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ARTICLE

Modelling and mapping natural hazard regulating ecosystem services in Sapa, Lao Cai province, Vietnam

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Abstract

Land use change due to the development of agriculture and community-based tourism has resulted in an increase in natural hazards (e.g. erosion and landslides) that affect sustainability in the Sapa mountainous area in northern Vietnam. Natural hazard regulating ecosystem services have protected the local people from the destruction of their villages, goods and natural resources, especially in the rainy season. However, it is difficult to identify which kinds of anthropogenic constructions support a co-production of regulating services in human-influenced social–ecological systems and in which specific types of land use and land cover the supply of such services takes place, especially in heterogeneous mountainous areas. Therefore, this research attempts to (1) distinguish between the potential and actual use (flow) of natural hazard regulating ecosystem services and (2) understand how soil erosion and landslide regulating ecosystem services can contribute to a sustainable management of different ecosystems, especially in rice fields and forest areas. Two models (InVEST for soil erosion, Analytic Hierarchy Process for landslide analysis) were used to analyze and map the contributions of natural versus anthropogenic components for regulating natural hazards in Sapa. The results show the incoherent distribution of erosion regulating services and low capacities of landslide regulating services in areas that have seriously been affected by human activities, especially forestry and agricultural development. The contribution of rice ecosystems to soil erosion mitigation is higher than in the case of landslides. Nevertheless, one-third of the area of paddy fields in the case study area have "no" capacity to supply natural hazard regulating ecosystem services and should therefore be re-forested.

Keywords Landslide · Erosion · Regulation ecosystem services · Landscape · InVEST · Analytic Hierarchy Process

Introduction

Humans receive many types of benefits from various ecosystem services in direct and indirect ways (Costanza et al. 1997; De Groot et al. 2002; MEA 2003). More recently, the ecosystem services approach has become a significant tool to improve the communication and understanding between science, policy and practice (Maes et al. 2012; Schulp et al. 2014). According to the "Salzau Message" on Sustaining Ecosystem Services and Natural Capital, ecosystem services are "the contributions of ecosystem structure and function—in combination with other inputs—to human well-being" (Burkhard et al. 2012a; P. 2). Ecosystem services are classified as ecological phenomena, and their indicators have been logically derived by the properties of the investigated ecosystems (Müller and Burkhard 2012). The Common International Classification of Ecosystem Services (CICES[1]) has divided ecosystem services into provisioning, regulating and maintenance, and cultural services (Haines-Young and Potschin 2012). Regulating ecosystem services (RES) include human benefits resulting from the prevention of harmful processes, natural hazards in particular (Kandziora et al. 2013; TEEB 2010). The mediation of mass flows, as a major group of RES, includes all types of solid, liquid

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and gaseous movements providing benefits to human beings (Haines-Young and Potschin 2012). However, the understanding of soil erosion and other natural hazard mitigation services is still limited (TEEB 2010).

The impact of natural hazards on human development, prosperity and poverty has increased in many regions around the world, especially over the past four centuries (Arouri et al. 2015; Gill and Malamud 2017; Islam and Ryan 2016). The reported number of people that were affected by natural disasters has increased globally from over 700 million in the 1970s to nearly 2 billion people in the 1990s (MEA 2003). In Vietnam, many geological and geomorphological investigations about natural hazards have been conducted (Bui et al. 2012; Meinhardt et al. 2015; Nguyen et al. 2011). However, most of them focus on assessing the risk at a certain location and providing support for appropriate protection methods. Only a few studies focus on the question of how humans benefit from natural hazard mitigation as it is usually done in ecosystem service-based approaches (Shoyama et al. 2017). Additionally, various studies revealed that natural hazards do not necessarily have only negative effects (Benda and Dunne 1997; Geertsema et al. 2009). For example, rice cultivation on terraces often takes advantage of the vestiges of hazards (such as alluvial fans), in which nutrient-rich sediments are accumulated by floods. Therefore, whether and how damages or benefits are obtained from natural hazards need to be better understood and quantified related to different forms of land use, land cover and further socio-ecological system conditions.

Assessments of RES are often complicated due to less clear ecosystem function–service–benefit relations compared, for example, to provisioning ecosystem services. In mountainous areas such as the Sapa region in the Lao Cai province in northern Vietnam, many ecosystems are highly modified by human land use activities such as terraced paddy fields as well as regularly occurring natural hazards (i.e. erosion and landslides). Thus, ecosystem function–service–benefit relations are relatively complex. Natural hazards do not only have direct effects on local human well-being, they also cause indirect harm by influencing numerous other ecosystem services such as rice provisioning ecosystem services (Le 2014) and cultural services (Dang et al. 2017). Therefore, it is necessary to safeguard a constant supply of RES in order to protect human interests and to prevent people from extreme events (Lelys Bravo de Guenni 2005). The costs for damage and mitigation of natural hazards were mentioned in various international studies (e.g. in Meyer et al. 2013; Pielke and Downton 2000). However, little has been done so far in Vietnam. Additionally, there is no universal solution for natural hazard treatment. Instead, scientists and decision-makers have to work out how humans can sustainably optimize the profit from nature, such as by man-made protection constructions, which lead to an improved ecosystem services supply (Kumar et al. 2010).

The ecosystem services "matrix" (Burkhard et al. 2009, 2012b, 2014) has been used to assess the capacities of different geospatial units to supply different ecosystem services with a regional focus mostly on Europe (such as different land use and land cover (LULC) types). Therefore, one research question is whether it is possible to apply this method to subtropical countries and the Sapa region, Vietnam, in particular, where a significant increase in soil erosion and landslides has been recorded during the last decades (Häring et al. 2014; Mai et al. 2013). The ES matrix concept helps to illustrate and assess the diverse benefits humans receive from ecosystems. The ecosystem services supply (including potential supply and actual ecosystem services flow) usually shows higher scores for RES in the matrices in near-natural land cover types (such as forests or natural grasslands) than in human-influenced or inhabited land cover types (such as urbanized areas). However, the distinction between ecosystem service potential, flow and demand is not trivial in regard to the regulation of ecosystem services (Zhou et al. 2013) because the actual quantification depends strongly on the chosen indicators and the investigated land cover (Müller and Burkhard 2012).

The aim of this study is to spatially quantify the capacity of erosion and landslide RES under the rapid growth of tourism and urbanization in different land use and land cover types with a special focus on terraced rice fields and forest areas in Sapa. A conceptual framework to understand the impacts of human activities on natural hazard RES is proposed in "Natural hazard RES assessment" section. Hence, in order to assess the supply of and demand for erosion and landslide RES, appropriate landscapes, which act as ES-providing units and benefiting areas, are identified, quantified and mapped. Maps are chosen to spatially visualize complex natural or human phenomena and are therefore powerful tools for decision-making (Burkhard et al. 2012a; Wood 2010). However, proper identification and mapping of those structures and processes that support erosion and landslide RES are challenging, especially in a mountainous area such as the Sapa district. This information can be used to improve landscape planning, monitoring and sustainable environmental resources and land use management (Crossman et al. 2012; Swetnam et al. 2011). In this study, two models to quantify and map erosion and landslide RES were used. One model is based on "sediment retention" calculation developed in the InVEST tool, and the second one is based on Analytic Hierarchy Process (AHP) models. Both are presented in detail in "Modelling soil erosion and landslide regulation ecosystem services" section.

Referring to the issues described above, the following three research questions are answered in this study:

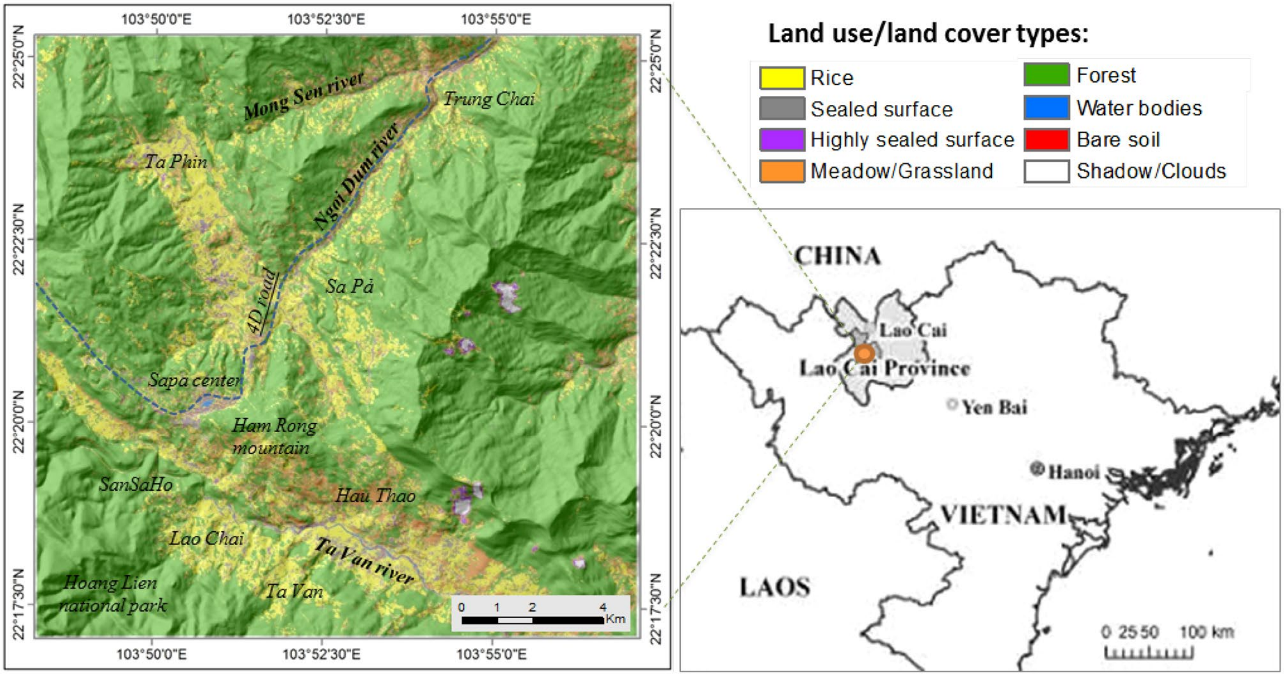

Fig. 1 Land use/land cover in Sapa, Lao Cai province, Vietnam. Classification based on SPOT5—satellite image taken on 21/10/2010, provided by the LEGATO (http://legato-project.net/) project

- How do different ecosystems affect the supply of erosion and landslide RES?
- How can providing units and benefiting areas of soil erosion and landslide RES be identified, related to different types of land use and land cover?
- Can soil erosion and landslide RES effectively be supplied in paddy fields and forest areas?

Materials and methods

Case study area

Sapa is a mountainous district in the western part of the Lao Cai province in Vietnam. The research area, which has a size of 15 km × 15 km in mountainous terrain, can be divided into three main basins: Mong Sen, Ngoi Dum and Ta Van (Fig. 1). The altitude fluctuates from 500 to 2.800 m, with many slopes greater than 25°. The average annual rainfall is very high with an average of about 1500 mm per year and maxima of more than 3500 mm. The wet season in Sapa is in the summer and lasts from June to September (Leisz 2017). A stable cool season occurs throughout the year although frost and snow are also recorded in winter. Rice agriculture, which is one of the main livelihoods in this region, has developed over centuries with terraced rice ecosystems (Hoang 2014).

The dynamics of land use and tourism in Sapa have created imbalances with respect to agricultural development and natural hazard prevention during the last years (Jadin et al. 2013). The area has experienced a high number of landslides and soil erosion events, compared with other regions in northern Vietnam. Some large landslides and soil erosion events were recorded during the last few years (such as along the national road 4D, Lao Chai and Mong Sen villages). At least 62 landslides, soil erosion and flash flood events have happened since 1998 in the whole province of Sapa (Tran 2013). The Mong Sen phenomenon is the most famous landslide in Sapa, occurred in 2009 (Nguyen et al. 2011). After 15 years, some of these landslide surfaces are still moving on slopes with more than 30°, and plants have not recovered yet.

The lack of knowledge about natural hazard RES has caused the destruction of many villages, the loss of goods and natural resources and threaten human well-being, especially during the rainy season. Exploring the relationships between natural hazards and ecosystem services can provide significant information and thereby help to improve the quality of life in this region.

Natural hazard RES assessment

Different approaches were used and combined in this study to assess erosion and landslide regulating ecosystem services. Landslides are a type of mass movements, such as

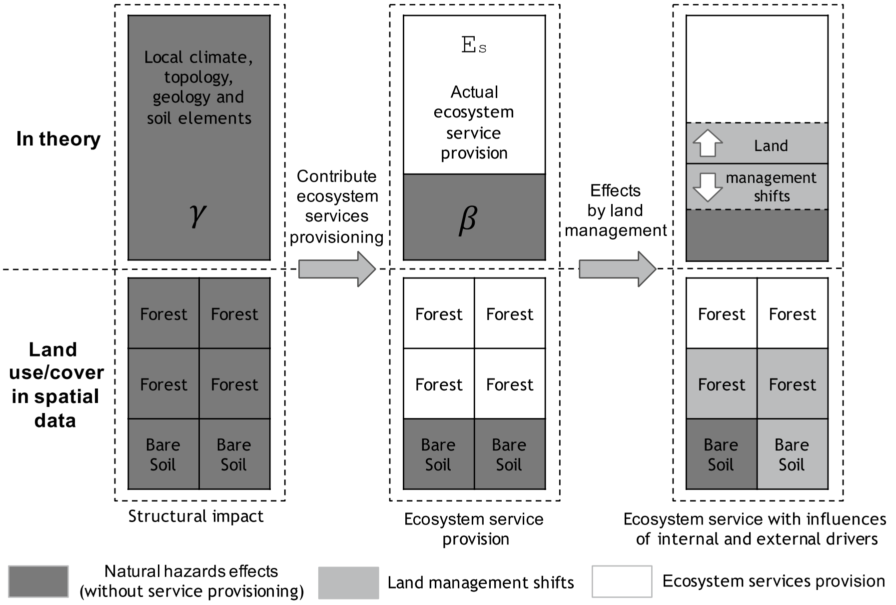

Fig. 2 Framework for erosion regulating ecosystem services (RES) assessment in particular land use/land cover types (γ as the total natural hazards impact in the absence of RES, β as the remaining ES mitigated impact). Adapted from Guerra et al. (2014, 2016)

rock fall and debris flow (Anderson and Holcombe 2013). Soil erosion is described as the loss of the top soil layer by wind or water (Pimentel 2006). In serious events, both of these hazards can occur alternately, which makes it difficult to identify them. Although many publications have discussed the risk of soil erosion and landslide at different scales (Chen et al. 2012; Kayastha et al. 2013), only a few papers studied the supply capacities of natural hazard RES. These ecosystem services have recently been assessed and quantified, for example, by Guerra et al. (2014, 2016; soil erosion RES) or Nedkov and Burkhard (2012; flood RES). The latter study, which was based on the ecosystem service "matrix" approach (after Burkhard et al. 2009), shows the distinct potentials of different LULC types for ecosystem services supply and demand. The more comprehensive matrix approach (Burkhard et al. 2014) differentiates between ES potential (available ecosystem services), flow (actually used ecosystem services) and demand (all ecosystem services used/consumed by people in a certain area). Such differentiation is not trivial for natural hazard RES, which mostly focus on avoided events. This means that the supply (flow) of these RES is highest in areas where no such events take place (Guerra et al. 2014). This again needs to be combined with demands for hazard RES, which is highest in areas with a high hazard risk. We can assume that, for example, in an old forest in a flat area with stable soils, dense vegetation cover and sufficient water infiltration, the risk for soil erosion is rather low. Thus, the demand for erosion regulating ecosystem services would also be low.

Guerra et al. (2016) have proposed a framework for the assessment of erosion RES, which describes the relationships between structural impacts (without ES provision), actual ecosystem services provision and actual ecosystem services loss by soil erosion (Fig. 2). Adapting this concept, the soil erosion and landslide regulating ecosystem services (Es) could be identified by the gradient between structural impact (γ) and actual natural hazard risk (β). With structural impact (γ), the natural hazards happen without protective vegetation cover and no ecosystem service is supplied. In this case, γ is influenced by natural conditions (such as local climate, topology and soil) and determines the potential of a natural hazard. As a key fraction to assess the quantity of the structural impact (γ) that is mitigated by human impacts, the actual ecosystem services provision (Es) can be defined by the capacity of RES in a given place and time. Meanwhile, the rest of γ relates to the remaining natural hazards (β). In a particular place and time, the high capacity of Es can reduce the amount of β. Therefore, both fractions have a negative correlation with each other. In fact, land management could modify the risk of natural hazards (β). The regulating ecosystem services might be expanded by appropriate land use policies but might also be destroyed by unsustainable development.

Natural hazards have been prevented to different degrees in different LULC types depending on respective actions/inactions of the land users and inhabitants. In Fig. 2, the forest cover (in white colour) would, for example, provide a higher capacity of natural hazard RES supply than bare soil (in black colour). However, under some negative conditions (such as deforestation, forest fires or climate change), certain forest regions (in grey colour) could not be protected from natural hazards, resulting in a reduction in RES. In contrast, under some positively consolidated conditions, areas with bare soil (in grey colour) could be protected from natural hazards. According to the framework of Guerra et al. (2014; Fig. 2), calculating the actual regulating ecosystem service supply requires the understanding of the different levels of risk of natural hazards (β) in each LULC type. It also helps to understand the potential of natural hazard RES (Es) in each LULC. The RES supply in each LULC can be assessed and compared using the ES matrix approach by Burkhard et al. (2014). Then, the potential RES supply (Es) can be overlaid with the management of different LULC to quantify the actual RES use.

Modelling soil erosion and landslide regulation ecosystem services

This section presents the methods that were used to assess natural hazard RES in three steps based on 13 natural and human components. The sources of input data are presented in "Database" section. In the first two steps, the risks of soil erosion and landslides were simulated by applying the model InVEST (Sharp et al. 2014) and the AHP approach (Ishizaka and Labib 2009). The soil erosion RES, that were calculated based on the amount of sediment retained in the different land cover types, were assessed. The capacities of landslide RES supply were calculated in the third step by using a risk map and a LULC regionalization. Modelling was supported by field work in order to update new natural hazard events and to detect extraordinary points (or outliers) of events.

Step 1 Modelling soil erosion risk and RES by using the "sediment retention" model

Natural phenomena like erosion and sedimentation contribute to the evolution of landscapes and cause severe consequences for ecosystems (Sharp et al. 2014). Sediment retention is one key element in soil erosion investigations and can be described by the Universal Soil Loss Equation (USLE) as a potential indicator (Kandziora et al. 2013). The InVEST tool, which has been used in 102 countries including the USA, the UK, Germany and Colombia (Posner et al. 2016), also applies USLE (Eq. 1) to assess the sediment retention service:

$$\mathrm{USLE} = R * K * \mathrm{LS} * C * P \tag{1}$$

in which, R is the rainfall erosivity factor, K is the soil erodibility factor, LS is the slope length factor, C is the land cover factor and P is the land management factor (Wischmeier and Smith 1978). The erosivity factor (R) is assessed through the intensity and duration of rainfall in each grid cell (Sharp et al. 2014). The higher the amount of precipitation is, the more serious the erosion potential becomes. The soil erodibility factor (K) assesses the detachment and movement of soil particles by rainfall and surface run-off. The erodibility value of each soil type is determined through its texture (percentages of silt, sand and organic matters, soil structure and permeability) and the soil erodibility nomograph generated by Wischmeier and Smith (1978). Using a digital elevation model (DEM), the geomorphological factors slope, flow direction and flow length can be simulated. These three factors are input variables of the LS function—generated by Govers and Desmet (1996)—to calculate the slope length factor. Lastly, the LULC and normalized difference vegetation index (NDVI) maps, respectively, determine the P and C factors by evaluating the influences of human activity on erosion.

The sediment, which is trapped in a particular region, is calculated by the run-off and the incoming sediment flowing from upstream regions. Land cover plays an important role in trapping materials. Therefore, the model simulates the process of soil erosion for two cases (with and without land cover and land management) (Keller et al. 2015). The difference between these two cases is the actual amount of sediment retention which is then used to indicate soil erosion RES. Meanwhile, the amount of sediment, which is exported from upstream areas and reaches downstream areas, is used to indicate soil erosion risk.

Step 2 Modelling landslide risk by using the Analytic Hierarchy Process (AHP) model

In this step, the AHP, which is a semi-quantitative method, is used to assess the weights of independent variables (e.g. natural and anthropogenic components in this study) on the dependent variable (e.g. landslide risks) (Saaty 2008). Each independent variable was compared with the other variables to assess their own weights. Firstly, the prioritized values are consigned into pairwise comparison matrices by assigning values from one (for the less important variable) to nine (for the most important variable) for direct comparison; from 1/2 to 1/9 for inverse comparison. Secondly, each eigenvalue of the variables was calculated based on a set of pairwise ratings in a consistent reciprocal matrix. Finally, the weight of each variable was calculated by each eigenvalue, following the study of Saaty and Vargas (2012). In this study, two AHP models were created for assessing landslide (1) potential and (2) risk.

1. The first AHP model was used for analyzing the landslide potential without human impacts. Choosing natural variables for analyzing landslide potentials has been described in many research studies (Kayastha et al. 2013; Pham et al. 2016; Pradhan and Kim 2016). In this study, ten natural variables to determine the landslide potential were used, including slope (F_1), lithology (F_2), weathering crust (F_3), bedrock orientation (F_4), rainfall (F_5), fault density (F_6), curvature (F_7), sediment retention (F_8), relief amplitude (F_9) and drainage density (F_{10}). With these variables, the landslide potential (LP) was simulated by the following function:

$$LP = 0.26 * F_1 + 0.18 * F_2 + 0.18 * F_3 + 0.12 * F_4 + 0.09 * F_5 + 0.06 * F_6 + 0.04 * F_7 + 0.03 * F_8 + 0.03 * F_9 + 0.02 * F_{10} \quad (2)$$

According to Eq. 2 generated from the first AHP model, the lithology (F_2) is considered as an important influencing variable for the occurrence of weathering processes and faults, as well as for the stabilization of terrains. The bedrock orientation (F_4) is constructed based on the differences between bedrock direction and topological aspects (as downslope directions for grid cells calculated from 0° to 360°). Three geomorphological variables which are important for landslide analyses were extracted by the use of DEM. These include slope (F_1), curvature (F_7) and relief amplitude (F_9). In case of a sufficiently thick weathering crust, the higher the local slope is, the more the terrain is threatened by landslides. The variable "relief amplitude" (the difference between the highest and lowest altitudes in a topological unit) assesses mass movements in vertical direction. Lastly, the variation of hydrologic and climatic factors is considered through two variables: rainfall (F_5) and drainage density (F_{10}). Detailed information of these input variables for the case study is presented in Chapter 2.4.

2. The second AHP model was generated to assess the actual risk of landslide under human impacts. Anthropogenic impacts are a part of the environment, and human activities have changed the potential of natural hazards in different ways. Human actions that contribute in a positive way to landslide risk regulation increase the capacity of erosion RES provision. In contrast, negative impacts, which can be generated by unsustainable local land management, can maintain or intensify landslide risks. Therefore, human variables are used in landslide risk quantifications as additional components that impact the landslide potential. In the second AHP model, human-derived variables, which include land cover (F_{11}), road density (F_{12}) and population density (F_{13}), are analyzed. Therefore, the landslide risk (LR) was computed by the following function:

$$LR = 0.56 * LP + 0.26 * F_{11} + 0.12 * F_{12} + 0.06 * F_{13} \quad (3)$$

Because the various input data do not all have the same ranks and units, all (natural and anthropogenic) variables need to be normalized into a common scale. With the numerical variables, this conversion process resized the original values into a continuous range of values from 1 (lowest impact on landslide risk) to 5 (highest impact on landslide risk). With the categorical variables (such as geology and weathering crust), expert experience was used to assign discrete values from 1 to 5 for each class of variables.

Step 3 Modelling landslide RES

In this step, the effectiveness of various "service providing units" in reducing the landslide risk was assessed before mapping landslide RES supply. The contribution of these units can be analyzed by calculating what percentage of each LULC has been protected effectively or ineffectively. All percentages were drawn in scatterplots to easily observe the distribution of risk levels in the different LULC types. These percentages were then compared with each other to evaluate the capacity of landslide RES supply in all LULC types. LULC types with higher percentages at the low-risk level supply more landslide RES than the other LULC types with higher percentages at the high-risk level. According to this evaluation, capacities of the different LULC types (or service providing units) to mitigate landslides were listed.

In general, the balance between the landslide risk and RES supply depends on their locations and capacities of the service providing units and demands in the benefiting areas. If the service providing units do not overlap with the benefiting areas, humans cannot receive benefits from landslide RES. Consequently, the landslide risk remains high in areas of landslide RES demand. Environmental managers need to know how RES supply and demand are distributed over space in order to target their actions accordingly. Spatial differences of actual RES supply can be shown in respective distribution maps. It can be assumed that areas with lower risks for landslides have a higher supply of RES and vice versa. The map of landslide RES potential was created by "reversing" the risk map.

Lastly, the LULC (seven types) and potential RES map (five levels) were overlaid. With this step, the potential RES map was divided into a maximum of 35 classes. The number of classes depends on the appearance of LULC in each level of the landslide risk. Then, the evaluation of the service providing units was used to sort the seven LULC types inside each capacity of the landslide RES potential. Accordingly, objects that are well protected from landslides could be distinguished from unprotected ones. In order to simplify the results, the actual landslide RES supply was reclassified into six classes (from zero to five) in the outcome map, corresponding to six classes of landslide RES supply capacities. The level "zero" represents no relevant and the level "five" represents the maximum relevant capacity of landslide RES supply.

Database

All data used for the spatial analyses needed to be transformed into an appropriate format and had to be georeferenced into the WGS84 coordinate system (48N). The topographic and hydrologic maps, the map of residential areas and transportation data were supplied by the FICHE project BL/10/V26.[2] A digital elevation model (DEM) was interpolated at 10-m resolution based on elevation data provided by the Vietnamese Ministry of Natural Resources and Environment. Hydrologic and climatic data were acquired from eight stations located around Sapa (Nguyen et al. 2011). Field work was carried out in 2015 in order to update the road network, to detect changes in land use and land cover and to map landslides. With respect to the landslide inventories, 22 events were found in 2015. Additional 16 events were recorded during the last 10 years in reports and other scientific studies (Tran 2013) from the Lao Cai province.

The geology, geomorphology and soil maps were acquired from different sources. The geological map with a scale of 1:50.000 was created by the Centre for Information and Archives of Geology at the General Department of Geology and Minerals of Vietnam. The geological map also shows information about slope, faults, formations, ages and bedrock directions. Such information is useful to analyze bedrock orientation and fault density. The soil map with a scale of 1:50.000 (from the Department of Geography at the Hanoi University of Science) illustrates five main types of soil including “humic alisols”, “plinthic alisols”, “dystric gleysols”, “humic alisols” and “humic ferralsols”. In addition, the soil map also provides information about soil thickness and particle sizes in the different soil types.

Satellite images of the SPOT5-series were used to create the NDVI map and the LULC types. The latter ones were classified by partners from the LEGATO[3] project from Europe and Southeast Asia (Burkhard et al. 2015). The LULC map is based on a satellite image from 2010 and was used as the main source for modelling and mapping the natural hazard RES. The image classification resulted in a map with eight classes (seven LULC types: rice, bare soil, highly sealed surface, sealed surface, grassland, forest and water bodies) based on an interpretation of SPOT5-panchromatic and SPOT5-multispectral data (Müller 2013). Areas that were covered by clouds and shadows were assigned as “no data”.

Verification of simulation methods

To assess the soil erosion risk, the N-SPECT tool, which was developed by the NOAA Coastal Services Centre (NOAA 2008), was used to find the relationships between land cover, pollution and erosion. The Revised Universal Soil Loss Equation (RUSLE) and the Modified Universal Soil Loss Equation (MUSLE) were used to analyze these relationships. The InVEST and the N-SPECT tools were run in parallel to compare their results and to assess related uncertainties. The N-SPECT tool changes the weight and equation of predicting rainfall erosivity and soil erodibility factors (NOAA 2008). The InVEST tool calculates the sediment that is trapped by each land cover type and the sediment that is exported from each pixel afterwards. Therefore, the results of InVEST may be more precise in this case than those from the N-SPECT tool.

Based on the landslide inventories from the fieldwork in 2015, this study used the Kappa index with 30 landslide and 30 locations without landslide to verify related results. The Kappa value is an index, which quantitatively measures the magnitude of agreement among observations (Viera and Garrett 2005) as follows:

$$\text{Cohen's Kappa} = \frac{p_0 - p_\text{e}}{1 - p_\text{e}} \tag{4}$$

with p_0 as the observed proportional agreement and p_e as the overall probability of random agreement. In predicting the precision of landslide results, the Kappa index calculates the difference between actually true agreements (or “observed” agreement) and faulty agreements (or “expected” agreement). The results are acceptable if the Kappa index is higher than 0.75.

For the landslide assessment with AHP, an index of consistency, known as the consistency ratio, was used to randomly indicate the probability:

$$\text{Consistency ratio (CR)} = \frac{\text{CI}}{\text{RI}} \tag{5}$$

where RI is the average of the resulting consistency index depending on the order of the matrix given by Saaty (2008) and CI is the consistency index expressed by the following equation:

$$\text{Consistency index (CI)} = \left(\lambda_\text{Max} - n\right) - (n-1) \tag{6}$$

where λ_Max is the largest eigenvalue, and n is the size of comparison matrix. Saaty (2008) explained that if the value of the CR is smaller or equal to 10%, the inconsistency is acceptable, but if CR is greater than 10%, the subjective value judgments need to be revised.

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[2] http://www.belspo.be/.

[3] http://legato-project.net/.

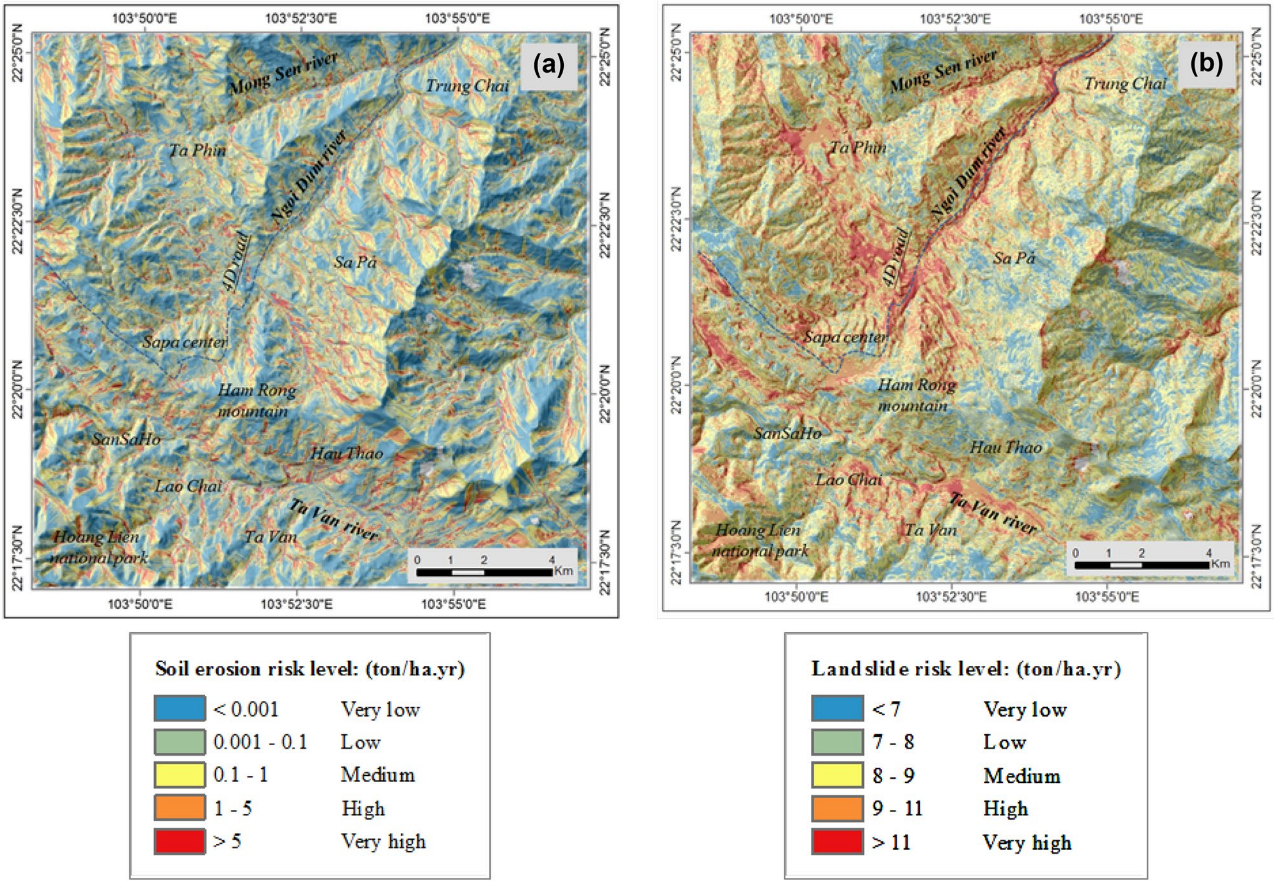

Fig. 3 Soil erosion risk map **a** based on InVEST and landslide risk map **b** based on AHP assessment

Results

Risk of soil erosion and landslides

Figure 3a shows the distribution of soil erosion in Sapa based on InVEST. The results were calculated based on exported sediment values that can reach to downstream areas from the original sediment positions. The map shows that erosion is mainly scattered along small streams. The "high" and "very high" levels of soil erosion reached 15% of the total area, especially around Ham Rong and the Hoang Lien National Park. Nearly one-third of terraced rice fields coincides with the locations of the "very high" and "high" risk levels. Moreover, continuous "very high" levels of soil erosion risk are predicted for the precipitous cliffs reaching from the Hau Thao village to the national road 4D in an eastern part of the Ham Rong mountain. The risk of soil erosion is considerably reduced in the flat terrain where most of the local people live, such as Sapa centre and the Ta Phin village. In contrast, an irregular distribution of soil erosion was modelled in the forest areas, especially in the Ta Van basin.

Based on the AHP model for potential landslides, the prioritized weights were calculated for each component in the LP function (see Eq. 2). The highest contribution to this function belongs to slopes of 26% or higher. With a total contribution of about 8%, the drainage density, height and sediment retention play less important roles for this function. According to the LR function (see Eq. 3), land covers, roads and population densities control about 26, 12 and 6%, respectively, while the variable of landslide potential contributes about 56% to risk prediction. The consistency indices of the two AHP models, which are about 6.6% (smaller than 10%), have validated the model results.

The different risk levels of landslide events can be seen in Fig. 3b. The Kappa index reaches about 0.77. In contrast to the results of soil erosion risk, the landslide risk in the Ta Van basin is mostly at a medium level. One-third of the area of the Ngoi Dum basin seems to be strongly impacted by landslide risk, such as in the north-eastern part of Sapa centre, the western part of Ta Phin village and along the national road 4D. A large area of forests was assessed at "low" and "medium" landslide risk levels. Compared with

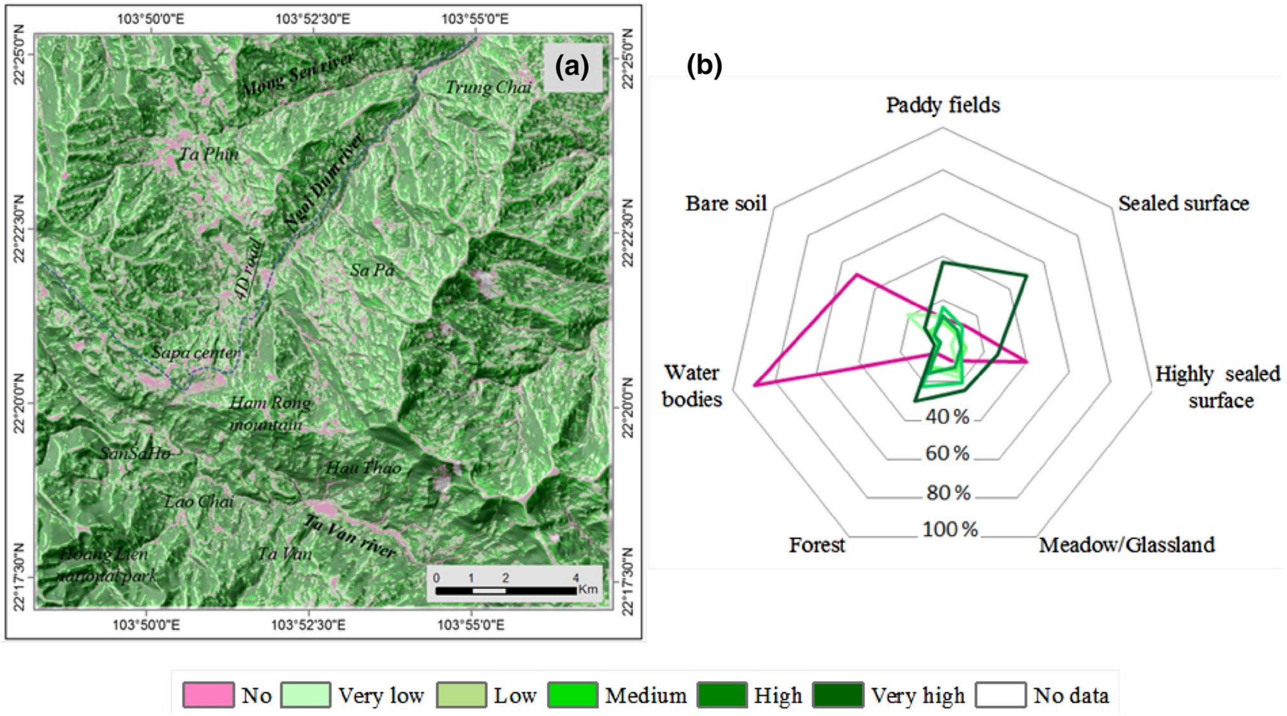

Fig. 4 Soil erosion regulating ecosystem services (RES) supply map (**a**) and distribution in each LULC type (**b**)

the soil erosion risk, the residential areas seem to be more vulnerable to landslide risk.

Landslide and soil erosion RES in Sapa

Figure 4a shows the soil erosion RES supply based on InVEST. The results were calculated based on retained sediment that originates from upstream regions and from the area (the modelled cell) itself. Similar to the erosion risk map, the distribution of soil erosion RES is very complex. About 45% of the area show efficient soil erosion regulation. "No relevant" soil erosion RES supply occurs in the eastern part of the Ngoi Dum basin, as well as in the Ta Phin and Sapa villages (about 10% of the total area). The residential areas show different levels of soil erosion RES supply, and more than 20% of the sealed surfaces do not benefit from the soil erosion RES.

Figure 4b illustrates the percentages of soil erosion RES in the different supply classes for each LULC type. "No relevant capacities" can be found in "water bodies" (such as lakes, rivers and ponds) and "bare soils" (such as sandbanks), which compose about 90%, and 50% in each type, respectively. "Sealed surfaces" (urban areas), "paddy fields" and "forests" show the highest percentages in the "very high relevant capacity" class, reaching 50, 37 and 30%, respectively. Accounting for three-fourth of the protected areas in Sapa, forests can prevent erosion at higher levels than paddy fields.

The resulting landslide RES map is presented in Fig. 5a. After comparing the risk map and the land management, the landslide RES supply was separated into 27 classes before reclassifying it into six classes. Most forest ecosystems are effectively protected from landslide risk. The "no relevant" and "very low" supply classes were observed in the northern centre of Sapa, the western Ta Phin village, the downstream regions of the Ta Van basin and along the national road 4D. In contrast to the soil erosion RES, nearly 40% of the residential areas do not receive any benefit from landslide RES.

The distribution of the landslide RES supply classes in each LULC type is shown in Fig. 5b. The "very high" and "high" landslide RES supply capacities make up about 40 and 35% of the "forest" area. These capacities account for 30% of the "meadow/grassland" area. Regarding the "paddy fields" and the "sealed surfaces", about 20% of these areas benefit from "high" landslide RES supply, while more than 40% do not supply landslide RES. Accounting for more than 68% in the "no relevant capacity" class, "bare soils" are not well protected from landslides.

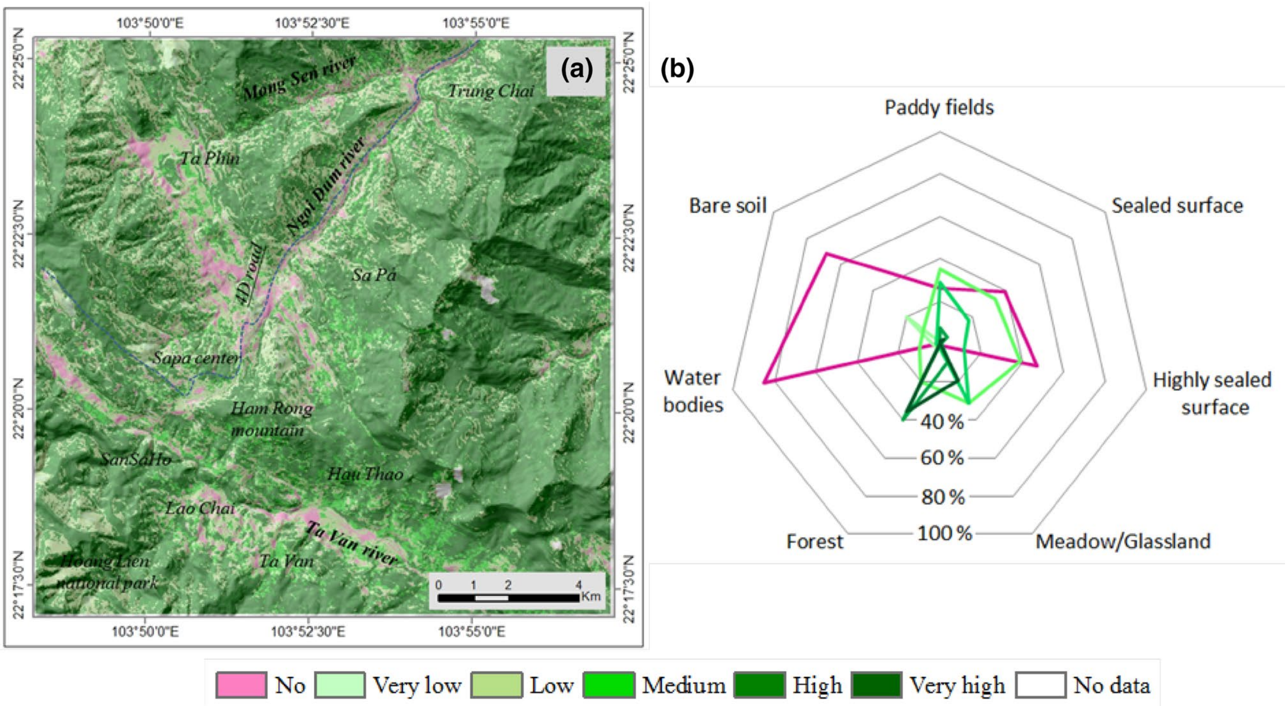

Fig. 5 Landslide regulating ecosystem services (RES) supply map (**a**) and distribution in each LULC type (**b**)

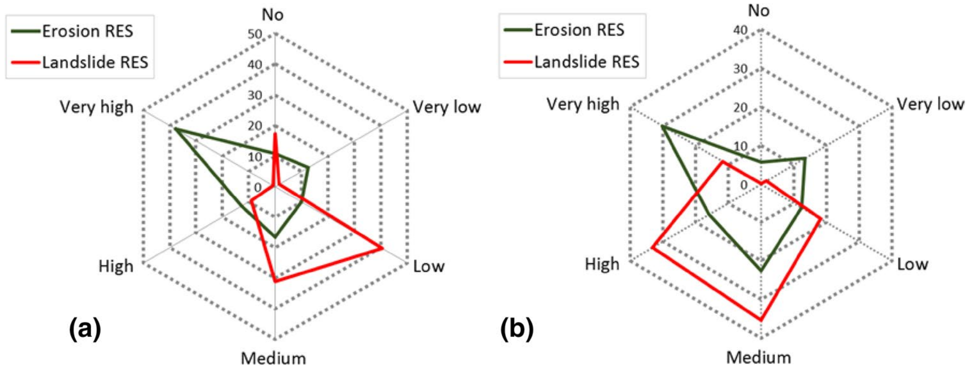

Fig. 6 Areal percentage of paddy fields (**a**) and forests (**b**) in relationship to soil erosion and landslide regulating ecosystem services (RES) supply capacities

Natural hazard RES supply in paddy fields and forest areas

Soil erosion and landslide RES bring heterogeneously distributed benefits to rice ecosystems. Figure 6a illustrates that nearly 20% (or 500 ha) of the paddy fields are located in areas of "no" capacity of landslide RES supply. This is far higher compared to the soil erosion RES, which account for about 10% of area with no relevant supply. In the "very low" landslide RES supply class, the area of paddy fields is ten times lower than in the erosion RES supply. Nevertheless, paddy field areas of altogether 1500 ha (approximately 50%) are well protected from soil erosion within areas of "high" and "very high" RES supply. In summary, paddy fields benefit more effectively from soil erosion RES than from landslide RES.

The positive contributions of natural hazard RES in forest ecosystems are illustrated by a varying RES supply distribution (Fig. 6b). In contrast to the paddy fields, the area of forests within the "no" capacity of erosion RES supply is approximately 5% (or 1000 ha) larger than the respective area in the landslide RES. About 25% of the forest area (about 4000 ha) are threatened within the "very low" and "low" erosion and landslide RES supply capacity classes. To sum it up, both types of natural hazards seem to be effectively regulated in the forest ecosystems in Sapa.

Discussion

The natural hazard RES assessment

The achieved results show interesting patterns of landslide and soil erosion RES supply in the research area. Compared with existing "ecosystem services matrix" assessments (e.g. in Burkhard et al. 2014), both assessments prove that forest areas supply soil erosion RES more efficiently than any other LULC type. The residential areas, which usually are located in more flat areas than other LULC, are well protected by soil erosion RES. However, landslides threaten many transport-related constructions. Soil erosion RES supply is comparably higher in agricultural areas than in meadow and bare soil areas, although paddy fields cultivated on slope terraces (with slopes of 15–25%) are more sensitive to landslides.

Although Nguyen et al. (2011) and Do et al. (2013) predicted and warned about landslide phenomena in the research area, perception or appreciation of benefits from the natural hazard RES capacity are still inadequate. In the study presented here, several aspects of soil erosion and landslide RES were analyzed based on the framework for RES assessment provided by Guerra et al. (2016). The maps of soil erosion potential and landslide potential were used as structural impacts (γ). The negative environmental effects associated with soil degradation, urban expansion or mining could increase the risks of natural hazards (β), leading to the degradation of RES provision (Es). In theory, γ, which is separated into β and Es, is modified by land management. In the Sapa case study, this process is clearly represented by the six classes of soil erosion and landslide RES supply capacities. These RES are supplied differently in each LULC type due to heterogeneous management measures and variation of climatic, hydrologic and topologic factors.

According to this study, the identification of effective/ineffective service providing units has become more efficient. On the one hand, the RES providing units supply services to the benefiting areas based on demands and following a specific service flow direction. Firstly, the effective service providing units in upstream areas (as identified mostly in forests and meadows in the case study) often overlap with the service benefiting areas (in situ service supply; after Syrbe and Walz (2012)). Secondly, these units additionally protect various objects (such as sealed surfaces and paddy fields) in downstream areas from natural hazards (*directional* service supply; after Syrbe and Walz (2012)), especially in the centre of villages and in the Lao Cai province (Nguyen and Dao 2007). On the other hand, after the occurrences of natural hazards in ineffective service providing units, for example, in more than 500 ha of paddy fields or about 1000 ha of forest located in areas of "no" capacity of natural hazard RES (Fig. 6), the run-off from upstream areas can transport enormous volumes of debris to downstream areas (Kean et al. 2013). Consequently, the functions of service providing units in the downstream areas to regulate natural hazards can be gradually reduced due to the loss of land cover, creating various unprotected surfaces, such as bare soils in the Mong Sen bridge and the Hau Thao village as predicted by Nguyen et al. (2011).

Contributions of natural hazard regulating ecosystem services to rice agricultural development

As shown by Lelys Bravo de Guenni (2005), landslides and soil erosion do not necessarily only have negative effects on agro-ecosystem functions and services. This could, at least for some areas, been proven in this case study. As reported in 2015 by local farmers from the Sapa region, several communities take advantage of landslides and soil erosion vestiges for rice cultivation in terraced fields in the Hau Thao and Ta Van villages. The erosion and landslide risks in these fields are at "low" to "medium" levels (Fig. 3). Following the process of mass movement, landslides and soil erosion can create fertile regions by providing nutrients to the soil that otherwise may be lacking. These areas are actually often considered to be the best places for farming terraced rice fields in combination with controlling water supply from upland forests. This has especially been the case for terraced rice fields in places with a "very high" capacity of erosion and landslide RES identified in Figs. 4 and 5.

Nevertheless, unsuitable crop selection—e.g. about 500 ha of paddy fields located in areas of "no" capacity of landslide RES supply (Fig. 6a)—and intensive farming in the mountainous regions can destroy the natural cycles and provide an impulse for subsequent erosion (Mai et al. 2013). The sediment retained has been continuously removed from these areas and deposited in downstream regions (such as in the centre of Lao Cai province) (Nguyen et al. 2011; Nguyen and Dao 2007). Consequently, the RES supply capacities, which may be reduced dramatically, can lead to an increasing occurrence of natural hazards, especially in the case of landslides. In Sapa, many human-made installations such as dams and agricultural lands were destroyed in the last few years. As reported by a local farmer in the Trung Chai village, the 2014 landslide occurred in a former landslide area, which was reclaimed for agricultural purposes. After long-lasting rain, a large amount of water was stored in the soil and eventually swept away everything, including the national road 4D, down to the valley. This was confirmed by results shown in Fig. 5a.

As shown in Figs. 4b and 5b, the class "no" capacity to provide erosion and landslide RES was mainly defined for rivers, streams and bare soils. In spite of lacking capacity to supply RES in those ecosystems, it is difficult to identify the exact time of erosion or landslide occurrences (as analyzed by Bui et al. 2016). Especially the structural impacts of natural hazards in the Sapa region depend on various temporary factors, such as rainfall dynamics or other extreme weather. Regarding the rainy season in mountainous areas (from June to September in Sapa), the high precipitation leads to an increase in surface water levels, causing erosion in riverbeds and banks where paddy fields are located. Although about 50% (about 1500 ha) and 10% (about 300 ha) of the paddy fields have, respectively, provided the erosion and landslide RES, most crops can become more vulnerable to both natural hazards if the local rainfall intensity suddenly increases within a short period. The coincidence of rainy season and harvesting season (September and October) in Sapa also results in the reduction in local rice production. This relationship needs to be understood further in order to reduce the negative trade-offs between natural hazards RES and rice production (food provision ecosystem service).

Uncertainties

Uncertainties related to limited knowledge of the assessed human-environmental system, data, modelling and technical issues are important challenges when analyzing regulating ecosystem services (Hou et al. 2013). RES assessments integrate environmental and human systems and are highly complex. Therefore, verification indices such as the Kappa index and the consistence index for the AHP model were used in this study. Nevertheless, the understanding and calculation of the landslide and soil erosion RES supply involved several uncertainties, which are discussed in the following.

Key uncertainties of this study relate to the spatial interpretation of the LULC map and the quantification of the different components of RES supply. The complexity of the local landscape was simplified in the LULC map in 10 m × 10 m pixels derived from the SPOT satellite images. This means that objects smaller than 100 m^2 (such as self-contained houses) may not be visible in the LULC map. Moreover, clouds and shadows of different objects were included in the satellite image. They can cover some areas and make the classification process more difficult, especially in the mountainous regions. However, the area of clouds and shadows accounts only for about 0.4% of the whole case study area.

Further uncertainties are related to the application of the different simulation models. Especially the combination of expert valuations and models needs to be improved. For the quantification of soil erosion, Sharp et al. (2014) claimed that the "sediment retention" model has been used for the identification of rill/inter-rill erosion, excluding gully and stream banks. In addition, the simplification of the model using the USLE as a main equation makes the erosion outcome more sensitive to the input variables (such as rainfall, soil types and land cover). Consequently, the weight of each input variable in the equation would need to be changed for studying soil erosion in mountainous areas. The analysis of landslides is quite complex due to the combination of quantitative and qualitative methods. In the landscape field inventories, some areas relevant for soil erosion and landslides could not be clearly identified in the topologic map. Some facilities for landslide prevention were indicated on the topologic map, but did not exist in reality or had been destroyed. In the validation process, the number of testing data did not cover all types of land uses/covers. Testing data were mostly collected near man-made land uses such as paddy fields and building constructions. Therefore, they did not represent well landslide regulation effects in more natural ecosystems, such as forests.

Finally, the simplification of natural and human-derived factors may increase the uncertainty of the outcomes. By normalizing the ten natural and three human-derived factors into the 1–5 classes, their importance for the RES supply capacities could be compared using the same scale instead of using the original values. This normalization process can avoid bias in magnitude differences of the input factors. Some factors, including complex data of lithology, weathering crust and land uses that originally were collected in categorical data format, were transformed to discrete values based on expert experience. Meanwhile, other factors (such as DEM and precipitation data) were calculated in continuous values. The combination of categorical and continuous data could regionalize the output maps and cause the loss of spatial information about direction, distance and area. The influence of regionalization on the outcomes depends on the weight assigned for the categorical data in the AHP model. As shown in Eqs. 2 and 3, the important roles of three categorical factors on landslide risk (as well as the landslide RES supply) were assessed based on semi-quantitative models (AHP). Thus, these assessments were also partly influenced by subjective factors from expert knowledge.

Conclusions

In order to answer the three research questions raised in the introduction, this study explicitly analyzed spatial soil erosion and landslide regulating ecosystem services supply in various ecosystems in the Sapa region. Firstly, it was shown that the current land management in different LULC type units plays an important role in determining the capacity of natural hazard RES supply. Regarding soil erosion RES, forest and urban areas show, as it could be expected, higher capacities of RES supply than meadow and bare soil areas. Landslide RES supply capacities are higher in forest and meadow areas compared to urban and bare soil areas. Natural hazard risk and RES supply maps are promising tools for decision-makers to safeguard a constant flow of ES between service providing units and service benefiting areas. Service benefiting areas can, for example, be identified in residential areas or planning units, whereas service providing units can be identified in forest or meadow/grassland areas. Two spatial relations between RES providing units and benefiting areas were identified, including in situ and *directional* ones ("The natural hazard RES assessment" section). The spatially explicit prediction of risks through natural hazards can be used to identify regions that need to be better protected, i.e. service benefitting areas with a high demand for landslide RES. More than one-third of the paddy field areas are not well protected from soil erosion and landslides, whereas more than two-third of the forest areas are well protected from both natural hazards.

The identification of areas without sufficient RES supply can help decision-makers to guide respective investments and to protect prioritized environmental and human resources. The current, in many aspects rather unsustainable, policy and land management regimes reduce the natural hazard mitigation capacities in the Sapa area. Local and national monitoring systems should focus on information that is relevant for the understanding of ecosystem functions and related ecosystem services. Thereby, local people could be better informed and more in time about areas threatened by landslides and initiate suitable prevention procedures. Especially the relations between the amount of sediment retention and erosion and landslide risks with rice provisioning ecosystem services should be quantitatively assessed to understand the (often indirect) contributions of natural hazard RES to agricultural development.

Erosion and landslide RES supply requires surfaces covered by vegetation such as forest or meadow/grassland areas, protective landscape structures or can be based on man-made constructions. As an effective nature-based solution, afforestation could help to improve the natural hazard RES supply capacities. Areas including bare soils, which contain very low capacities of natural hazard RES supply, should be recovered by forests, suitable vegetation or protective constructions such as bio-engineering measures (e.g. erosion control blankets, silt fences or geotextiles) and engineering techniques (such as diversion drains and rocky barriers). Mainstreaming of natural hazard RES into policy and decision-making requires a better understanding of the essential controlling components and the links between environmental and societal systems.

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