Relative Age Estimation at Landslide Mapping on LiDAR Derivatives: Revealing the Applicability of Land Cover Data in Statistical Susceptibility Modelling

Helene Petschko, Rainer Bell, and Thomas Glade

Abstract

In statistical landslide susceptibility modelling the identification of appropriate explanatory variables describing the predisposing and preparatory factors for the landslides of a given inventory is important. In this context information on the age and the respective land cover at the time of occurrence is beneficiary. The potential of mapping very old (or prehistoric) landslides using LiDAR derivatives has not been analysed yet. Additionally, performing a visual interpretation of derivatives of a single LiDAR DTM it is not possible to assign the accurate age or date of the occurrence of the event to each mapped landslide. Therefore, commonly no information on the land cover at the time of landslide occurrence for these very old landslides (but also for younger ones) is available. The objective of this study is, to estimate the relative age of landslides during the mapping and to explore differences of the recent land cover distribution in the relative ages of the landslides. This is performed to evaluate the sustainability of including recent land cover data into susceptibility modelling. The relative age of the landslides is estimated for each landslide according to its morphological footprint on the LiDAR DTM derivatives and to its appearance on the orthophoto. The different relative ages assigned are "very old", "old", "young" and "very young". The study area is located in three districts of Lower Austria, namely Amstetten, Baden and Waidhofen/Ybbs. The resulting inventory includes 1834 landslides and shows that the "very old" and "old" landslides (60 % of all mapped landslides) are mainly covered by forest (~60 % of all land cover types). We conclude that using this inventory including recent land cover data in the susceptibility model is not appropriate for Lower Austria. There is a potential of mapping "old" or "very old" landslides on the LiDAR derivatives. The absolute age remains unknown.

Keywords

Landslide inventory mapping • LiDAR derivatives • Relative landslide age • Recent land cover map

Introduction

As no detailed information on the date of occurrence of the landslides can be determined from the LiDAR derivatives (or other remote sensing techniques, Van Westen et al. 2005) the age of the landslides can only be estimated relatively in the study area. Whereas the determination of relative landslide age is very common in studies mapping landslides on aerial photographs or orthophotos (e.g. Ardizzone et al. 2002;

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Table 1 Land cover evaluated for landslide polygons according their landslide type and relative landslide age

Land cover unit	Study area (%)	All landslides (%)	Slide (%)	Area with slides (%)	Flow (%)	Complex (%)	Young (%)	Very young (%)	Old (%)	Very old (%)
Coniferous forest	12.77	19.97	25.72	16.60	11.80	16.60	5.80	0.92	16.89	23.65
Mixed forest	13.89	20.04	20.05	19.52	24.96	10.14	13.27	7.18	26.04	17.65
Deciduous forest	13.65	20.19	18.08	21.86	21.74	24.46	11.91	5.19	17.90	22.91
Arable land	17.70	15.93	10.66	19.08	19.89	19.01	29.81	20.89	18.01	13.14
Grassland, pasture	10.14	11.25	10.21	11.85	12.10	20.66	22.03	38.08	10.05	10.10
Rough pasture	10.48	8.21	9.96	7.09	8.85	8.37	13.58	23.45	8.47	7.16
Snow, Ice	0.02	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.01
Debris	9.38	1.54	3.73	0.15	0.01	0.00	0.09	3.63	0.08	2.39
Fallow land	9.76	2.49	1.41	3.36	0.54	0.63	3.35	0.53	2.25	2.58
Housing settlement	1.66	0.31	0.20	0.39	0.10	0.13	0.15	0.11	0.32	0.32
Water	0.41	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.01
NA	0.14	0.06	0.00	0.09	0.00	0.00	0.01	0.00	0.00	0.09

Cardinali et al. 2002; Guzzetti et al. 2003; Guzzetti 2005; Zanutta et al. 2006), in studies using LiDAR derivatives as mapping basis only few attention is dedicated to this topic so far (e.g. Bell et al. 2012). Therein the potential mapping of "very old" (prehistoric (Schulz 2004)) landslides and its effects on the subsequent application of the inventory are not considered or analysed yet. The quality of the inventory and the information on the landslides stored in it are of importance for any application of the inventory (Ardizzone et al. 2002; Guzzetti et al. 2012; Petschko et al. 2014; Van Westen et al. 2005). Precisely in the context of this study the inventory is a basis for statistical susceptibility modelling in Lower Austria (Petschko et al. 2014) where the resulting susceptibility map is dependent on the model input data and their geomorphological relevance. In this context the landslide age or event date is of importance, as trigger factors or also the land cover is considered as an explanatory variable for landslide susceptibility modelling. However, if the inventory contains "very old" (or prehistoric) landslides, they cannot be related to a trigger event (Van Westen et al. 2005) and the recent land cover information might not match the land cover at the time of the occurrence of the mapped landslides.

This study is aimed to analyse the potential of LiDAR derivatives to map landslides of different age and to assess the landslide age in a relative manner within the study area. Furthermore, the objective is to compare the relative landslide age with the recent land cover map. This is done to evaluate the sustainability of including recent land cover data into susceptibility modelling using a landslide inventory originating from visual analysis of LiDAR derivatives.

Study Area

The study area is located in the three districts Amstetten (1,187 km^2), Baden (754 km^2) and Waidhofen/Ybbs (131 km^2) in the province of Lower Austria. These districts show a high heterogeneity regarding their land cover, topography and susceptibility to landslides (Petschko et al. 2012). Whereas 40 % of the study area is covered by forest (coniferous, mixed and deciduous forest) 48 % of the area is covered by farmland (arable land, (rough) pasture and fallow land, Table 1). However, the predominant land cover type changes distinctly, as for example in the districts Amstetten and Waidhofen/Ybbs the North is mainly covered by farmland but the South is dominated by forest (Fig. 1).

The main lithological units in the study area are (from North to south) the Bohemian Massif, the Molasse Zone (including the "Schlier"), the Loess and Loam, the Flysch and Klippen Zone and the Austroalpine Unit with dolostone or with limestone and marls.

Landslides are abundant especially in the Flysch and Klippen Zone, as an existing landslide inventory resulting

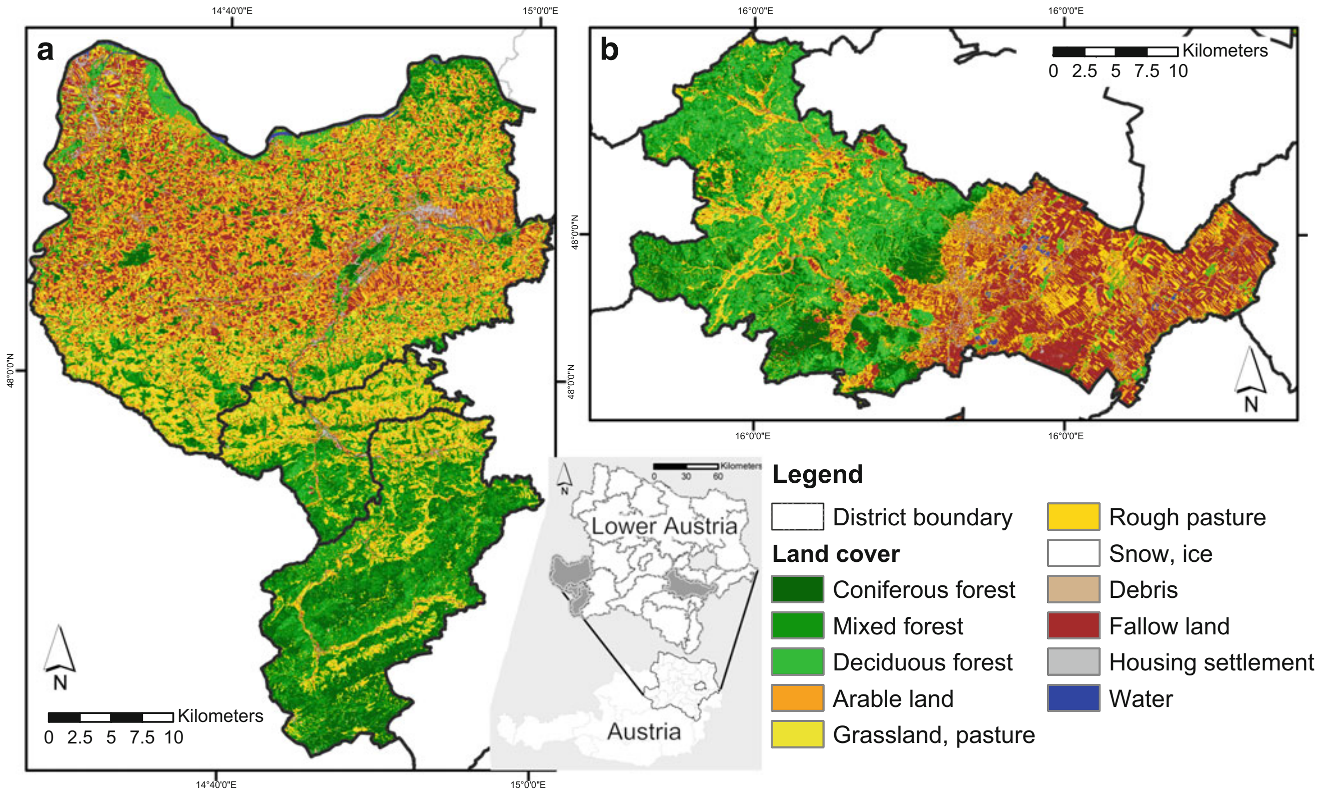

Fig. 1 Land cover in the study area in Lower Austria ((**a**) Amstetten, Waidhofen/Ybbs, (**b**) Baden)

from an archive of the Geological Survey of Austria (building ground register (BGR)) shows (Petschko et al. 2013; Schwenk 1992). The landslides mainly occurred under very wet conditions either due to heavy rainfall, rapid snow melt events or a combination of both (Schweigl and Hervás 2009).

Data

Data available in this study include a high resolution LiDAR DTM (1 × 1 m, acquired in 2006–2009, multiple acquisition years were necessary to cover the entire area), an orthophoto from 2002 (25 × 25 cm) and a land cover map derived from ASTER data (resampled to 10 × 10 m; 2007).

Methods

Landslide Inventory Mapping

During the landslide mapping the specific morphological features, which are left after a landslide event occurred, are visually analysed and used to identify landslides, also in forested areas. The landslide inventory mapping was performed in a previous study (Petschko et al. 2013) by visually interpreting hillshade maps of different azimuth angle (315°, 135°, 45°, (as used by Schulz 2004)), a slope map, contour lines with 4 m elevation difference and an orthophoto to delineate landslide polygons (Petschko et al. 2013). The mapping scale for identifying landslides was 1:2,000, however the polygons have been digitized at a scale of 1:200–1:1,000. During the mapping of the landslides different types were distinguished: “slide” (earth and debris slide), “flow” and “complex” following Cruden and Varnes (1996) (Petschko et al. 2013; Petschko et al. 2010). Areas with many landslides of different generations and where the delineation of single landslides was hardly possible were mapped as an “area of slides” (Petschko et al. 2010). Furthermore, the certainty of the delineation of the polygon was assigned as certain or uncertain for each polygon.

Relative Age Estimation

The relative age estimation is based on an approach proposed by McCalpin (1984) interpreting the morphology and the “freshness” of the morphological features that remain visible after the occurrence of a landslide on LiDAR DTM derivatives and orthophotos.

According to this concept the landslide morphology experiences a transformation starting from a feature showing every landslide detail (e.g. main and minor scarps, landslide

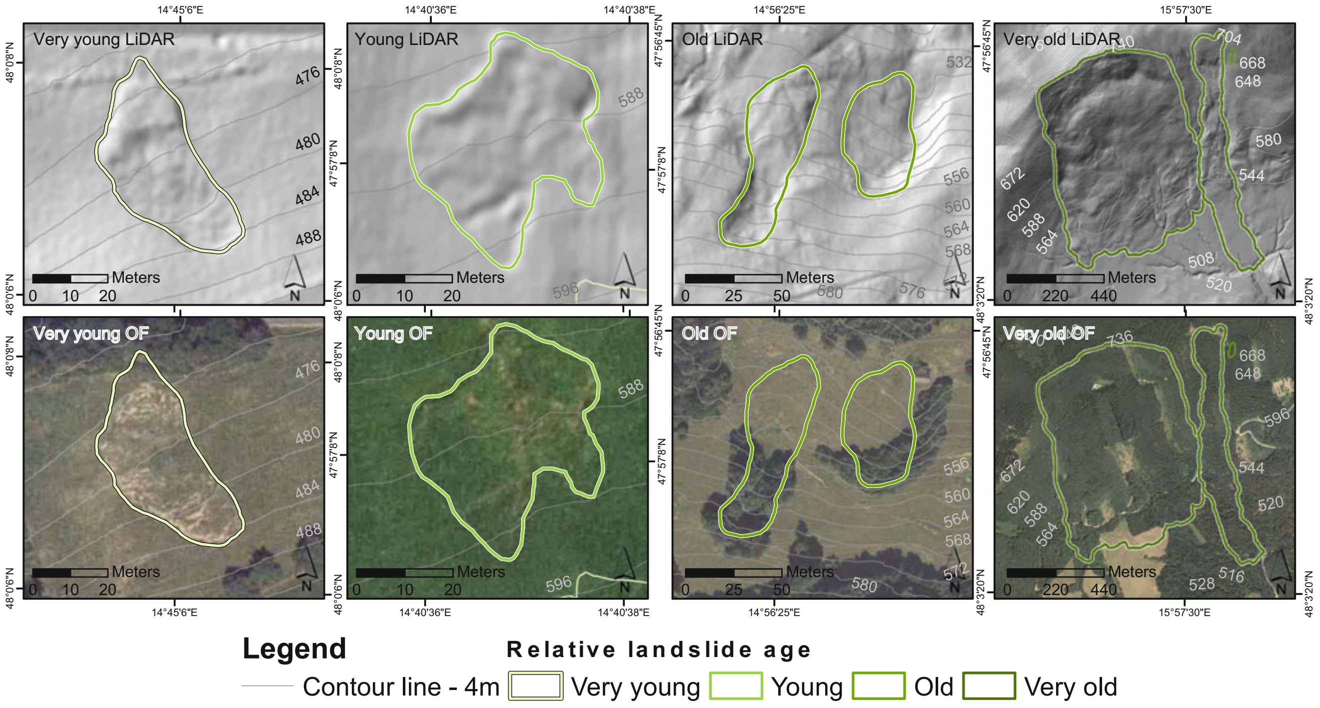

Fig. 2 Relative landslide age as estimated by the morphology visible on the LiDAR derivatives and by the vegetation cover visible on the orthophoto (OF). The relative age classes were defined “very young”, “young”, “old” and “very old”. Note the different size of the four presented landslides as indicated by the scale bar

toe and fissures) very clear. The older the landslide gets and the longer it is exposed to erosion the more features of erosion will be visible. First the landslide forms will get smoother, later erosion and incision of streams will occur and reshape the morphology (Bell et al. 2012; McCalpin 1984). Furthermore, the vegetation cover is of importance to assess the relative age of the landslides (McCalpin 1984). We assume that in our study area the first occurrence of landslides is mainly on open land (not forested land). In literature this assumption is often related to the reinforcing effect of tree roots on the slope stability (Rickli and Graf 2009). In the field we learned that often after the landslide occurred farming of the land became more difficult and it was abandoned to forest growth.

Adapted after McCalpin (1984) we assign (1) “very young” to landslides which are not vegetated at least at the main scarp and which show a very fresh, rugged morphology (Fig. 2); (2) “young” to landslides which are fully vegetated (grass) and have a smoother morphology, which shows first modifications of the original topography due to erosion and deposition; (3) “old” to landslides which still show a distinct main scarp but a smooth morphology with dense vegetation cover (partly brushes or forest); (4) “very old” to landslides which are characterized by a very smooth morphology, by the re-establishing of the valley drainage pre-slide profile and by a dense vegetation cover. This vegetation cover is of the same age or density as the surrounding vegetation. This relative age estimation was performed for each landslide and landslide type during the mapping process.

Comparison of Land Cover and Relative Landslide Age

The land cover of the mapped landslides was derived from the available land cover map on a grid cell base. Therefore, only the landslides classified as certain in their delineation and type were analysed further. This landslide inventory was split according to the assigned landslide age in four data sets. Each of this data set was used to mask the land cover map in ArcGIS (Version 9.3). Therewith the amount of pixel in each land cover class per landslide age was determined.

Results and Discussion

Landslide Inventory Mapping

The resulting landslide inventory contains 2,014 landslides of which 1,834 are considered to be of high certainty regarding the delineation and type of process (Petschko et al. 2013). The main mapped landslide type was “slide”

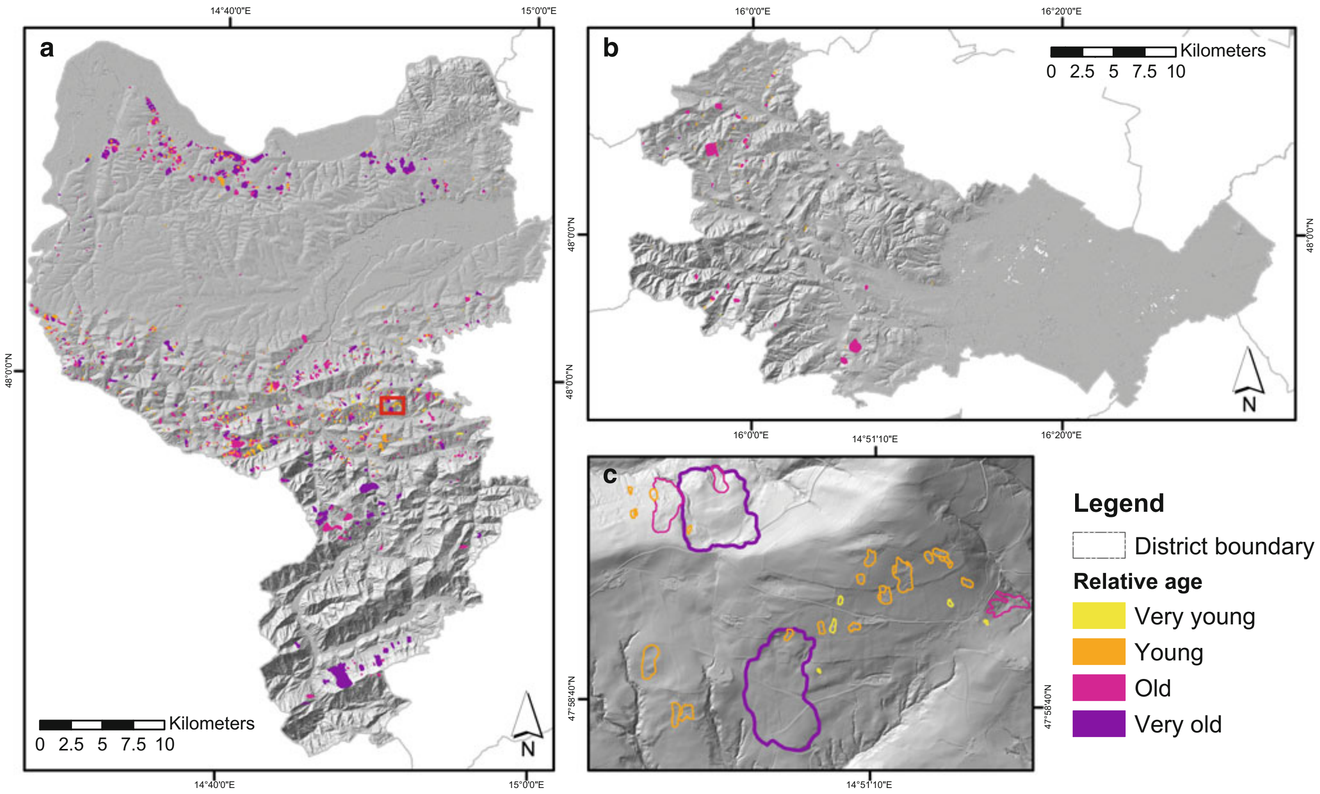

Fig. 3 Results of the relative landslide age estimation for (**a**) Amstetten and Waidhofen/Ybbs, (**b**) Baden. (**c**) Zoom to an example area. The relative age classes were defined “very young”, “young”, “old” and “very old”

(75 %). 20.5 % of the polygons of the landslide inventory were classified as “area with slides”.

Analysing all landslide types we found that these landslides are mainly located in forested areas (20.2 % in deciduous forest, 20 % in mixed forest and 19.9 % in coniferous forest, Table 1). Around 16 % of all landslides are located in arable land and 11 % are covered by grassland or pasture. Within the different landslide types the variation of land cover (forest (coniferous, mixed and deciduous)/no forest (arable land, grassland, pasture, fallow land and rough pasture)) is minor (Table 1). “Slides” (earth and debris slides) show the largest proportion of forested cells (64 %) whereas “complex landslides” only show a forest cover for 51 % of the cells. However, these results show, that more than half of the landslide cells are covered by forest.

Relative Age Estimation

With the relative age estimation we found that 8 % of the landslides were classified as “very young”, 10 % as “very old”, 34 % as “young” and nearly half of the landslides (48 %) were assigned as “old” (Fig. 3). During the mapping of “young” or “very young” landslides the combined interpretation of orthophoto and LiDAR derivatives was found to be effective. In this way, also landslides with a very short travel distance and a clear but small main scarp could be easily identified. However, for “old” and “very old” landslides the availability of LiDAR derivatives is important. On orthophotos (or aerial photographs) the vegetation cover (mainly forest) does not allow the interpretation of the morphology and therefore the identification of a landslide, as shown in Fig. 2 with the “very old” landslide, is not possible (Brardinoni et al. 2003). Nevertheless, the interpretation of the LiDAR derivatives only might be misleading due to effects of morphological convergence (Antonini et al. 2002) or the conservation effect of forest cover on the landslide morphology. Examples for morphological convergence found in the study area are quarries or artefacts in the DTM due to the removal of single trees, houses and infrastructure. The conservation effect describes morphology that appeared to be fresh and “young” but the type of vegetation (forest), field checks and the starting re-establishing of the valley drainage in the lower part of the landslide revealed the landslide to be “very old” (Fig. 2). Therefore, the comparison with the vegetation cover (grass or forest) during the mapping is of high importance.

Furthermore, regarding the completeness of the inventory it has to be taken into account, that in agriculturally used areas the persistence of the landslide morphology is restricted.

Among the landslides with low persistence mainly “young” or “very young” landslides are not visible on the orthophoto or the LiDAR derivatives anymore (Bell et al. 2012). In these areas, the visibility of landslides is influenced by the activity of local farmers. Immediately after a landslide event smaller landslides are levelled to ensure the harvest or the usability of the area as pasture (Bell et al. 2012; Fiorucci et al. 2011). However, the number of landslides with low persistence and therefore landslides that are potentially missing from the inventory is unknown (Petschko et al. 2014).

In general it has to be pointed out that the relative landslide age estimated in this study is only applicable to the study area and its specific setting (e.g. topography, geology, vegetation, climate (Antonini et al. 2002)). Therefore, comparisons to the relative age of other areas are not possible.

Comparison of Land Cover and Relative Landslide Age

In contrast to the results of the land cover of all mapped landslides the splitting of the data into the different classes of relative age reveals large differences between the classes “very young” to “very old”. In more detail we found that the percentage of the grid cells covered with forest (coniferous, deciduous or mixed) increases the older the landslides were estimated. An exception to this general trend is the mixed forest. Here the “old” landslides show the highest proportion of forested grid cells (26 %, Table 1). All forest types summed up, 13 % of the “very young” landslides, 31 % of the “young” landslides, 61 % of the “old” and 64 % of the “very old” landslides are covered by forest.

With 38 % the land cover class grassland and pasture covers a large area of the “very young” landslides. This land cover class was found for only 10 % of the “very old” landslides. Combining all not forested land cover classes (open land) we found that these cover 83 % of the “very young”, 69 % of the “young”, 39 % of the “old” and 33 % of the “very old” landslides.

These findings match the assumption that landslides mainly occur on open land and the forest grows after abandonment of the land. However, a Swiss study on six event landslide inventories in a lithological similar region showed, that directly after a rainstorm event nearly 50 % of the landslides occurred in forested terrain (Rickli and Graf 2009). Furthermore, a dendrogeomorphology study showed that landslides can reactivate under forest (Van Den Eeckhaut et al. 2009).

Besides, this results show, that also “very young” and “young” landslides are covered by forest (according to the ASTER land cover map). This is clearly contradictory to the age estimation criteria. However, the possible reasons for this misclassified grid cells can be (1) the difference in the resolution of the land cover data and the mapping scale of the landslides, (2) the algorithm used in the masking of the land cover by the landslides or (3) general problems in the supervised classification of the ASTER data.

Conclusions

The results of this study show that landslides of different relative age can be and are mapped when mapping landslides on the basis of LiDAR derivatives of one acquisition time only. Furthermore it was shown, that the interpretation of the morphology only can be misleading. Therefore, the combined usage of LiDAR and orthophotos is necessary. This potential mapping of very old landslides has to be considered before starting the mapping and might be overcome by restricting the mapping criteria on mapping young landslides only. However, the limited persistence of the landslide morphology of “young” and “very young” landslides in agricultural areas has additional influence on the completeness of the inventory.

At modelling with data on recent land cover the relative landslide age has to be accounted for, as no information on past land cover (at the time of the landslide occurrence) is available. Otherwise, there is a chance of introducing an unwanted bias into the susceptibility modelling. One solution can be the exclusion of “old” and “very old” landslides from the modelling sample. The alternative we propose is to use all landslides but to leave the land cover data out of the modelling. This might be considered, as the range of information on the topographical conditions (which are available in a much better spatial resolution as the land cover data) of the landslides might be better represented including the “old” and “very old” landslides in the analysis as well. Furthermore, leaving out the land cover but having better information on the topography can be of interest in case the land cover changes fast, e.g. by logging, and therefore the susceptibility map is soon not up-to-date anymore.

The absolute age of the landslides remains unknown. With the availability of multi-temporal LiDAR imagery the information on landslide age can be improved. However, this was not analysed in this study.

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