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Mapping the economic value of landslide regulation by forests

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ABSTRACT

The role of forests in regulating landslide risks is well established but estimates of the economic value of this ecosystem service are limited. In order to incorporate the role of forests for landslide risk mitigation in spatial planning and other decision-making contexts, there is a need for spatially explicit information regarding the value of this service. We develop a methodological framework to combine bio-physical modelling of natural hazard risk and socio-economic exposure in a predictive model to estimate and map of the economic value of forest regulation of landslides. This method is applied in a case study of Adjara Autonomous Republic of Georgia to examine alternative scenarios for forest management and associated land cover change. The approach produces credible spatially explicit results to inform policy decisions regarding investment in forest management; and has the potential for replication in other data scarce regions.

1. Introduction

It is expected that damages from landslides will increase steadily over the coming years (Dai et al., 2002). Underlying this trend is an increase in human activity in landslide prone areas, which increases risk through two channels: development generally involves deforestation, which increases the probability of landslides occurring; and more human activity generally means more assets that are exposed to damage (Nadim et al., 2006). An additional factor that will drive increasing landslide damage is that climate change is predicted to cause increased precipitation in many areas already prone to landslides and may result in additional areas facing the risk of slope erosion and landslides (Dale et al., 2001; Ciabatta et al., 2016; Crozier 2010).

The role of forests in regulating landslide risks is well established (Endo and Tsuruta, 1969; Megahan et al., 1978; Wu and Swanston, 1980; Preston and Crozier, 1999; Jakob, 2000). The economic value of this regulating service has, however, received limited attention in the economic valuation and ecosystem services literature (Chiabai et al., 2011; de Groot et al., 2012; Häyhä et al., 2015). Existing research has tended to focus on the value of forests for timber (Phan et al., 2014; Pohjanmies et al., 2017), non-timber forest products (Schaafsma et al., 2014; Mutoko et al., 2015), water supply (Ojea et al., 2012; Wang et al., 2017), recreation (Zandersen and Tol, 2009) and carbon storage (Triviño et al., 2015). The relatively limited number of studies that do estimate the economic value of landslide regulation by forests tend to be for small-scale study sites (e.g. Olschewski et al., 2012; Dominati et al., 2014).

Information on the economic value of forests in regulating landslides is useful for informing forest management decisions (Langner et al., 2017). Quantification of the damage costs of deforestation (or avoided damage costs resulting from reforestation) provides input for the appraisal of investments in conservation and restoration. Mapping ecosystem service values delivers additional information to support decision making, particularly for land use policy development, spatial planning and resource allocation (Schägner et al., 2013; Nahuelhual et al., 2015). In order to incorporate the role of forests for landslide risk mitigation in spatial planning and other decision-making contexts, spatially explicit information related to the value of forest landslide regulation needs to be developed.

Many regional governments, especially in the developing world, do not have the resources to create and gather such data in usable forms, in the absence of which, policy attention is not paid to investments in forests as a landslide mitigation measure. While reliable techniques for assessing landslide hazard often require detailed geotechnical information on existing conditions, the high cost of which means they are available only where high risk is already anticipated, more exploratory

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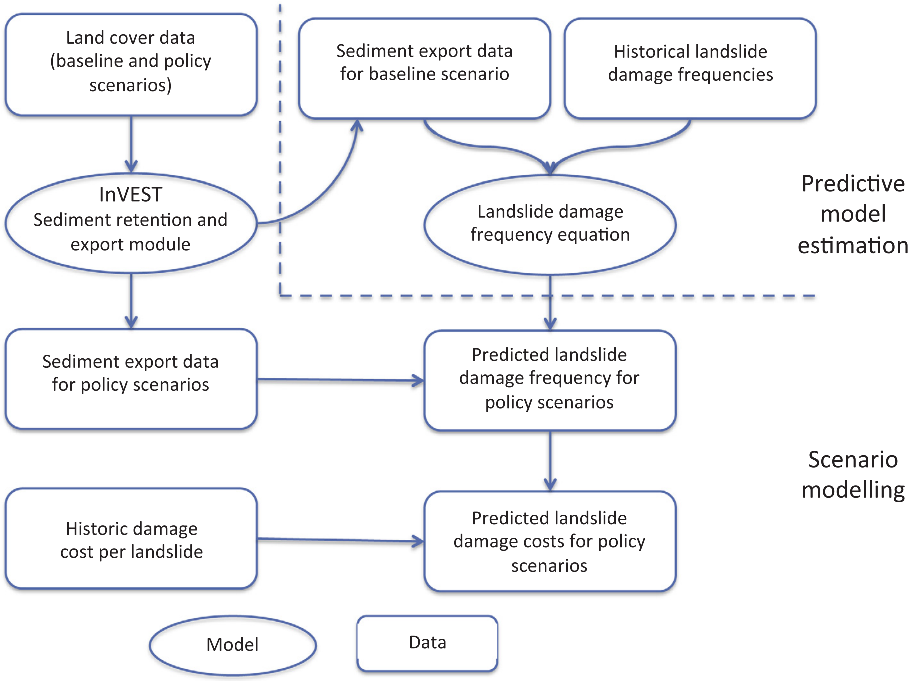

Fig. 1. Methodological framework for the valuation of landslide damages.

techniques of hazard and risk can provide frameworks for development planning and environmental protection measures (Gaprindashvili and Van Westen, 2016).

This paper contributes to the literature on ecosystem service assessment and forest management by developing a methodology to estimate spatially explicit values for the regulation of landslides by forests using widely available data and relatively simple models that can be applied at broad geographic scales. We apply this methodology at a regional scale to the Adjara Autonomous Republic in Georgia. Like the rest of Georgia, Adjara is mostly mountainous and its steep slopes are prone to landslides. By mapping the value of landslide regulation by forests in Adjara, we aim to deliver information to support political and administrative decision-making regarding long term forestry management.

The structure of the paper is as follows: Section 2 describes the methodological framework that is developed to map the value of forests in regulating landslide damage; Section 3 provides a description of the case study area on which the method is tested; Section 4 describes and maps alternative future land use scenarios for the case study area (spatially defined deforestation or restoration pathways for the period 2015–2035); Section 5 presents the empirical estimation of a predictive model for landslide damage; Section 6 combines the estimated landslide damage model with future scenario data to predict spatially explicit changes in landslide damage occurrence and costs; Section 7 draws conclusions regarding the application of the analysis to inform decision making and the scope for replication in other landscapes.

2. Methodological framework

The literature on natural hazards describes four broad methodological approaches that have been developed for studying landslide risks (Remondo et al., 2008). The first approach—inventorying—is based on mapping the locations of past landslides. The landslide inventory allows the estimation of landslide probabilities and forms the basis of susceptibility mapping techniques. A second approach—heuristics—is also based on historic information about landslides and involves eliciting expert opinions to estimate landslide potential from data on preparatory variables. The third approach is statistical and involves building multivariate statistical models to determine the risk of landslides based on an analysis of the variables that have in the past led to landslide occurrences. Finally, there are deterministic approaches, which are based on modelling the stability of the slope of the area under investigation. The most commonly used deterministic model sets the relative hazard level of a landslide as a function of the slope of the site, its lithological composition, the moisture conditions of the soil at the site, and the precipitation and seismic conditions at the site (Nadim et al., 2006, Mora and Vahrson, 1994).

Building on models that determine the probability of landslide events occurring, vulnerability models calculate the risks of the potential damage or degree of loss for a given asset subject to a landslide of a given intensity. Assessing vulnerability therefore requires calculating the risk of a landslide and also understanding the interaction between a landslide and the impacted assets (de Ruiter et al., 2017). Physical vulnerability indicators include infrastructures (such as in the transport, utilities and health sectors) and buildings, while social vulnerability indicators include demographic variables such as the size, structure and distribution of population and economic variables related to wealth and livelihoods.

In this paper we develop an approach to modelling the economic value of forests in regulating landslide damage that draws on elements of statistical, deterministic and vulnerability modelling. We estimate a multivariate statistical model using data on past landslide events, population and deterministically modelled rates of sediment export, combined with data on human settlements and damage compensation payments. Output data are spatially referenced to enable the results to be mapped. The general methodological framework for quantifying the economic value of landslide regulation as an ecosystem service provided by forests follows those of Balmford et al. (2011), Bateman et al. (2011) and Brander et al. (2012). In particular it incorporates several critical insights from the environmental economics literature by comparing future scenarios that are driven by alternative policy interventions and modelling spatially explicit variation in the delivery and value of ecosystem services. The general methodological framework is represented in Fig. 1.

The approach involves first developing land cover maps for a baseline scenario and alternative policy scenarios. Spatial data on land cover is then combined with a bio-physical model of sediment retention and export to estimate spatially variable rates of sediment export as a proxy measure of landslide susceptibility. In the case study application we use the InVEST model to quantify changes in sediment export resulting from changes in land cover (Sharp et al., 2016). The data on sediment export is combined with spatially referenced historic data on the frequency of landslide damage to houses and used to estimate a predictive function for landslide damage.[1] To model changes in the frequency of landslide damages under alternative policy scenarios, spatial data on sediment export under each future scenario is fed into this function to predict changes in landslide damage frequency. The costs of predicted damages are estimated using data on compensation payments to impacted households.

3. Case study site description

The methodological framework for assessing changes in landslide frequency and damage costs outlined in the preceding section is tested in a case study application in the Autonomous Republic of Adjara, Georgia. This section provides a description of the case study site in terms of the geography, climate and forest cover.

Adjara is located in southwestern Georgia on the coast of the Black Sea (see Fig. 2). It has a total area of 2880 km^2 and a population of 334,000 (2014 Census). Adjara is divided into six administrative units: Batumi city, Qeda, Khelvachauri, Khulo, Kobuleti, and Shuakhevi municipalities.

Adjara has the highest density of forest cover in Georgia (MENRP, 2015), covering approximately 66% or nearly 192,500 ha of total area (UNDP, 2013). The majority of this forest cover comprises of natural forests. Planted forests, pastures, and forest farms make up the rest of the area, along with burned groves, hayfields, and vineyards, which cover a negligible proportion. Adjara's forests are home to a wide range of tree and shrub species, with more than 400 in total. The dominant species are beech, oak, chestnut, spruce and fir. A notable characteristic is the average age of these trees, with most over 70 years old and some species, such as fir and beech, averaging more than 120 years.

About half of the forest area is located between 1000 and 2000 m above sea level, while approximately 12 percent of forest lies above 2000 m. The accessibility is limited given that more than 60 percent of the forests are located on slopes with an inclination of more than 25 degrees and of this, about a third lie on slopes of more than 35 degrees inclination (MENRP, 2015).

The climate conditions in Adjara's regions are varied. The temperatures differ significantly between the coastal and mountainous areas with the average annual coastal temperate of around 14 °C and going as low as 2.4 °C in Goderdzi Pass. Adjara receives the highest amounts of precipitation in the Caucasus with an average of 1500–2500 mm annual precipitation and a maximum in excess of 4000 mm. The highest precipitation is in the coastal areas, particularly Batumi, and decreases at greater elevations.

Adjara's forests play an important role in the regulation of erosion, water flow and protection from landslides and flooding. More than two-thirds of the forests in Adjara provide soil protection and water regulation functions (UNDP, 2013). Adjara is highly susceptible to frequent landslides, which cause damage to infrastructure and houses, lead to displacement of local communities and require compensation from the government. Protection from landslides is recognised as a key ecosystem service provided by Adjara's forests.

4. Land use change scenarios

To answer policy relevant questions (such as what is the change in landslide damage over time under alternative forestry management regimes?), it is necessary to develop scenario descriptions of future alternative management paths and associated land use change. The economic value of landslide damages under each alternative "policy scenario" can then be assessed relative to a "business-as-usual" or "baseline" scenario. The purpose of such a scenario analysis is to provide useful reference points for policy development. In the context of Adjara, we develop scenarios to describe how alternative management pathways will lead to spatially explicit changes in land use over time.

The scenarios developed for this case study are not predictions of the future (i.e. projections with estimated levels of likelihood); they are alternative storylines for what the future might look like following alternative development and policy paths. The scenarios are therefore speculative and intended to enable the comparison of contrasting but plausible futures.

Three alternative future scenarios are defined for the period 2015–2035. Land cover changes under each scenario are modelled in a GIS and the resulting changes in sediment export are modelled using the InVEST tool. Changes under each scenario are assessed at two points in time (2020 and 2035) in order to enable the evaluation of short term and long term impacts on landslide damages. The storylines underlying each scenario in terms of the development, institutional and policy change are described here.

The *baseline scenario* represents the region as narrowly oscillating around current capacities and interests. The transitions that began with independence of Georgia are stabilizing. With the return of political and economic stability, widespread deforestation in the region has stopped. Regulatory and management capacities are inadequate for regenerating degraded forests, but because population and economic pressures have stabilized, further degradation of forests is not a significant threat. Nevertheless, there are continuing damages and losses from soil erosion and landslides provoked by earlier forest degradation.

The *degradation scenario* represents a region in crisis. There are intertwined economic and political pressures, from within and outside. Political uncertainties and conflicts in neighbouring countries reduce tourism in Adjara and investments in it and related sectors. Unemployment in Batumi increases and with it there is a reduction in rural to urban migration. The resulting decrease in tax revenues puts public sector budgets under pressure. Government agencies, including the Forest Agency, have to work with limited and even reduced financing. Budgetary cuts in personnel, equipment and activities become necessary. This means that patrolling and enforcement activities are curtailed and less of an emphasis on sound forest management. The prohibition of clear cutting and conversion to pasture, however, is still enforced. Budgetary pressures also result in less maintenance of infrastructure, particularly roads. As a result, there is increasing pressure on more easily accessed forest areas, such as those around villages. The combined impact of these trends leads to more woodcutting around villages. The existing and newly denuded areas increase the risk and incidence of landslides leading to damage of residential and agricultural assets, compensating which puts further fiscal pressure on the government.

In quantitative terms, the *degradation scenario* represents a decline in forest cover and density relative to the *baseline scenario*. The decline in forest cover in Adjara is 1% per year. The land cover change is from forest woodland to scrub and sparse vegetation. In the short term (2015–2020), there is a 5% decline in forest cover. Over the full time horizon of the scenario (2015–2035) there is an 18% decline in forest cover. These changes take place in areas close to population centres reflecting human use as the main driver of change. The changes in land cover are spatially located within a 5 km radius of villages.

The *restoration scenario* represents a region of relative stability where political institutions are maturing and the economy is growing.

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[1] In principle, it would also be possible to specify a predictive model of landslide damage that directly includes the geological and meteorological variables underlying the sediment export model. In this application we chose to specify the predictive model using sediment export in order to produce a simple model; and used InVEST to model sediment export since it provides a well-developed framework for the integration of spatial data.

Fig. 2. Location of case study site.

As a result, tax revenues are predictable and increasing and the political and administrative institutions are able to take on increasingly complex governance tasks including social and environmental obligations. The budgets, staffing and equipment of the Forest Agency are increased and they are able to undertake more strategic and long term planning for forests in Adjara. By aiming to manage the cut more scientifically, the Adjara Forest Agency channels resources to centralize and professionalize the forest cut. It also obtains resources to reforest the degraded forest areas around the villages. The process of fuel wood harvesting and sale by the Forest Agency becomes an attractive service, overcoming the practice of local community members to cut the trees themselves. As a result, forest cuts outside demarcated areas or of unmarked trees are largely eliminated, leading to a regeneration of currently denuded forests and maintenance of the larger landscape.

The *restoration scenario* represents the full implementation of the Adjara Forest Agency (2015). Degraded forests are restored and communities no longer harvest their own wood for social uses. Household demands for fuel wood and timber are supplied by the Forest Agency, which expands and develops energy forest plantations. Currently cleared forest is gradually restored. The targeted land use change is from pasture, scrub and sparse vegetation to forest woodland. Pastures are reforested by improving grazing and feeding systems to reduce pressure on land. Areas cleared by fuel wood harvesting that have scrub or sparse remaining vegetation are allowed to regrow and become dense woodland. The better forest cover around villages reduces the risk and incidence of landslides, thus protecting habitations and farms and facilitating investments in rural production systems.

In quantitative terms, the *restoration scenario* results in 10.5% of pasture and 8.3% of scrub and sparsely vegetated land being converted to forest in the short term (2015–2020). Over the full time horizon of the scenario (2015–2035), 34.5% of pasture and 27.3% of scrub and sparsely vegetated land is converted to forest. This results in a 4.8% increase in forest area by 2020 and a 15.7% increase by 2035. These changes in land cover are spatially concentrated within 5 km radius of rural villages.

To generate maps of future land use, random points are selected for land use conversion within the target areas (5 km radii of each village). For instance, to map the 5% of forest area converted to scrub and sparse vegetation under the *degradation scenario*, random points are generated within the forest areas proximate to each village. Each point represents the location of forest area that will potentially be converted to scrub and sparse vegetation in the future. From the random points, 5% are randomly selected to represent the land cover change. The steps are similarly applied for the other future scenarios.

Land use maps for each scenario are presented in Fig. 3. Under the *degradation scenario* it can be seen that forested areas become more orange as the proportion of scrub and sparse vegetation increases. The changes in the area of forest, pasture, and scrub and sparse vegetation relative to the baseline are represented in Fig. 4.

5. Predictive model for landslide damage

In order to examine the influence of future land use change on landslide occurrence, we estimate a predictive model of landslide damage. Historic data on landslide damages in Adjara (2009–2014) were obtained from the Directorate of Environment Protection and Natural Resources of Adjara (DEPNR, 2016). These data are reorganized into count data indicating the number of houses that are damaged by landslides in each village in each year. The data cover 383 villages and 6 years, giving 2,298 data points.

These data on landslide damage frequency are combined with data on sediment export for baseline land cover estimated using the InVEST tool.[2] Using information on the geographic coordinates of each village, the annual quantity of sediment exported within a 5 km radius of each village was extracted. Geographic coordinates are only available for 237 out of 383 villages so the remaining 146 villages were omitted from the analysis.

Data were also added on the number of households in each village

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[2] V.3.3.1 (http://www.naturalcapitalproject.org/invest/).

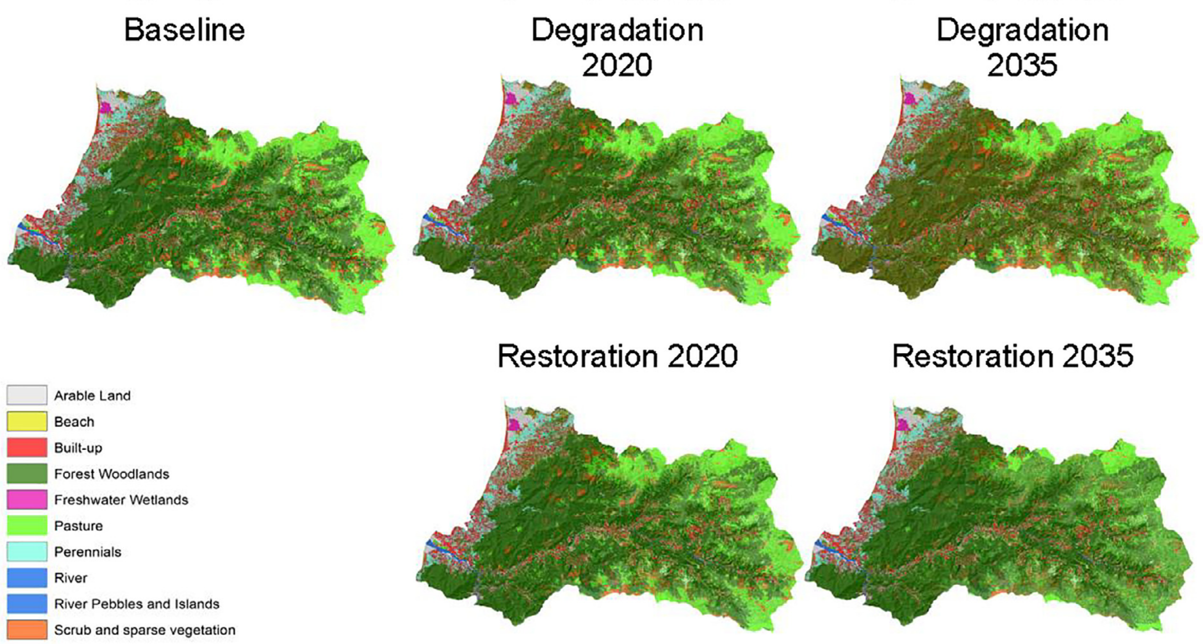

Fig. 3. Baseline and future land use maps for Adjara.

(DEPNR, 2016), which is used as a measure of exposure to landslide hazard. Data on the number of households is available for only 41 villages so the sample is further restricted leaving a total of 246 data points (41 villages * 6 years = 246). The mean number of houses damaged per year in the sample of villages is 3.22 with a median of 1 house per year.

These data were then used to estimate a predictive function relating the frequency of landslide damage to sediment export and number of houses. The function is estimated using a generalised Poisson loglinear model since the dependent variable is count data. Poisson regression assumes the response variable (in this case the number of houses in a village damaged by landslides) has a Poisson distribution, and assumes the logarithm of its expected value can be modelled by a linear combination of unknown parameters. A Poisson distribution is a discrete probability distribution that expresses the probability of a given number of events occurring in a fixed interval of time if these events occur with a known average rate and independently of the time since the last event. Poisson regression is appropriate when the dependent variable is a count, for instance the number of houses damaged by landslides in a year. The events must be independent in the sense that one house damaged by a landslide does not make another more or less likely, but the probability of events per unit time is related to covariates such as the quantity of sediment export in the vicinity of a village and the number of households in the village.

The estimated landslide damage frequency function is reported in Table 1. The dependent variable is the number of damaged houses per

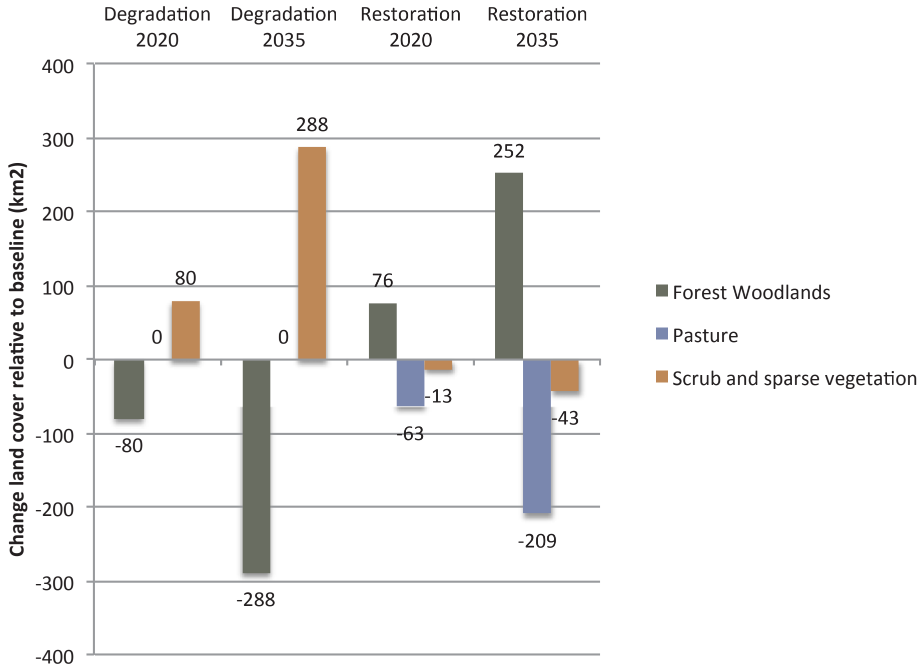

Fig. 4. Changes in area of forest, pasture, and scrub and sparse vegetation relative to baseline land cover (km^2).

Table 1
Landslide damage frequency function. The dependent variable is defined as the number of houses damaged by landslides per village per year.

Parameter	Coefficient	Std. error	95% Wald confidence interval	
			Lower	Upper
Constant	-11.225^{***}	1.2998	−13.773	−8.678
Sediment export (tonnes; ln)	0.995^{***}	0.1447	0.711	1.279
Households (ln)	0.847^{***}	0.0513	0.747	0.948
2010 dummy variable	0.346^{**}	0.1509	0.05	0.642
2011 dummy variable	-0.68^{***}	0.1991	−1.07	−0.29
2012 dummy variable	0.617^{***}	0.1433	0.336	0.898
2013 dummy variable	1.476^{***}	0.128	1.225	1.726
2014 dummy variable	0.346^{**}	0.1509	0.05	0.642
N	246			
Likelihood ratio	706.131			

***, ** indicates statistical significance at the 1% and 5% levels respectively.

village per year. All estimated coefficients on the explanatory variables are statistically significant at the 5% level or better. The positive estimated coefficient on the sediment export variable indicates that landslide damages are higher in areas with higher sediment export. Similarly, landslide damage also increases with the number of houses in a village (i.e. there is a higher likelihood of damage in villages with more houses that may be damaged). The dummy variables for each year 2010–2014 are used to control for year specific variation in the number of houses damaged by landslides, possibly related to the occurrence of extreme weather events in each year. The omitted category year to which other years are compared is 2009. Relative to the number of houses damaged by landslides in 2009, there were significantly more houses damaged in 2013.

The validity of using the estimated function is tested by performing an in-sample test to predict the number of damaged houses in the historical data. The mean number of houses damaged by landslides per village per year in the data is 3.22 and the mean predicted number is 2.79, indicating that the landslide damage function tends to slightly (13%) under predict the scale of landslide damage. In particular, the function does not predict well extreme events in which multiple (> 10) houses are damaged in a single village. Such events, however, are relatively rare, with 97% of historic landslide events resulting in damage to fewer than 10 houses. Since the analysis is focused on estimating the expected value of landslide damage to villages within a region rather than predicting the occurrence of specific events, the function is considered to be sufficiently accurate albeit slightly conservative.

6. Estimation of future landslide damages

Estimating future landslide damages involves three steps: (1) modelling sediment export under each mapped policy scenario; (2) applying the predictive landslide damage model to the scenario data; (3) computing the value of landslide damage compensation payments.

Spatially explicit changes in sediment export under each scenario are modelled using the InVEST tool and represented in Fig. 5. For the purposes of presentation, these maps show the quantity of sediment export aggregated at the level of water sub-catchments. The level of analysis, however, is for individual pixels and subsequently 5 km

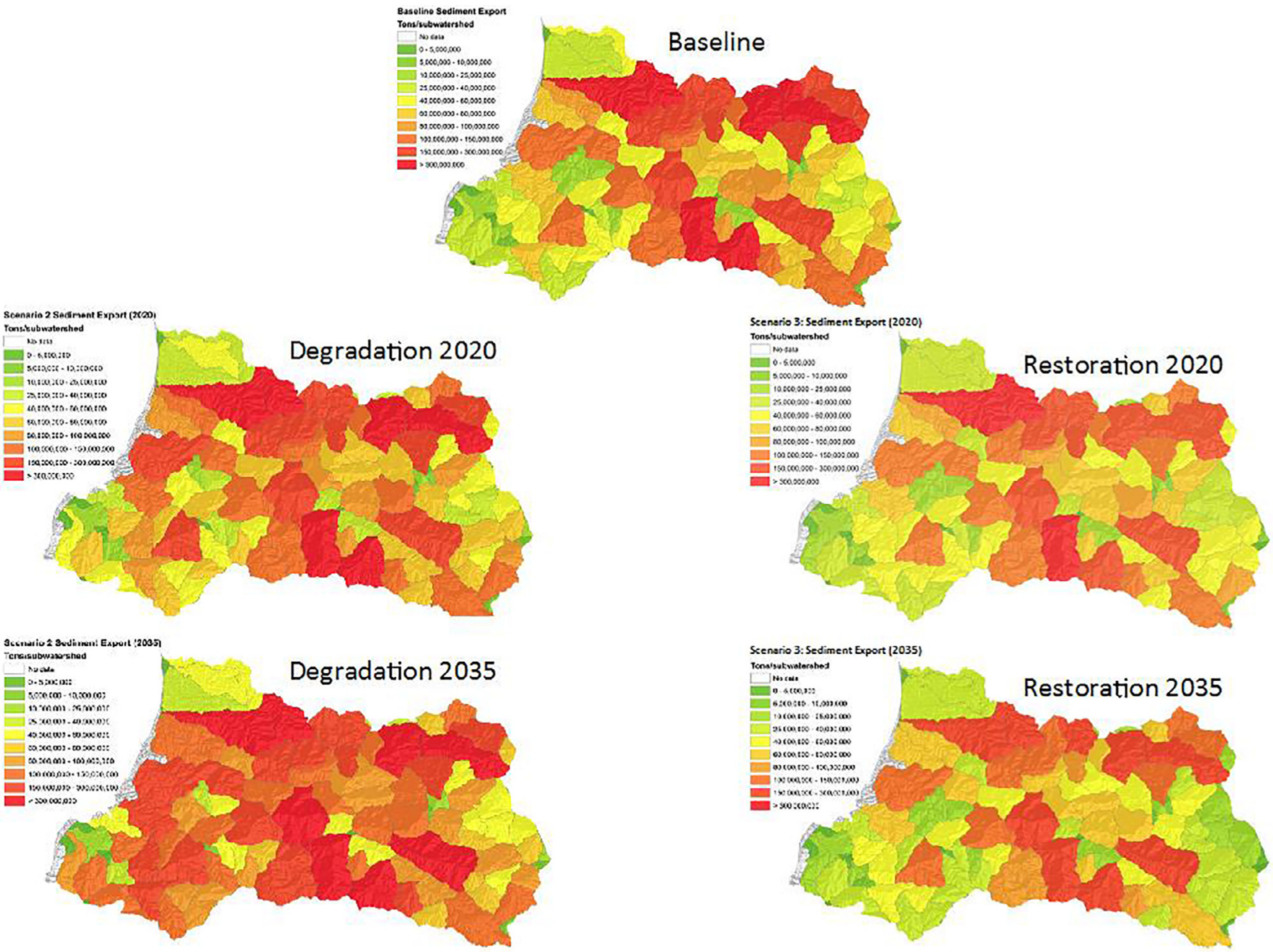

Fig. 5. Sediment export per water sub-catchment.

Table 2
Predicted number of houses damaged by landslides per year under alternative scenarios, 95% confidence intervals in parentheses.

	Baseline	Degradation 2020	Degradation 2035	Restoration 2020	Restoration 2035
Mean per village	1.43 (0.47–2.40)	1.65 (0.54–2.76)	2.29 (0.75–3.82)	1.38 (0.46–2.30)	1.28 (0.42–2.14)
Total	549 (181–917)	632 (209–1055)	876 (289–1462)	528 (174–882)	492 (162–821)
Difference from baseline	–	83 (27–138)	326 (108–545)	−21 (−7 to −35)	−58 (−19 to −97)

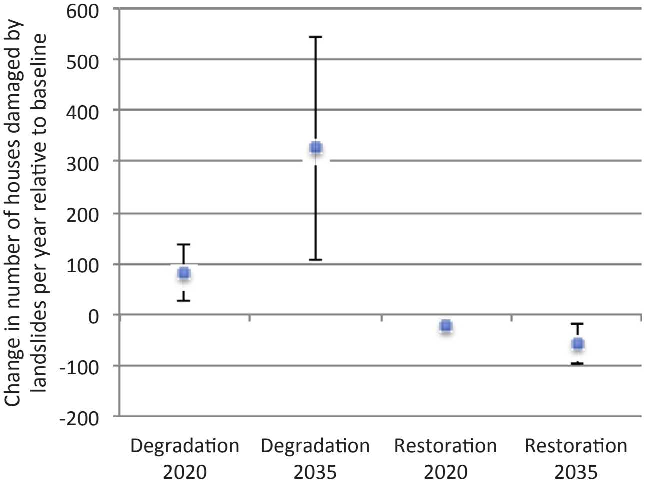

Fig. 6. Change in the number of houses damaged by landslides per year relative to the baseline scenario. Error bars represent 95% confidence intervals.

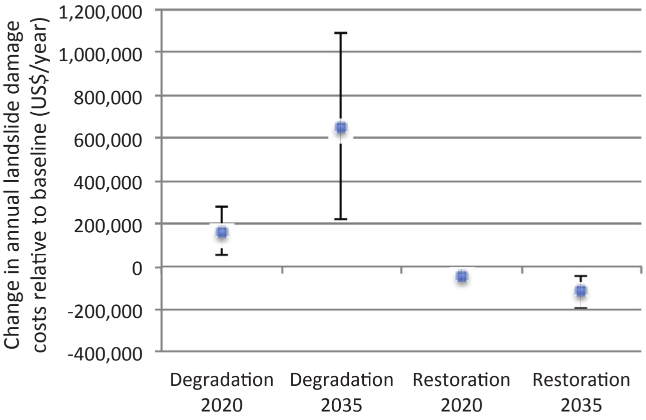

Fig. 7. Change in annual landslide damages (US$/year). Error bars represent 95% confidence intervals.

buffers around each village location. The maps indicate where sediment export increases under the degradation scenario and decreases under the restoration scenario.

To predict changes in the frequency of landslide damage to houses, a separate database was prepared for all villages in Adjara that includes information on the explanatory variables used in the damage function (i.e. sediment export within a 5 km radius of each village; and the number of households). Estimated sediment export under each scenario was extracted for a 5 km radius buffer around each village using a GIS. Data on the number of households in each village was obtained from DEPNR (2016) and the 2014 population census (GEOSTAT, 2016). In cases for which village specific information on sediment export and number of households was not available (due to missing coordinates for some villages), the municipality averages were assigned.

These data were then combined with the estimated landslide damage model to predict the number of houses damaged by landslides in each village per year. The results are presented in Table 2 and Fig. 6. 95% confidence intervals were computed and reflect the relatively high uncertainty of the predictions. The total number of houses predicted to be damaged by landslides per year under the baseline land cover is 549, which is slightly lower than the annual average (632 houses) for the period 2009–2014. The number of houses damaged by landslides increases substantially under the degradation scenario, rising to an additional 326 houses damaged in 2035 relative to the baseline scenario. Under the restoration scenario, the number of houses damaged by landslides is predicted to decrease by 58 houses per year in 2035.

The economic value of the role forests play in regulating the occurrence of landslides is estimated as the damage costs that are incurred due to loss of forest area (or the damage costs avoided due to increasing forest cover). More specifically, the change in damage costs due to changes in land cover under each scenario is estimated. Damage costs were computed by multiplying the number of houses damaged by the average government compensation payment to households that had suffered natural hazard damage during the period 2013–2015. This is US$ 2010 per household (DEPNR, 2016).[3] This measure of the monetary value of damage to private property represents only one component of total landslide damage costs, which includes damage to public assets, loss of income, distress and loss of life. As such, the estimated value of changes in landslide damages is an underestimate of total welfare impacts.

The results of this valuation are represented in Fig. 7. Damage costs increase substantially under the degradation scenario relative to the baseline case, increasing by US$ 166,000 in 2020 and rising to US$ 656,000 in 2035. To put this in perspective, current annual compensation payments to households for damage caused by natural hazards is US$ 196,000. Under the restoration scenario there is a moderate decrease in damages from landslides of US$ 42,000 in 2020, rising to US$ 116,000 in 2035, relative to the baseline case. Fig. 8 represents the spatial distribution of changes in damage costs. The increases in landslide damages under the degradation scenario are fairly evenly distributed across villages in all five municipalities. The benefits of reducing landslide damages under the restoration scenario are largely received in Khulo and Shuakhevi municipalities in the east of Adjara, where most forest restoration takes place.

7. Conclusions

In this paper we develop and apply a method for estimating spatially explicit economic values for the role of forests in regulating the occurrence of landslides. The approach combines available data and models on land cover, sediment export, population, landslide frequency and compensation payments to predict how the value of landslide damage is likely to change under alternative future scenarios for forest management.

The approach is illustrated in a case study of Adjara Autonomous Republic of Georgia and shown to produce somewhat conservative

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[3] Total compensation payments due to natural disasters were US$ 590,000 to 293 household for the period 2013–2015. This is equivalent to US$ 196,000 per year or US$ 2010 per household.

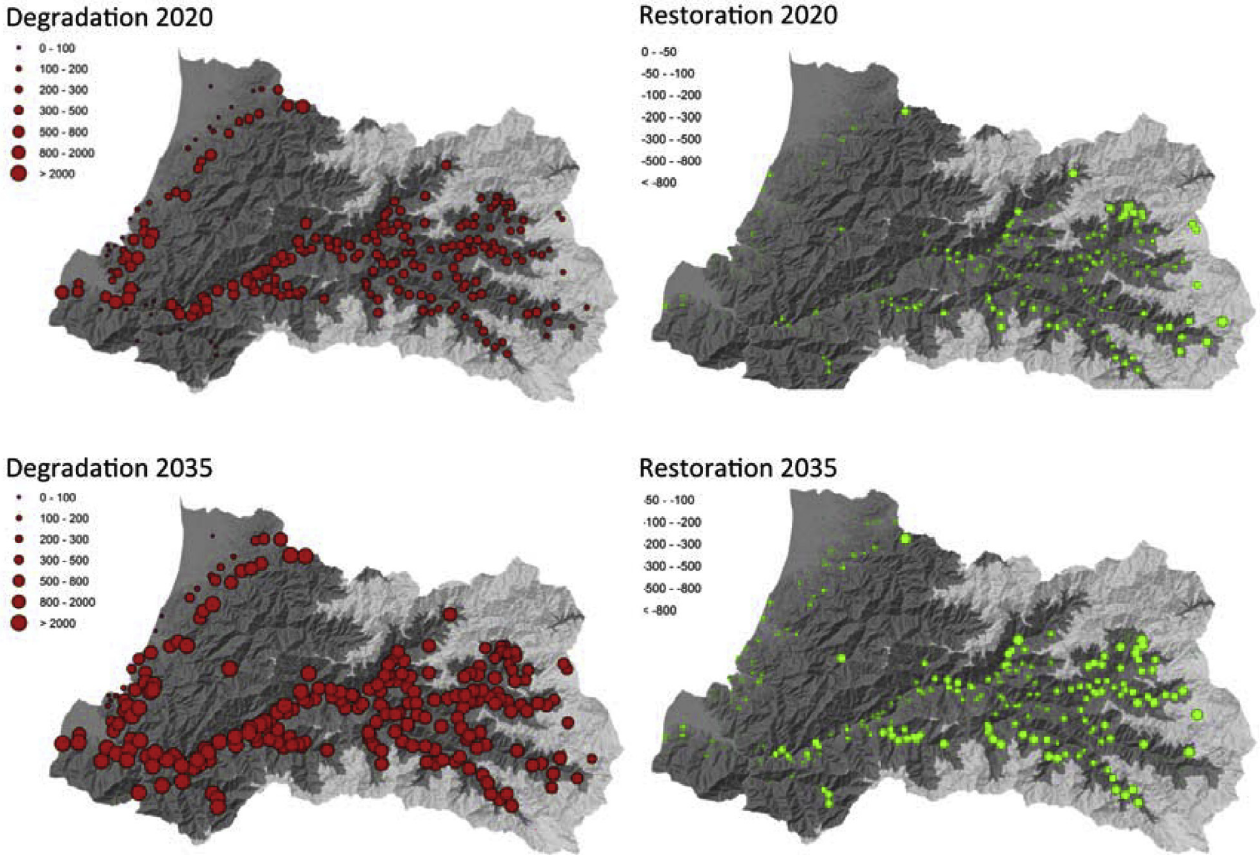

Fig. 8. Spatial distribution of annual change in landslide damages (damage costs relative to the baseline; US$/year).

estimates of historic landslide damage. The case study results were presented at a workshop in Batumi, Adjara, for stakeholders including the Directorate for Environmental Protection and Natural Resources, Adjara Forest Agency, other ministries of Adjara, representatives of the NGO sector and individual experts. The workshop provided an opportunity to validate the results and begin the process of applying the information to support decision making. The workshop participants judged the scenarios, predicted changes in landslide risk and associated changes in damage costs to be credible and highly useful for developing investments in forest management.

The method for valuing landslide regulation by forests is relatively simple in that it utilises secondary data sources (i.e. does not involve any primary data collection) and makes use of an available model of sediment export to estimate a basic proxy for landslide susceptibility. The estimated predictive model for landslide occurrence contains few explanatory variables and is empirically derived, as opposed to theoretically or mechanistically derived, but still proves able to explain significant variation in landslide frequency. As such, this pragmatic approach offers a viable means for modelling landslide damages in regions characterised by data scarcity and limited resources. The application of this method requires some GIS and statistical expertise but by design only uses data that are generally available in many contexts.

Future applications of this approach could adjust or refine the method in several directions. In particular, the measure of landslide damage could be improved to reflect the extent of damage rather than simply whether damage occurs or not. For example, the extent of damage to houses could range from superficial damage to total loss – and this distinction is likely to be important for informing the selection of landslide mitigation measures. The monetary valuation of damage could also be extended beyond the amount of compensation that is paid to affected households for damaged assets and would ideally reflect the full impact of landslides on economic welfare. Moreover the value of assets at risk is likely to be endogenously related to the developments and investments driving land use change, and the costs of landslide damage could be modelled to reflect this. A further extension of the valuation would be to account for risk aversion to major landslide events. Arguably it may be deemed more important to avoid low frequency but highly destructive events and this could be reflected in the valuation, potentially by using increasing marginal damage costs with the scale of impact. The complexity of the damage assessment can be expanded in cases with greater data availability. The application presented in this paper arguably provides a conservative appraisal of the value of forests in regulating landslides, but nevertheless delivers useful spatially referenced estimates to inform forest management.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecoser.2018.06.003.

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