas whereas the smallest portion of the records is related to buildings.

The analysis of the land cover in the study area is based on the orthophotograph of 2005. The digital cadastre shows that two predominant land cover types are *forest* and *grassland*. Further, the land cover types *rock* and *water* only represent a very small portion of the whole investigation area. Some land cover types (e.g. *acreage*) fluctuate more than others (e.g. *farms)*.

Datasets

The aerial photographs available for the study area cover the years 1962, 1979 and 1988. The orthophotographs for 1992, as well as a combination of 2005 and 2007 (later referred to as 2005 only) are available. Further the digital cadastre including a high number of land use classes serves as basis for the analysis. Additionally a layer comprising protectorates and the digital elevation model (DEM), are available as basis for restricted areas according to slope or aspect. The scenarios used for the land cover development is explained separately in the following paragraphs.

Land cover development scenarios are available from the Agency "Austrian Conference on Spatial Planning". The scenarios are part of the outcome of discussions of four workshops by experts, as well as expert public, in the context of the project *Scenarios for the spatial and regional development of Austria in the European context* (Hiess et al., 2009). The future driving forces are presented in the form of megatrends with different facets e.g. ageing of society, wild cards like extreme events with strong effects on total system and scenarios which are aimed to be consistent and representing the most diverse potential of the future (Hiess et al., 2009). These quantitative approximations for Austria are then described for the different sub regions e.g. peripheral regions, urban regions (Hiess et al., 2009). In the following the different available scenarios are described in more detail.

Scenario 1: overall growth

The *Overall growth* scenario considers a general increase of the main forces driving spatial development, such as economy, population, tourism, mobility and transport. Moreover, this scenario type is characterized by improved energy efficiency, resulting in reduced emissions. Although the interactions between state, market and civil society prevent widening of disparities, the pressure on space grows rapidly according to the *Overall Growth* scenario. These developments lead to a conflict of the usage of space between the different sectors, such as tourism, nature conservancy, agriculture, as well as settlement areas. (Hiess et al., 2009)

Scenario 2: overall competition

In the scenario *Overall competition*, the main driving factors of spatial development are also growing strongly. However, the social and, consequently, the spatial disparities widen. This implies that pressures on the growth zones and other regions are confronted with out-migration. The basic assumption in this scenario is that markets respond in time to scarcities, thus far reaching energy and environmental crisis are avoided. (Hiess et al., 2009)

Scenario 3: overall security

In contrast to the previous scenario types, the *Overall security* scenario considers a moderate growth of the main driving factors (economy, population and tourism). This moderate growth results in an increase in pressure in areas being used for farming and agriculture, due to high demand for biomass energy. Increasing disparities can only be avoided by strict government regulation, social security systems and restrictive in-migration. (Hiess et al., 2009)

Fig. 2. Gentle hillslopes in the Northern area of the district (a) and scattered settlements (b) in the region Waidhofen/Ybbs, Lower Austria (pictures taken by (a) Canli, 2012 (b) Gokesch, 2012).

Scenario 4: overall risk

This is similar to the *Overall competition* scenario; however, the market does not develop any mechanisms against sudden energy scarcity. For this reason, energy prices rise suddenly in the absence of adequate countermeasures. High energy and mobility costs are the main driving forces in this scenario. The consequences for rural areas imply migration of enterprises population. (Hiess et al., 2009)

Application of the methodology and results

The application of the methodological steps ensures that the quantitative changes in land cover can be analysed spatially. In the following paragraphs, the detailed analysis of the development of the land cover classes is described in accordance to the succession proposed in the Methodology chapter.

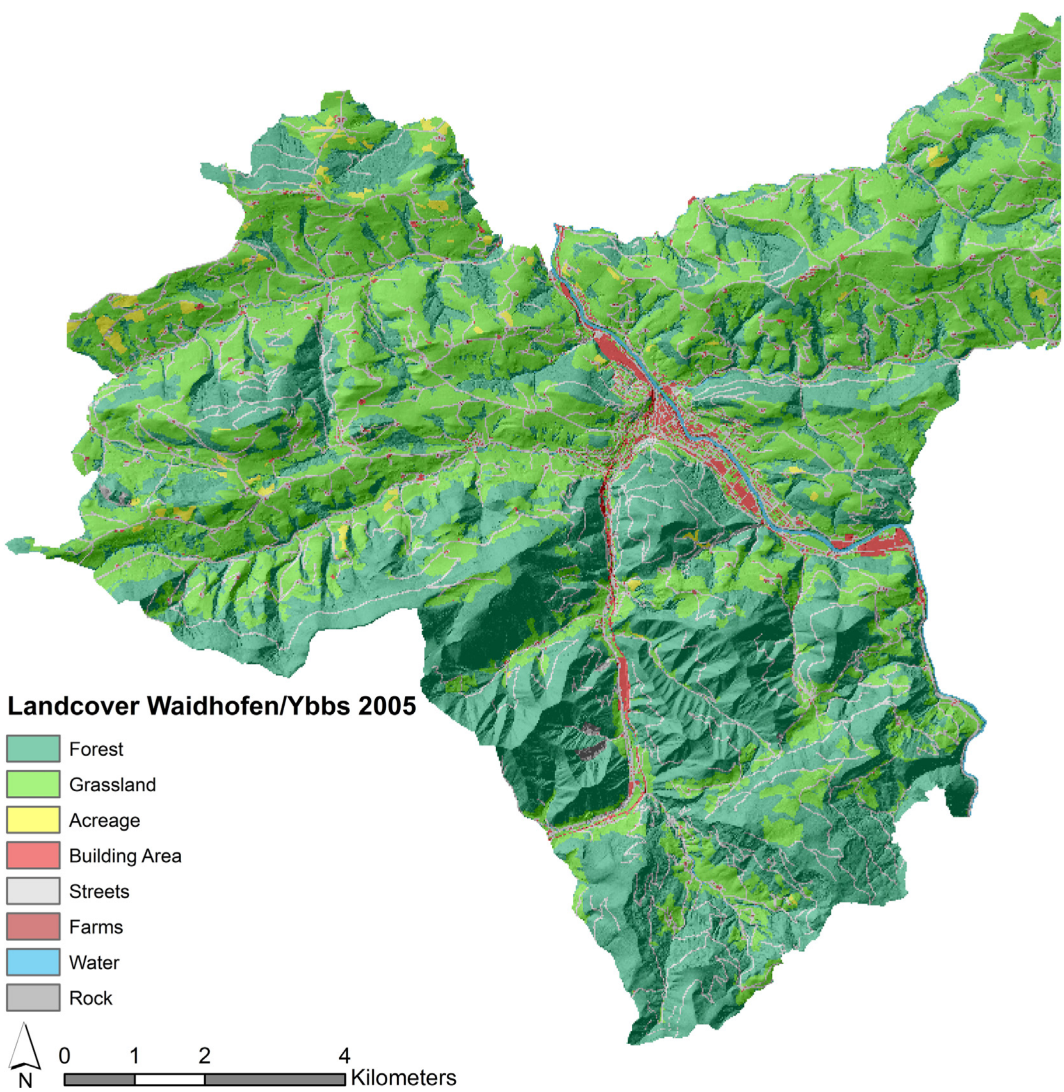

Fig. 3. Land cover map of Waidhofen/Ybbs 2005.
Source DEM: Provincial Government of Lower Austria.

Time scale

The four orthophotographs of 1962, 1979, 1988 and 2005 are used as mapping basis. The orthophotograph of 1992 is excluded due to the short time period between 1988 and 1992. This leads to the final analysis periods that are displayed in Fig. 4. Due to the availability of aerial photographs, the time slices for the past differ from 9 up to 17 years.

Spatial and quantitative analysis of land cover changes

The results of the land cover mapping from 1962 to 2005 indicate a clear trend towards an increase in *building* as well as *street* areas. The land cover type *farms* remains more or less the same over the analysis period. However, the acreage is fluctuating constantly, reaching the largest extension in 1979. The lowest extent of acreage is in the first time slice. Regarding the dominant land cover class *forest* and *grassland* the development is controversial. The *forest* area is decreasing from 1979 onwards, whereas the extension of grassland is fluctuating over time reaching its minimum in 2005. The coverage of grassland decreased from approximately 50% of the study area to its minimum of approximately 40% over the investigation period. The *forest* area always fluctuates around 40%. The land cover classes *water* and *rock* range below 1% of the whole study area summarizes to a total area of approximately two hectare. In Fig. 5, these changes are presented as percentage of the whole study area from 1962–2005.

Scenarios development

The development of the scenarios implies data preparation and the tuning of the scenarios to the respective study area. This is necessary due to the specific characteristics of the region of interest.

Data preparation

The applied land cover scenarios were developed for whole Austria (see chapter Datasets), and thus need to be adapted for the regional analysis. Within the scenarios, the changes for the different land cover classes are described in hectares of increase/decrease per year. Adaption to the study area was performed by accustoming the numbers for the whole area of Austria to the area of Waidhofen/Ybbs. As model input the estimation of a balanced increase and decrease of hectare land cover is demanded. In a first step, the focus was on the increasing land cover types; in a second step, the decreasing areas were calculated proportionally.

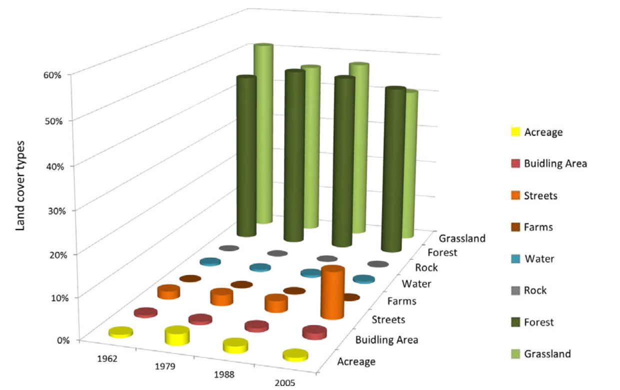

Fig. 5. Changes in land cover delineated from aerial photographs between 1962 and 2005.

The Table 1 details the demand specifically calculated for Waidhofen/Ybbs in hectare per year. These numbers indicate the increase or decrease in hectare area, considering all top down factors that are incorporated additionally.

Quantification of the scenarios

Regarding the future development of the different land cover types, the scenario-based approach is presented in Fig. 6. Note that the building area includes the farms, due to the very low number of farms in the study area. The past development of the land cover classes shows an overall trend within the investigation period. However, it is important to consider that this figure represents the demand that was set for the different scenarios. Thus, it only allows to visually comparing the different trends, also in correspondence to the past development.

Fig. 6 shows a clear trend for future increase in *forest* areas, for all scenarios. Moreover, a clear trend towards an increase of the building area is indicated. On the opposite, the future trend for grassland is decreasing. In more detail, the *scenario 2* shows the highest number of changes compared to the other scenarios.

Table 1
Land cover demand adapted for Waidhofen/Ybbs for each scenario.

Change in ha/year for Waidhofen/Ybbs	Forest	Grassland	Acreage	Building area
overall growth	5.0	−5.8	−0.4	1.2
overall competition	18.5	−19.7	−0.3	1.5
overall security	12.3	−13.0	−0.2	0.9
overall risk	12.3	−12.9	−0.1	0.7

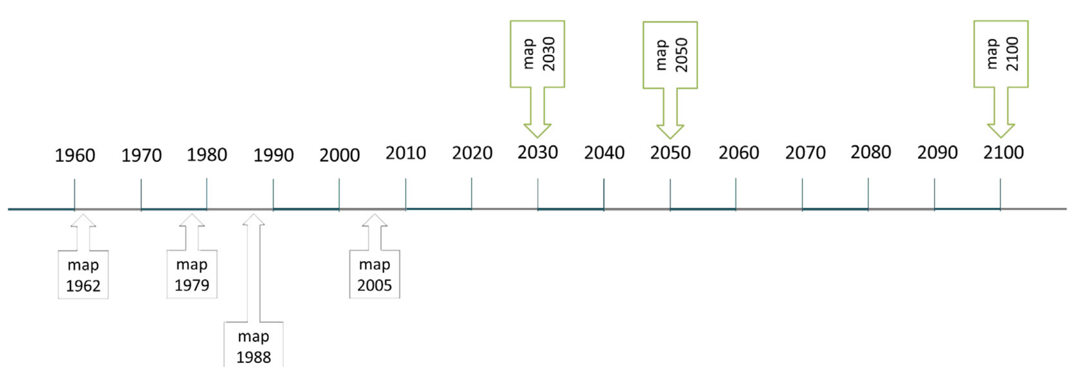

Fig. 4. Time periods of the past and future land cover analysis.

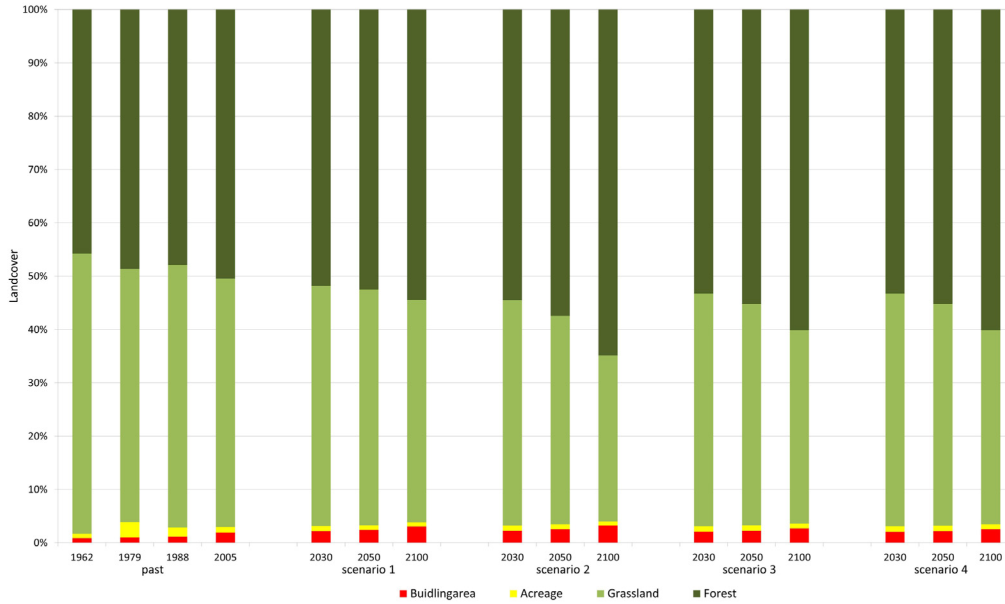

Fig. 6. Changes in land cover types in percentage of total changes for the past periods, the current land cover map and the four scenario developments.

Especially the forest areas increase by more than 10% of the total changes from 2030 up to 2100. Comparing this area of forest to the forest area in 1962, the increase is more than 20%. In each scenario, the building area shows an increase, however, *scenario 2* shows the highest overall increase of building area.

Location specific restrictions

These top-down factors were included to create location specific criteria where certain land cover conversions are not possible. Further, these are used to keep distances between specific developments within the modelling process. The restrictions were set by expert judgement and computed by analysing the distribution of the different land cover types in the current land cover map. The Table 2 represents the location specific restrictions used for this study.

Modelling process

The modelling was carried out with the Dyna-CLUE (Dynamic Conversion of Land Use and its Effects, v 2.0) modelling framework (Verburg & Overmars, 2009). The model combines bottom-up and top-down effects and allows modelling several land cover types in one modelling set-up. This model combines a non-location specific demand module and a spatially-explicit allocation procedure (Verburg et al., 2002). The demand described in the chapter Scenarios development was used as top-down input on how the land cover should develop quantitatively. For the location specific restrictions (Table 2), different binary maps, including these restricted areas only, were created. Further the analysis of the land cover classes and their driving factors were evaluated by using logistic regression.

The allocation of the pixels within the model are then, based on these probability maps, the decision rules and the actual land use map, conducted by an iterative procedure (Verburg et al., 2002). This iteration is conducted for each year, thus each output map already incorporates all changes that have occurred up to this specific moment in time. The spatial analysis of the results follows in the following paragraphs.

Table 2
Location specific and non-location specific restrictions.

Restriction	Land cover type	Applied restrictions
Location specific	Building area	Distance to existing building area max. 100 m Distance to existing roads max. 100 m Distance to existing farms max. 100 m Restricted within natural reserves
	Acreage	Aspect: 180°–270°
Non location specific	Forest	Change only allowed after 30 years

Location specific analysis of land cover changes

More insight into changing patterns is provided by the location specific analysis, as well as the examination of which land cover types change to which other land cover type. Scenario 2 is selected as an example for the spatial analysis because it indicates the largest areas of changed land cover. This probably relates to the story line that energy scarcities are prevented timely. The changes for the other scenarios are similar, due to the same location specific parameters applied. Fig. 7 shows the changes from 2005 to 2030 and 2005 to 2100 for the respective scenario.

The intense colours "New areas" in Fig. 7 indicate clearly the new land cover type. The changes from 2005 to 2030 mainly show an increase in *forest* in the central and southern parts of the study area. Additionally, an increase in *building* area along the valley in the South is observed. Referring to Tables 3 and 4 this change is on the expense of *grassland* only and covers around 0.3% of the total study area. On the hill slopes, in the South Eastern part of Waidhofen/Ybbs, a new area of *acreage* is also visible. The *forest* area increased mostly at the expense of grassland and covers approximately 4% of the study area however, new grassland has also developed on forest areas. The change from *forest* to *acreage* is extremely low, but it can occur.

The changes from 2005 to 2100 cover a larger area, indeed. The increase of forested areas expands towards the north-eastern part as well. Regarding the building area, the expansion is vast and covers almost completely the valleys in the southwest. Further, it increases on the hillslopes in the South Western part and, in the last

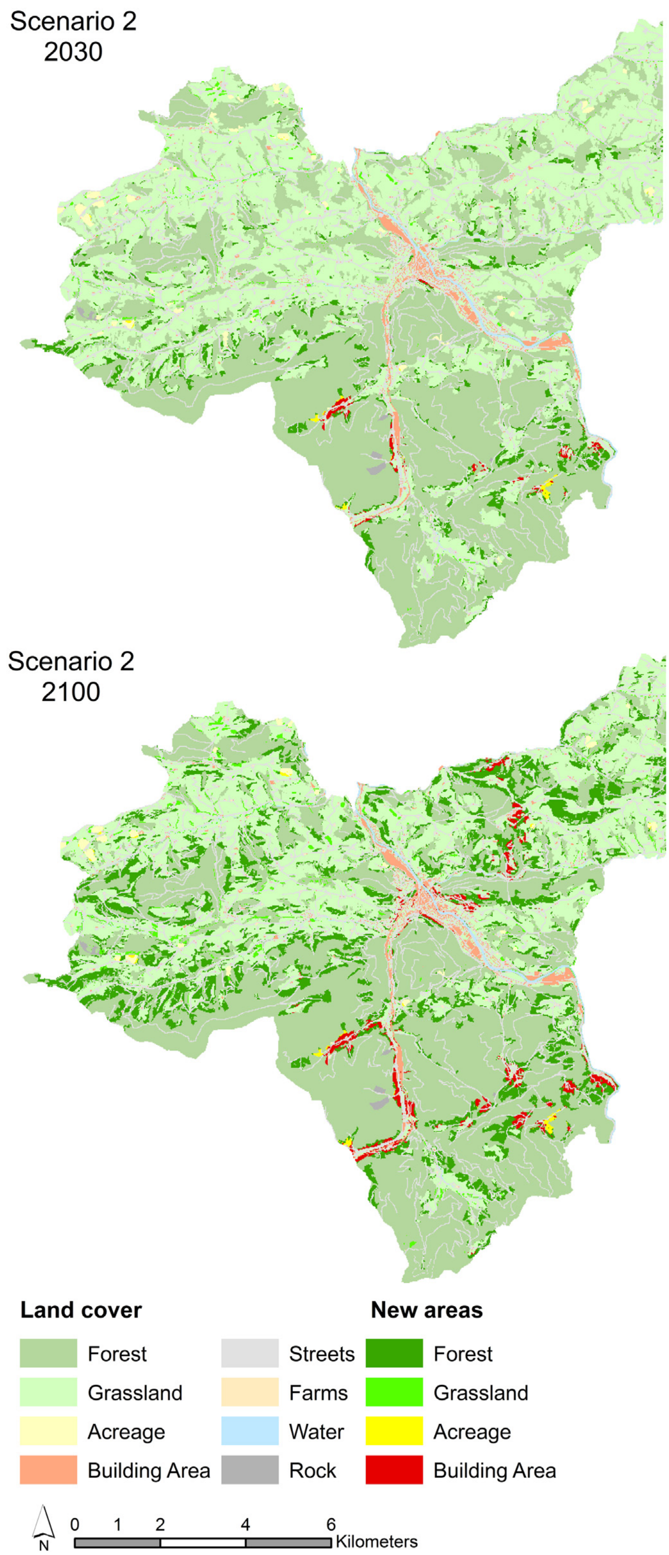

Fig. 7. Spatial changes in land cover *scenario 2* between 2005–2030 and 2030–2100.

developments steps, also in the North Western part of the study area. Moreover, it is striking that new acreage areas seem closely linked to locations of new *building* area. Approximately 13% of the study area turned from *grassland* to *forest* areas and less than 1% from forest to grassland. The building area increases solely at the expense of *grassland* (Tables 3 and 4). In contrast to the changes up to 2030, there are changes from acreage to forest and a larger shift from *acreage* to *grassland*. However, the new grassland in 2100 mostly developed at the expense of forest (Tables 3 and 4).

Discussion

The results of this analysis show two different types of data: the mapped results and the scenario based analysis on possible future developments. In both analysis, uncertainties have to be accounted for, however, the nature of uncertainty is different. In the following paragraphs, the sources of uncertainty are explained in more detail.

On the one hand, the mapping procedure is affected by different problems e.g. visual interpretation may change with enhanced practice, quality of the aerial photographs due to overexposure or shading, etc. Regarding the modelled data, this analysis is bound to "what-if" scenarios which have exploratory and projective capacities. However, these can be used as a communication and learning environment (Verburg, Kok, Pontius, & Veldkamp, 2006).

The results of the analysis from 1962 to the scenarios up to 2100 show a vast range of changes over the study area. Especially the increase in *forest* over *grassland*, as well as the increase of *building* area on the hillslopes in the Southern part of Waidhofen/Ybbs is evident. In the following sections, these results are discussed in more detail alongside the chronology of the analysis.

Past land cover analysis potential

Additionally to the aforementioned limitations the outer rim of the coverage of Waidhofen/Ybbs is less accurate than the central parts, where more aerial photographs were available.

The fact that between 1988 and 2005, some land cover types register an abrupt rise can partially be related to the long time span of 17 years; however, it may also be related to the incorporation of the digital cadastre which offers additional information, which might not be visually recognizable. Anyway, the results definitely show an increase in building area, as well as a lot of fluctuation concerning *acreage* and *grassland*.

Future land cover scenarios potential

The scenarios for the future analysis represent general trends like increase in *building* and *forest* area. The location explicit analysis demonstrates clearly possible areas of development for the given constraints. All scenarios suggest potential for building area in the southern part of the study area and on the long run also in the north-eastern part. Moreover, all scenarios suggest an expansion of existing *forest* areas all over the study area. The expansion of these areas on the expense of *grassland* and *acreage* follows a trend that can be observed throughout the Alps (e.g. Gellrich, Baur, Koch, & Zimmermann, 2007; Gehrig-Fasel, Guisan, & Zimmermann, 2007; Tasser, Walde, Tappeiner, Teutsch, & Noggler, 2007). This phenomenon is observed at moderate to high altitudes, steep slopes, areas with low temperature averages, but also to former alpine pastures (Gellrich et al., 2007). Further, Gellrich et al. (2007) refer to this phenomenon as a regional development which is largely restricted to municipalities with increasing population, higher proportions of part-time farms and higher farm abandonment (Gellrich et al., 2007). Apart from farm abandonment these characteristics apply for the study area, which support the suggested increase of forest area represented in the demand of the scenarios.

Table 3
Matrix of land cover changes for *scenario 2* from 2005 to 2030.

Scenario 2 in ha/year 2030	Forest	Grassland	Acreage	Building area	Streets	Farms	Water	Rock
Forest	43.84	**0.36**	**0.00**	–	–	–	–	–
Grassland	**3.91**	36.48	**0.12**	**0.29**	–	–	–	–
Acreage	–	**0.19**	0.73	–	–	–	–	–
Building area	–	–	–	1.54	–	–	–	–
Streets	–	–	–	–	11.65	–	–	–
Farms	–	–	–	–	–	0.14	–	–
Water	–	–	–	–	–	–	0.59	–
Rock	–	–	–	–	–	–	–	0.16

Bold values represent change to other land cover type.

Change in possible landslide consequences

The location specific analysis, offers the possibility to analyse not only potential future consequences but also the development of the spatial pattern of elements at risk. This evolution of landslide risk is strongly connected to the spatial development of elements at risk, thus analysis corresponding to this paper is inevitable for future risk management (Promper & Glade, 2012).

Regarding location specific changes of potential consequences, all new building area needs to be examined in detail. Especially the building area that increases in the north-eastern part of the study area approaching the year 2100 requires in depth analysis. These areas are within the Flysch zone, where most of the landslides occurred in the past within the study area (Petschko et al., 2010). Moreover, the southern part of the study area where building area is increasing on the hillslopes, the steep hillslopes below need in depth analysis. This increase is location wise the same for all scenarios. The difference is the expansion of the new built up area.

Modelling framework

The modelling framework Dyna-CLUE allowed incorporating a lot of different datasets, also at different spatial and temporal scales, covering different parameters. However, the necessity of quantified scenarios can be regarded as disadvantageous on this scale of analysis in a dichotomous study area, due to the fact that the same demand must apply for the whole study area. Further it is difficult to quantify the demand in ha/year at such scale because the portions of the different classes are partially very small. Generally there are several limitations to land cover modelling. On the one hand, it can be a constraint or a consequence of land use (Verburg, van de Steeg, Veldkamp, & Willemen, 2009), which leads actually to a desired modelling of the interactions. On the other hand, these drivers of change, thus interactions are very data intensive resulting in a lack of data, limiting the modelling results.

Incorporation of results in landslide risk assessment

The results enable the implementation of the modelled land cover maps in future landslide hazard assessment. Further the potential future distribution of elements at risk on a regional scale is shown within the different scenarios. With further analysis it is therefore possible to develop landslide susceptibility and hazard analysis using the results as one model input. Combining these landslide hazard maps with the existing modelling results, landslide exposure hotspot can be delineated. These hotspots then serve as a basis for detailed analysis in order to meet the local characteristics and needs regarding hazard and vulnerability to obtain a solid risk assessment for each hotspot.

Transferability

The basic inputs for this regional assessment further imply the transferability of the method in other regions where textual or quantitative scenarios regarding land cover are available. Further the transferability is not only given on a spatial extent but also towards risk assessment regarding other kind of hazards e.g. floods or torrential processes. Moreover the method allows additional input and therefore the results could be refined.

Conclusion and perspectives

The complex and dynamic process of land-use change links natural and human systems (Koomen, 2007). In the context of natural hazard and risk assessment, this linkage is a key issue. However, the importance of the consequence analysis is underlined by the fact that these have a greater influence on the risk than the hazard (Alexander, 2004). Concluding the social system has a large influence on land cover development, thus on the distribution of elements at risk, the linkage between the system is evident but not balanced. Consequently, depending on the elements at risk of interest, land cover analysis can serve as a solid tool for the consequence analysis. Regarding the predictive character, the scenario based analysis of possible future distribution of e.g. buildings or agricultural areas may be a first indication of future implications. For further analysis the land cover maps can be directly implemented in hazard models, considering land cover, in order to evaluate different scenarios of hazard susceptibility e.g. landslides. The comprehension of past risk development, as well as the incorporation of these results into the scenario-based analysis of

Table 4
Matrix of land cover changes for *scenario 2* from 2005 to 2100.

Scenario 2 in ha/year 2100	Forest	Grassland	Acreage	Building area	Streets	Farms	Water	Rock
Forest	43.48	**0.72**	**0.00**	–	–	–	–	–
Grassland	**13.31**	26.16	**0.16**	**1.16**	–	–	–	–
Acreage	**0.05**	**0.37**	0.51	–	–	–	–	–
Building area	–	–	–	1.54	–	–	–	–
Streets	–	–	–	–	11.65	–	–	–
Farms	–	–	–	–	–	0.14	–	–
Water	–	–	–	–	–	–	0.59	–
Rock	–	–	–	–	–	–	–	0.16

Bold values represent change to other land cover type.

future risk development, may support emerging issues connected to sustainable development. Rounsevell et al. (2005) state that scenarios themselves are models of how the real world functions and like in other models, exploration of understanding is allowed. Further, the development of the scenarios aimed at representing the most diverse potential scenarios and being as consistent as possible (Hiess et al., 2009). This leads to the fact that the results support an enhanced awareness regarding land cover developments and, through the follow up risk analysis, the understanding and consideration of the related change in potential consequences of natural hazards.

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