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Research, part of a Special Feature on Sustainable Land-Use Practices in Mountain Regions: Integrative Analysis of Ecosystem Dynamics Under Global Change, Social-Economic Impacts, and Policy Implications

Integrating Expert Knowledge into Mapping Ecosystem Services Trade-offs for Sustainable Forest Management

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ABSTRACT. Mountain ecosystems are highly sensitive to global change. In fact, the continued capacity of mountain regions to provide goods and services to society is threatened by the impact of environmental changes on ecosystems. Although mapping ecosystem services values is known to support sustainable resource management, the integration of spatially explicit local expert knowledge on ecosystem dynamics and social responses to global changes has not yet been integrated in the modeling process. This contribution demonstrates the importance of integrating local knowledge into the spatially explicit valuation of ecosystem services. Knowledge acquired by expert surveys flows into a GIS-based Bayesian Network for valuing forest ecosystem services under a land-use and a climate change scenario in a case study in the Swiss Alps. Results show that including expert knowledge in ecosystem services mapping not only reduces uncertainties considerably, but also has an important effect on the ecosystem services values. Particularly the iterative process between integrating expert knowledge into the modeling process and mapping ecosystem services guarantees a continuous improvement of ecosystem services values maps while opening a new way for mutual learning between scientists and stakeholders which might support adaptive resource management.

Key Words: *Bayesian network; climate change; ecosystem services; expert survey; forest management; land-use change; mapping; mountain ecosystem; trade-offs; uncertainty*

INTRODUCTION

Forest ecosystems generate a variety of important goods and services for human well-being such as timber production, carbon storage, habitat for plants and animals, provision of scenic beauty, recreation opportunities, water regulation, and protection against natural hazards, collectively called ecosystem services (e.g., Constanza et al. 1997, Busch et al. 2012, Deal and White 2012). Although production services have traditionally been prioritized in forest management strategies, the objectives of silviculture have moved within the last 30 years toward fostering multifunctional forest ecosystems supporting different ecosystem services (e.g., Führer 2000, Schönenberger 2001, Fürst et al. 2007). Recent studies have shown that mapping ecosystem services can be highly useful for informing land-use and management decisions on trade-offs and win-win situations between ecosystem services (e.g., Chan et al. 2006, Naidoo and Ricketts 2006, Egoh et al. 2008, Chen et al. 2009, Nelson et al. 2009). Particularly in alpine areas, where the provision of ecosystem services is heterogeneous, spatially explicit information on ecosystem services provision across landscapes is essential for decision makers to target their programs and investments (Grêt-Regamey et al. 2008, Briner et al. 2012).

If the concept of ecosystem services is used for sustainable resource management, ecosystem services mapping needs to be conducted under global change. Land-use and climate changes are among the most important and intense drivers affecting the provision of ecosystem services (e.g., Foley et al. 2005, Schröter et al. 2005, Metzger et al. 2006, Turner et al. 2007). Since the end of the 19th century, a significant forest expansion with positive and negative effects on a variety of ecosystem services has been observed in several mountain ranges of developed countries because of socioeconomic transitions (McDonald et al. 2000, Schröter et al. 2005). At the same time, mountain forest ecosystems and their services are increasingly influenced by climate change through, for example, extreme events such as droughts or storms, subsequent bark beetle attacks, or shifts in species distribution and abundance (e.g., Lindner et al. 2008, Rigling et al. 2012). Whereas wood harvest is costly and timber prices have gradually been falling in steep terrains, the protection of human settlements against natural hazards (Olschewski et al. 2012) and the potential of forests to sequester carbon are becoming of emerging interest (Chhatre and Agrawal 2009). However, although progress has been made in ecosystem services mapping under global change at the global (Scholze et al. 2006), continental (Schröter et al. 2005, Metzger et al. 2006), and landscape scale (Nelson et al. 2009, Ditt et al. 2010, Briner et al. 2012), uncertainty in the quantification and valuation process has not explicitly been accounted for in these studies.

Furthermore, although these approaches combine the rigor of small-scale studies with the breadth of broad-scale assessments (Nelson et al. 2009), they do not integrate knowledge of local forest managers nor their adaptation potential to expected land-use and climate changes in their modeling. Local actors can, however, provide spatially explicit knowledge on ecosystem dynamics and social

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responses to global change based on their local understanding of the complex interactions within ecosystems and between management and ecosystem responses (Folke 2004 and references therein). In addition, integrating local needs and building on indigenous knowledge in resource management is known to secure local participation and to provide opportunities for achieving higher returns at lower investment costs (Saxena et al. 2001). Thus, including local knowledge in ecosystem services assessments and modeling not only fosters the acceptance of management strategies and mutual learning between stakeholders and scientists but can support improving model set up as well as facing issues of missing data (Salerno et al. 2010).

For stakeholder involvement in spatial modeling, new computational approaches ask either for modular approaches with an intuitive model set-up such as in the agent-based models CORMAS (Etienne et al. 2003) or SAMBA-GIS (Castella et al. 2005) or in the dynamic models of Bajracharya et al. (2010), Lippe et al. (2011), and Manfredi et al. (2010), or for a probabilistic framework such as Bayesian networks (BN), which are known to allow taking into account simultaneously quantitative data and expert knowledge. A key feature of BN is the probabilistic representation of the interactions of model variables allowing on one hand to picture the explicit relationships between the variables of the models, thus facilitating communication to decision makers (Pearl 1988, Jensen 2001). On the other hand, the probabilistic framework enables quantifying uncertainties and updating model outputs as soon as new knowledge becomes available, thus supporting iterative decision processes and adaptive resource management (e.g., Ellison 1996, Ascough et al. 2008). In the last decade, applications of Bayesian statistics have spread into many areas in environmental and resource management (for a review, see Ascough et al. 2008), but they were mostly nonspatial. Aspinall (1992) was one of the pioneers trying to explicitly address uncertainties in a Geographic Information System (GIS). Further attempts at incorporating BN in spatially explicit decision support tools are found in other disciplines, for example, in risk assessment of desertification of burned forest (Strassopoulo et al. 1998), in avalanche risk assessment (Grêt-Regamey and Straub 2006), in vulnerability assessment of marine landscapes (Stelzenmüller et al. 2010), in prediction of land-use change for reforestation planning (Ordóñez Galán et al. 2009), and lately also in ecosystem services assessments (Villa et al. 2011). To our knowledge, however, no study has investigated the relevance of integrating spatially explicit expert knowledge into mapping ecosystem services.

Following Grêt-Regamey et al. (2013), we demonstrate the importance of integrating local knowledge into the spatially explicit valuation of ecosystem services. Knowledge acquired in expert surveys flows into a GIS-based BN for valuing forest ecosystem services under a land-use and a climate change scenario. We illustrate changes in spatially explicit values and ecosystem services trade-offs of five ecosystem services including carbon sequestration, habitat provision, recreation, timber production, and avalanche protection in a case study in the Swiss Alps when considering expert knowledge. We map uncertainties in the values of the forest ecosystem services and show the effect of the integration of expert knowledge on ecosystem services values in trade-offs graphs. The maps might allow narrowing down where adaptive management is most beneficial and the trade-offs graphs can support forest managers mitigating threats from climate and land-use changes while prioritizing management strategies under parameter uncertainties.

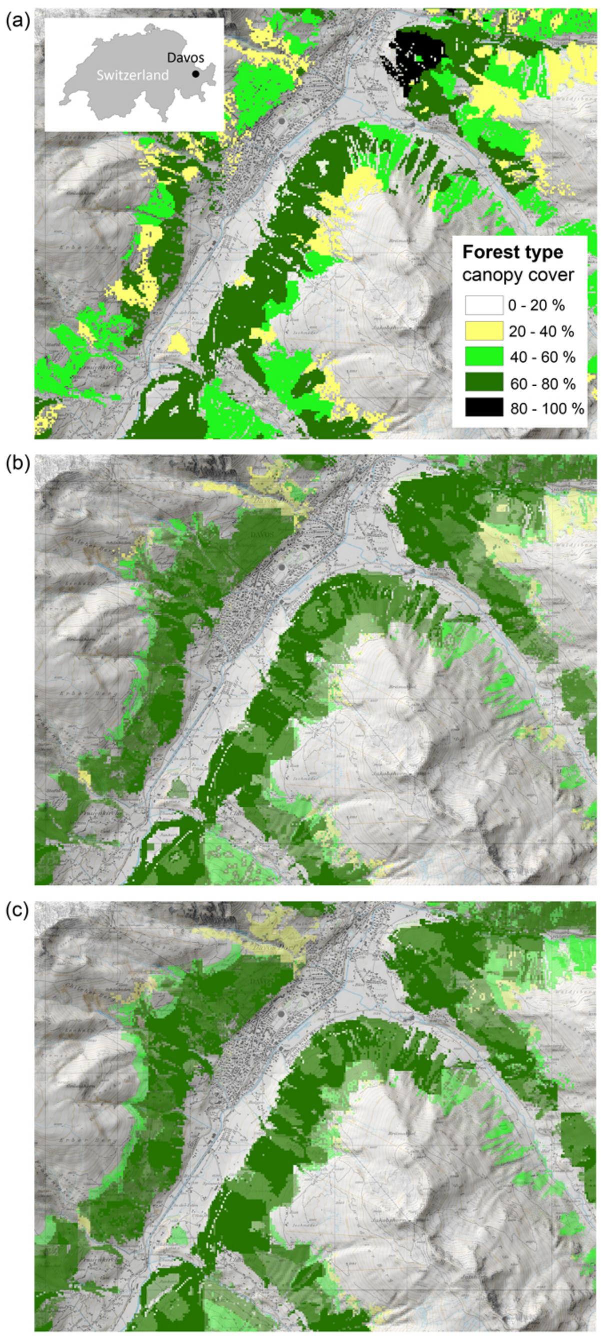
CASE STUDY

The ‘Landschaft Davos’ is a 254 km² landscape around Davos, the highest town in the Swiss Alps, with a population of around 13,000 permanent residents and up to 28,000 tourists during the winter peak season. The length of the NE-SW oriented main valley stretches across more than 20 km ranging in altitude from the valley bottom of around 1500 to over 3000 m.a.s.l. Although the main settlement with the urban center and most of the tourist infrastructure is quite densely populated, the surrounding areas have maintained their rural character, with scattered villages and a typical alpine landscape shaped by traditional mountain agriculture. Most of the 90 farms in the area obtain a secondary income from tourism. Whereas the farming activities in the region have consistently decreased as of the end of the 19th century, the forest has gradually expanded, currently occupying an area of 22% of the total landscape and providing a variety of ecosystem services to residents and visitors.

Figure 1 shows the land-use and climate change scenarios for the forest in the case study area developed within the frame of the Swiss National Research Project 48 (Bebi et al. 2005, Walz et al. 2007). Spatially explicit land-use changes in 2050 were modeled using forest transition matrices based on land-use maps of 1950 and 2000 (Kulakowski et al. 2011). The transparency scheme in Figure 1 indicates the uncertainty associated with the predicted forest type. In highly transparent patches, different forest types occur with similar probability pointing at larger uncertainties in land-use changes. These uncertainties are most pronounced (i) at higher elevations, (ii) in stands with major changes in forest structure, (iii) in the climate scenario, where changing climatic conditions have additional unknown impacts on forest development. Assumptions taken in land-use modeling were based on storylines designed during several regional workshops.

The ‘trend scenario’ is a land-use change scenario that assumes continuous development of the landscape as observed between 1950 and 2000. Forest management practices continue as before focusing on small-scaled intervention to maintain a sustainable protection against natural hazards. Forest growth

Fig. 1. Forest types in the case study area of Davos, Switzerland in (a) the year 2000 (total forest area: 4499 ha); in (b) the year 2050 in a trend scenario (total forest area: 5085 ha); and in (c) the year 2050 in a climate scenario (total forest area: 5422 ha). In the scenario maps, high transparency indicates high uncertainties in the predictions. The inset shows the location of Davos in Switzerland.



exceeds harvest (Brang et al. 2006), and the abandonment of alpine pastures leads to subsequent forest invasion (13% more forested area than in 2000).

The ‘climate scenario’ is a land-use and climate change scenario characterized by an increase in the average temperature of 2.4°C (OcCC 2003), and an accelerated abandonment of alpine pastures caused by a decrease in governmental subsidies (Bugmann et al. 2005). Forest management is assumed to continue as in the trend scenario including measures to maintain protective forest areas. In this scenario, the transition model additionally accounts for a shift of the vegetation zones due to higher temperatures when assigning forest types and related probabilities to grid cells. The most noticeable land-use changes associated with warming are an increase of the forest cover by 21% and a forest densification near tree line. The probability of forest structures with canopy cover between 60% and 100% is 20% higher under climate change than under the trend scenario.

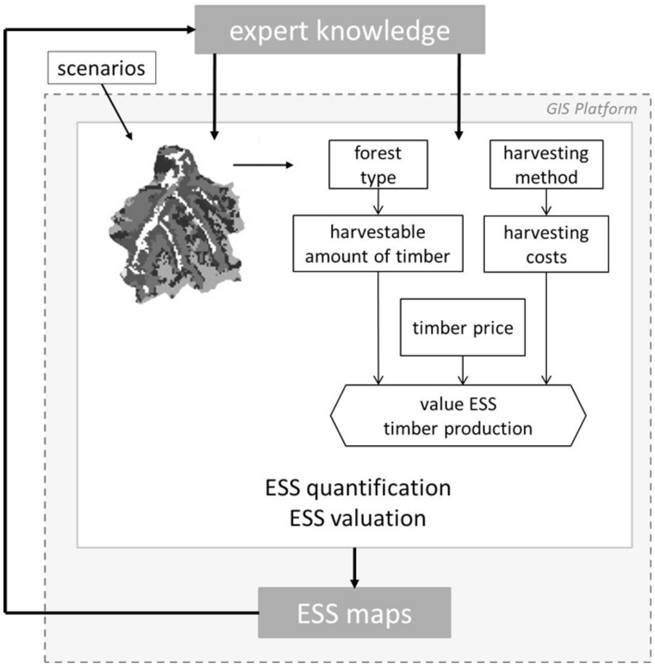
METHODS

Figure 2 illustrates how we integrated expert knowledge into the mapping of ecosystem services in an iterative cycle. In a first step, scenario-specific forest maps were generated as an input to a GIS-based BN that called a set of ecosystem services quantification and valuation models. In a second step, we presented the resulting forest ecosystem services value maps to experts for spatially explicit feedback on the plausibility of the results as well as on parameter assumptions of the BN. In this updating process, experts refined forest maps for each scenario based on their knowledge of local ecological and socioeconomic conditions and identified implausible values of individual variables. Fed with that “evidence,” the BN automatically updated the probabilities for the other variables of the BN in a third step. The resulting maps showed updated ecosystem services values and related changes in probability distributions.

Ecosystem services mapping

We embedded the spatially explicit ecosystem services quantification and valuation processes into a GIS-based BN. Figure 3 shows the BN representing the causal relations among the factors that influence the five selected forest ecosystem services values. Variables are represented by nodes characterized by different states and related probabilities and connected through arcs showing causal relationships among these variables. The resulting joint probability distribution $P(\mathbf{x})$ represents the expected ecosystem services values and their related probability distribution. The BN propagates the probabilities associated with the different input variables as following:

Fig. 2. Illustration of the iterative integration of expert knowledge into the mapping of ecosystem services (ESS).



$$P(\boldsymbol{x}) = P(x_1, \ldots, x_n) = \prod_{i=1}^{n} P\left(x_i | \boldsymbol{pa}(x_i)\right) \qquad (1)$$

where $\boldsymbol{pa}(x_i)$ is a set of values of the parents of a variable x_i. Details on the input data to the BN presented in Figure 3 are given in Appendix 1. Most input data were spatially explicit and site-specific. We classified the values of the nodes into discrete categories using normal distributions in most cases because efficient algorithms for solving BN are available only for discrete or Gaussian distributions. In a first step, we ran the BN in an IF-THEN form for the current situation as well as under the trend and climate scenarios described above for estimating ecosystem services values in 2050. In a second step, we integrated information from local actors into the BN as described in the next section resulting in new ecosystem services values and their related probability distributions.

We ran the BN in a spatially explicit manner at a 25m x 25m resolution using the BN modeling shell Hugin (Hugin Expert 2005) and integrated it into ArcGIS 8.3 (ESRI 2000). Vector data was converted into raster cells as input to ArcGIS.

The selection of the five ecosystem services was based on a list of key forest functions defined in the local forest development plan elaborated by forest experts in collaboration with local actors (Kanton Graubünden 2012). We assigned the selected ecosystem services to the four Economics of Ecosystems and Biodiversity (TEEB 2010) categories: timber production was attributed to the production services category, carbon sequestration and avalanche protection to regulation services, habitat for *Capercaillie* to habitat services, and recreation to cultural services.

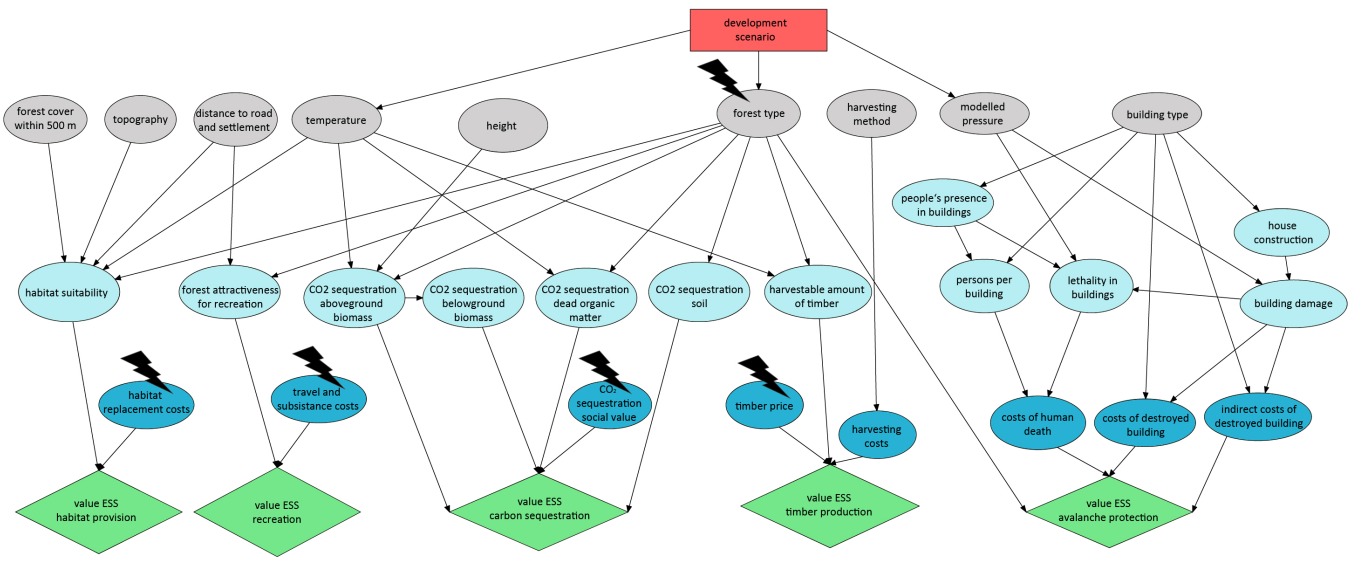
We quantified timber production based on the amount of harvestable wood derived from the present growth rate of different forest types in Davos (Table A2.1, Appendix 2). The loss during harvest and the nonmerchantable tree portions, e. g., bark, were assumed to account for 15% of the growth rate (LFI 2008). On newly afforested plots, we assumed a 50% lower growth rate than in current forest areas (FOEN 2011). In the climate scenario, we accounted for a temperature-induced upwards shift of the altitudinal vegetation zones by increasing the type-specific growth rates by 1.2 m^3/ha and year (LFI 2008). We estimated the economic value of the harvestable wood subtracting the spatially explicit harvesting costs from the average regional market price for different timber types. Harvesting costs were differentiated between ground harvest, by a mobile or conventional cable way or with a helicopter (Grêt-Regamey et al. 2013). In a first step, we modeled the market price based on price fluctuations of the past and expert knowledge (Grêt-Regamey et al. 2013) and updated the values of the variable in a second step by the results from an extended expert survey among regional foresters (Table A3.1, Appendix 3).

For carbon sequestration, we tracked the annual carbon flow from the four main terrestrial carbon pools: aboveground biomass, belowground biomass, soil, and dead organic matter. The amount of carbon sequestered in the soil across the 50 years modeling period was determined by subtracting the carbon stored in the area at the beginning of the time period from that stored in the area at the end of the time period. For the other carbon pools, carbon stored aboveground, belowground, and in the dead organic matter was estimated based on the yearly growth rate of different forest types (i) in existing forests, (ii) on newly afforested areas, and (iii) under climate change (Appendix 2). We converted the growth volumes of biomass into a carbon storage capacity following Thürig and Schmid (2008) accounting for a regional biomass expansion factor:

$$\begin{aligned} CO_2\,[t/ha] = {} & \\ & G[m^3/ha] \times \rho[kg/m^3] \times BEF \\ & \times C/biomass[kg/kg] \times C_1 \times C_2 \end{aligned} \qquad (2)$$

where G is the growth volume of a specific forest type (Appendix 2), ρ the density of coniferous wood (394 kg/m^3), *BEF* the biomass expansion factor of 1.49 for areas below 1800 m.a.s.l. and of 1.57 for areas above 1800 m.a.s.l. (Thürig et al. 2005), *C/biomass* is 0.5 kg/kg, and C_1 and C_2 the

Fig. 3. Bayesian network set up for the valuation of five forest ecosystem services (ESS). The grey nodes are spatially explicit input variables; the light and dark blue nodes are variables used to quantify and value the ESS; the red decision box on the top defines the land-use scenarios; the green nodes are the expected utilities in terms of changes in ESS values. Values of the variables in the nodes tagged with a black blizzard are updated by expert knowledge.



conversion factors to CO_2 (44/12) and to tons (0.001), respectively. Growth of belowground biomass and associated sequestration capacity was estimated with the “root to shoot” ratio of belowground to aboveground biomass (Tallis et al. 2011), which is 0.24 in the ecoregion of Davos (IPCC 2006). We accounted for carbon stored in dead organic matter resulting from forest growth by allocating values measured for dead organic matter stocks in Swiss forests between 1990 and 2009 (FOEN 2011) to the four forest types proportionally to their growth rates. Soil organic carbon content of mineral forest soils was assumed to be similar in all forest areas in the case study region (FOEN 2011). Thus, no additional carbon was sequestered if the forest remained forest in the future. However, we accounted for an increase of soil organic carbon on afforestation sites because carbon stocks in cropland and arable areas are reported to be lower than in forest soils (FOEN 2011). Details on average carbon sequestration rates for different forest types and pools are given in Appendix 4. Current estimates and forecasts of the social value of carbon sequestration (Nelson et al. 2009) were used to determine the value of the service in the prior model (Tol 2005, EcoSecurities 2009) while experts’ opinions were used to update the node in the expert model (Table A3.2, Appendix 3).

We estimated habitat services based on the quantification of suitable habitats for a flagship species recognized as a symbol for wildlife fauna in Western Europe forests, by the Swiss federation (FOEN 2008) and also by local actors (Kanton Graubünden 2012). *Capercaillie (Tetrao urogallus)* is listed in the European Council Directive 79/409/EEC on the conservation of wild birds (the ‘Birds Directive’), and is protected locally by laws on nature conservation, reserves and parks, as well as in the Natura 2000 framework. We are, however, fully aware that the consideration of one flagship species and its habitat requirements is only one of many aspects that should be considered in the TEEB category “habitat.” Biodiversity has other key roles at all levels of the ecosystem services hierarchy that have not been considered in this contribution. The quantification procedure selected here resembles thus more a conservation perspective, in which humans value places with a diversity of species, especially the more charismatic animals and plants, and where retaining a full complement of wild species has a distinct value in itself (Mace et al. 2012). The quantification of suitable habitats for *Capercaillie* was based on a *Capercaillie*-habitat-suitability model for Switzerland (Graf et al. 2005). We used the results of univariate logistic regression models to predict the suitability of forest patches for *Capercaillie*. Dominant environmental variables included forest cover within 500 m, June temperature, topography, distance to human activity, and forest type (Fig. 3, Appendix 1). Based on the regressions, we first identified three states for each variable representing the suitability of the habitat for *Capercaillie* (highly, partly, or not favorable). The BN was then used to estimate the overall suitability of a cell by multiplying the suitability of the single variables, which had been set to 1 for highly and 0.5 for partly supporting conditions. Including all five predictor variables the suitability of a cell for *Capercaillie* habitat could thus range from 1, if all variables were highly supportive, to 0.0625, if one variable was highly and four were partly supportive. If one environmental variable was unfavorable for habitat conditions, the overall suitability of the forest stand became 0. The habitats for *Capercaillie* were valued by habitat replacement costs using values reported in Swiss projects targeting the restoration of grouse habitats (Grêt-Regamey et al. 2008), and updated by the results of an expert survey in a second step (Table A3.3, Appendix 3).

The attributes that determine the attractiveness of forests for recreation can be grouped into two major categories (Laws 1995), which have been recently subcategorized by Lee et al. (2010). The first category includes innate site characteristics such as natural resources. The second category comprises man-made developments, primarily infrastructure and facilities for tourists. We evaluated the attractiveness of a forest for recreational use based on one variable for each main category, namely the accessibility of roads and the structure of the stand. These factors have been identified as highly important for visitors in Swiss forests and can directly be influenced by forest managers (Scarpa et al. 2000, Brändli and Ulmer 2001, Bernasconi et al. 2005). Short distances to roads and settlements as well as multilayered close structures appraised as calm and protective environments by visitors favor the destination attractiveness for recreational activities. The relative weight and joint influence of these factors on the attractiveness of forest sites was evaluated based on Brändli and Ulmer (2001) and with the aid of a local expert. We prized the recreation service using different literature values from studies on travel costs to and subsistence costs of different forest stands in Switzerland (Beck 2008) and experts' estimates in the updated model (Table A3.4, Appendix 3).

We quantified avalanche protection using the numerical two-dimensional avalanche model RAMMS (Christen et al. 2010). In a first step, RAMMS identified the size and location of avalanche release zones based on terrain characteristics and snow fracture depths from statistical analysis of the historical record of snow accumulation. In a second step, the model predicted avalanche run-out distances, flow velocities, and associated impact pressures in a spatially explicit manner. We then identified the potentially endangered buildings by overlaying the run-out zones with the vector25 data set based on the National Map 1:25,000 (Swisstopo 2004) and priced damages to buildings and fatalities using a risk-analysis approach (Grêt-Regamey and Straub 2006). By transferring back the total costs of potentially endangered dwellings to the protective forest area, we obtained a raster-based value for avalanche protection.

Expert survey

Bayesian networks have the advantage that they can be updated when new information becomes available, thus laying the ground for the iterative procedure described in Figure 2. Updating the probability distribution of selected variables of the BN with new probability distributions given by experts (*P (e)*) and propagating them through the network results in a posterior distribution *P(x | e)* of the joint probability of all nodes:

$$P(x|e) = \frac{P(x,e)}{P(e)} \tag{3}$$

We updated five variables of our network by probability distributions obtained from expert surveys (Fig. 3, nodes tagged with a blizzard). For each variable, we asked at least five independent experts for an estimate of the probability distribution. Local stakeholders provided their knowledge on land-use changes in a spatially explicit manner as well as their estimates on the future regional wood price. Habitat and replacement costs were updated by persons involved in Swiss projects targeting the restoration of forest areas for grouse habitats. Environmental economists were asked for predictions on the future social CO_2 sequestration value and scientists working on ecosystem services valuation estimated the recreational value of forests to update the node on travel and subsistence costs. Contrary to the update of the land-use node, the valuation nodes were updated independently of the scenarios because (i) incisive economic restrictions were not included in the land-use and climate scenarios and (ii) estimates of long-term ecosystem services values are inherently subject to uncertainties larger than the variability of values generated under the different scenarios. In a first step, the experts were asked whether they agree with the value range of the variable which was then adjusted according to their recommendations. In a second step, each expert estimated the probability of all states presetting a total of 100%. The evidence that was fed into the BN was calculated as the mean value of the probability estimates for each state of the node provided by the single experts (Appendix 3). If expert information was spatially explicit and scenario dependent, it was also fed as such into the BN, thus allowing a local updating of the variables under the two development scenarios. The calculated posterior probability distributions of ecosystem services values were then compared to the ecosystem services values calculated without expert knowledge.

RESULTS

Expected values for all ecosystem services but timber production increased substantially between 2000 and 2050, especially in the climate scenario and including expert knowledge in the models (Table 1). These changes are mostly due to the expansion of the forest at altitude and forest structural changes. Under a trend scenario, forest expansion

Table 1. Expected values and related uncertainties of selected forest ecosystem services in the region of Davos, Switzerland under different scenarios, calculated with a Bayesian network in which variables were not updated (no experts) or updated (experts) by an expert survey. Standard deviations (stdev) are given as percentages of the expected ecosystem services values.

Ecosystem service	Value 2000 [CHF/year]		Value trend scenario 2050 [CHF/year]				Value climate scenario 2050 [CHF/year]			
	no experts	stdev (%)	no experts	stdev (%)	experts	stdev (%)	no experts	stdev (%)	experts	stdev (%)
Avalanche protection	90,626,000	177	86,423,000	252	106,633,000	180	83,320,000	270	109,184,000	177
Recreation	14,024,000	60	15,123,000	151	21,166,000	79	14,797,000	163	23,045,000	81
Carbon sequestration	1,118,000	26	2,483,000	135	2,798,000	63	2,780,000	147	3,491,000	69
Habitat provision	80,000	39	117,000	80	151,000	51	168,000	85	225,000	53
Timber production	-301,000	87	-387,000	176	-299,000	149	-434,000	198	-355,000	161

on steep slopes supported additional avalanche protection and carbon sequestration services, while structural forest stand changes in addition enhanced habitat services and the recreational value of the forest. In contrast, young forests near timberline with relatively open canopy cover are too remote for profitable timber production. Considering the total forest area in the case study region, the services values ranged from 107 million CHF (Swiss Francs)/year for avalanche protection to 151,000 CHF/year for the provision of around 1200 ha *Capercaillie* habitat (126 CHF/ha and year), with a value of 21 million CHF/year for recreational opportunities and additional services of almost 3 million CHF/year as a carbon sink under a trend scenario. Compared to a study conducted in Davos Platz, which estimated a decreased damage potential of 41 million CHF/year in the lower urban center due to protective forest (Bebi et al. 2004), the high expected values modeled for the protection service highlight the priority role of protective forest especially above densely populated areas in mountainous areas. The estimated value of *Capercaillie* habitat in Davos is comparable to governmental financial support for one of the largest recently established special reserves for *Capercaillie* in Amden, Switzerland, which amounted to 180 CHF/ha in 2006 (Kanton St.Gallen 2006). The value of 21 million CHF/year estimated for the recreational forest service lies in the annual sectoral contributions of tourism to welfare amounting to, for example, 18 million CHF from ski lifts and gondolas in Davos (Bühler and Minsch 2004). Finally, an economic valuation of European forests in terms of carbon regulation services estimated an average value of 5000 CHF/ha and year for carbon stocks in Swiss forests in 2005 ignoring soil carbon (Ding et al. 2010). Acknowledging that we valued only incremental changes in storage capacity because of densification on forested areas and afforestation, the estimated yearly value of 250 CHF/ha in 2000 for carbon sequestration seems reasonable.

Without considering subsidies provided for controlled clearances necessary to maintain ecosystem services such as avalanche protection, timber production is currently and will in the future not be profitable in Davos because of poorly accessible terrain and associated high harvesting costs. Under the climate scenario, the additional effect of an expected temperature increase of 2.4°C on forest ecosystem services provision became apparent. The higher temperatures in the model were particularly beneficial for *Capercaillie*, whose potential habitats expanded by 17% from 1201 ha in the trend scenario to 1404 ha under climate change, corresponding to a monetary gain of around 75,000 CHF/year. Moreover, the temperature shift accelerated wood growth and increased the carbon uptake of trees.

However, all the ecosystem services quantification and valuation processes applied in this contribution were accompanied by considerable uncertainties. This is particularly evident in the climate scenario under which ecosystem services values were estimated using many assumptions. Table 1 shows the standard deviations of the expected ecosystem services values with and without the integration of expert knowledge. Accordingly, the effect of the integration of expert knowledge in the quantification and valuation processes was largest under the climate change scenario. Standard deviations decreased by more than 90% for avalanche protection, by approximately 80% for recreation and carbon sequestration, and by more than 30% for timber production and habitat provision under a climate scenario when integrating local knowledge.

Including expert knowledge not only reduced uncertainties considerably, but also had an important effect on the ecosystem services values. Particularly the expected increase in the social value of carbon sequestration anticipated by local experts had an important impact on the value of the forest as a carbon sink. Ongoing climate change and related current political resolutions restricting further greenhouse gas emissions lead the experts to forecast a substantial raise of the social value of the service until 2050 (up to 200 CHF/tCO_2), tripling the value of the forest as a carbon sink. If priced by a current estimate of social carbon sequestration value (around 30 CHF/tCO_2), carbon sequestration values in the climate scenario would only amount to 1,444,000 CHF/year.

Similarly, experts expected a growing regional importance of the forests for recreation. Located within a beautiful scenery, equipped with hiking trails and various touristic infrastructure, the valley will possibly attract larger visitor crowds in the future, especially under climate change, making alpine areas more attractive in summer months because of increased temperatures. The integration of knowledge from the expert survey increased the average value of forests suitable for recreation from 5400 CHF/ha to 6900 CHF/ha. The value of timber production was also highly sensitive to future price development. Although timber production at current and expected timber prices is not profitable, managers could draw profit from timber harvest on 81% of the current forest area if future prices only slightly exceed the experts' forecasts and stabilize at 120 CHF/m³. Still, these timber production values remain small compared to other services in most forest stands.

Figure 4 illustrates the spatially explicit uncertainties related to the quantification and valuation of the ecosystem services. We calculated the difference in ecosystem services values between 2050 (in the trend scenario) and 2000 at each location, as well as related standard deviations. For mapping and comparing uncertainties at different locations we normalized the standard deviations by the difference in values of the ecosystem services at each location between 2050 (in the trend scenario) and 2000. Large uncertainties can be observed at the tree line especially for carbon sequestration and recreation. Furthermore, uncertainties were large over the entire study area for the recreation values because the expert model used in the BN included major uncertainties that could not be improved by the experts because of lack of knowledge. The color coding in Figure 4 also gives information on where ecosystem services values were predicted to increase or decrease since 2000 in a trend scenario. The decrease in avalanche protection values from 2000 to 2050 is due to the fact that while forest expansion fosters more protection under the future scenarios, the values of the potentially protected dwellings were transferred back to a larger forest area to obtain a raster-based value, thus leading to a decrease in value per cell. Potential *Capercaillie* habitats are concentrated on small areas because of the specific requirements of the bird. On the contrary, the forest has an ubiquitous value for recreation and as a carbon sink. Belts around settlements and hiking trails provide good recreational opportunities while remote areas are of low value for leisure activities.

Because not all ecosystem services are fostered by the same forest structure, global changes will cause ecosystem services trade-offs. Figure 5 shows the ecosystem services trade-offs under the two scenarios with and without expert updating. Overall, the trade-off pattern is similar in both scenarios. Carbon sequestration and habitat services increased, while avalanche protection stayed similar and timber production decreased between 2000 and 2050. When considering expert knowledge in the modeling processes, trade-offs in ecosystem services became much more pronounced. Particularly under the climate change scenario, trade-offs were larger than under the trend scenario, demonstrating that the selected models generated a good representation of expert knowledge, and that spatially explicit local knowledge can significantly reinforce modeling outcomes. Feeding back these results to the stakeholders might show them that the modeled results reflect their expectations of future changes, thus probably increasing their trust in the use of such models, specifically when mapping ecosystem services under uncertain global changes.

DISCUSSION

Uncertainties associated with the quantification and valuation of ecosystem services are considerable. If trustworthy ecosystem services-based management strategies are to be developed, these uncertainties have thus to be accounted for in ecosystem services assessments (Carpenter et al. 2009). The GIS-based BN approach presented in this study allows on the one side to include parameter uncertainties. On the other side, it provides the option to integrate spatially explicit expert knowledge into the modeling for reducing these uncertainties.

Although results show that integrating expert knowledge can improve the results, they also disclose that the uncertainties in the modeling procedures are important. The quantification and valuation approaches selected in this study come along with many simplifying assumptions, though we used recognized procedures described in peer-reviewed literature. However, better models relating forest structure to protection efficiency against natural hazards could for example considerably refine the avalanche process model and thus improve ecosystem services value estimations (Bebi et al. 2009). Likewise the recreation model could be improved if more data on forest preferences in the Alps, particularly under increasing temperatures in the lowland, would be available. In addition, long-term estimates of ecosystem services values will strongly depend on future price developments. Whereas economic experts forecast a substantial increase of the social carbon price, local foresters made rather conservative estimates regarding future timber prices. Iteratively applying the presented approach could therefore help improve the models and support a mutual learning between local experts and scientists eventually fostering adaptive resource management.

Acknowledging the effectiveness of the Bayesian approach for addressing uncertainties, we should, however, aim at a more systematic gathering of the expert knowledge as described in Bromley (2005) or Celio et al. (2012), and conduct sensitivity analyses of the results to different data collecting approaches. The parameterization of conditional probability tables with stakeholders is an especially difficult and time-consuming task requiring deep understanding of the

Fig. 4. Uncertainty maps of forest ecosystem services (ESS) values. Green areas show an increase in ecosystem services values between 2000 and a trend scenario in 2050. Red areas show a decrease in values since 2000 under a trend scenario. The transparency indicates the magnitude of the uncertainties related to the difference in expected values between 2000 and 2050 in each cell.

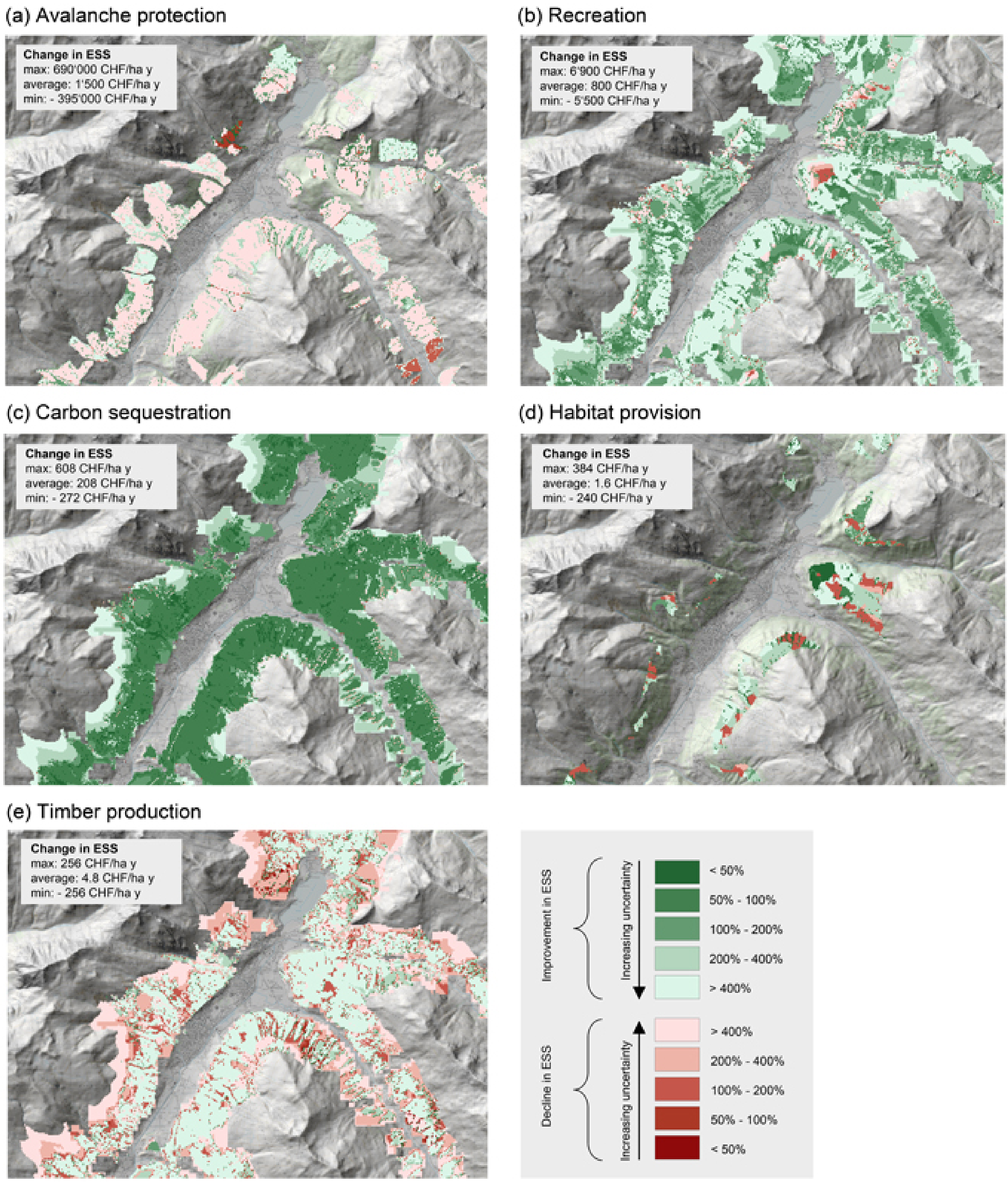
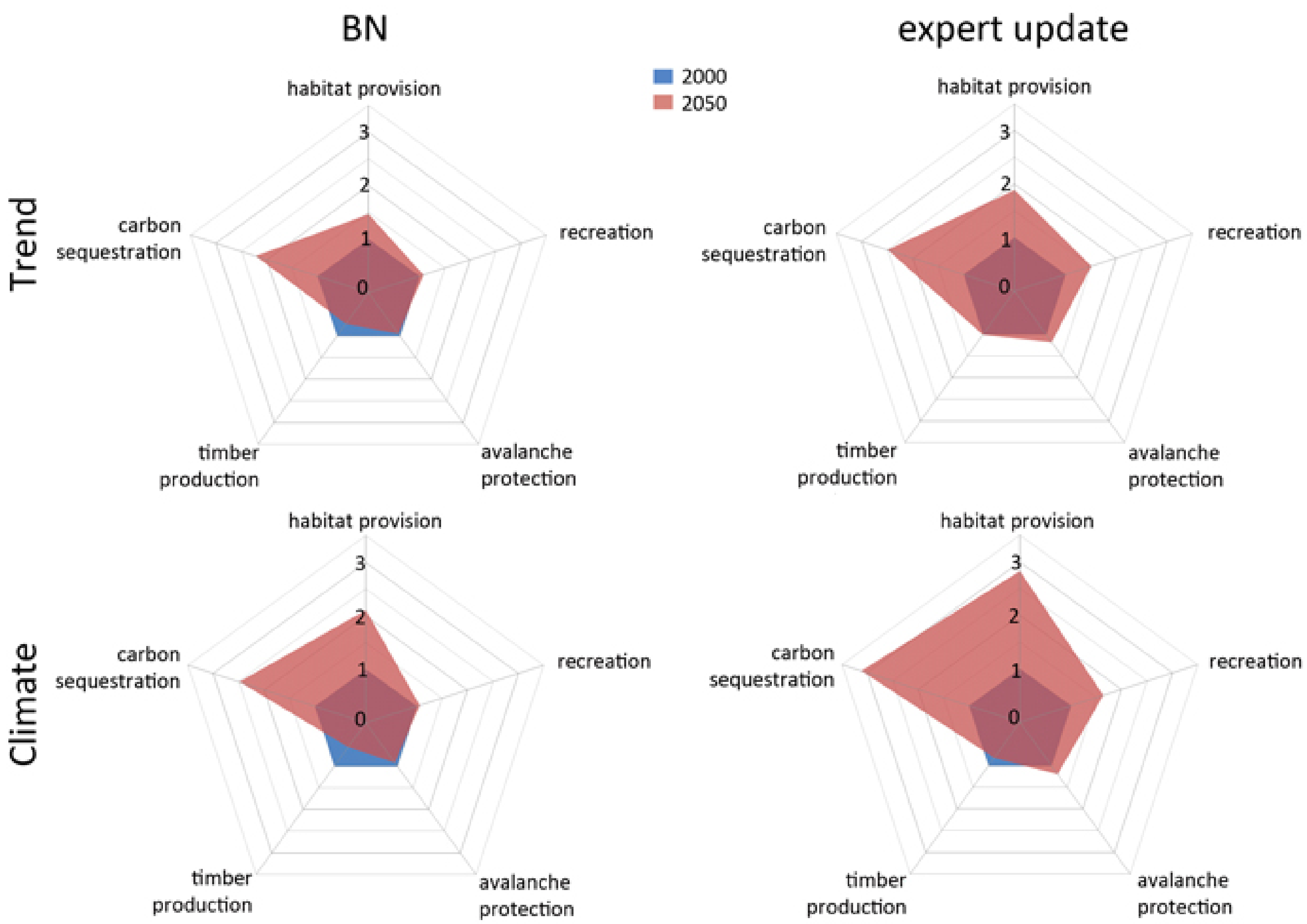


Fig. 5. Trade-offs between the selected ecosystem services avalanche protection, recreation, carbon sequestration, habitat provision, and timber production in a selected stand under a trend and a climate scenario in 2050 calculated using a Bayesian network (BN) and including expert update. Ecosystem services values under the trend and climate scenarios were normed to the values in 2000.



ecosystem investigated. Furthermore, whereas the approach presented in this contribution allows integrating local expert knowledge in a spatially explicit manner, the BN in its present form is evaluated for each cell individually. Spatial dependency structures might, however, be eminent for resource management and should be investigated in further studies. Likewise, land-use decisions are strongly dependent on neighbor and actor interactions. A further improvement of the land-use model implemented in this BN into a land-use decision model including local actor characteristics and their knowledge linked to biophysical variables is a next necessary step for using such an approach in ecosystem services-based resource management. At last, modeling uncertainties could also be considered in such an approach but would need a transdisciplinary set-up process of the BN at the beginning of the analysis to secure a thorough understanding of the causalities and hierarchical structure between the nodes.

Not only the quantification and valuation of ecosystem services, but also predictions of land-use changes are bound to large uncertainties. The transition approach used to generate the scenarios was based on past developments of the forest in the case study area. Natural disturbances such as blowdown, bark beetle, fire, or avalanches were thus only included within the range of variability they exerted during the past decades. Climate change can, however, affect forests by altering the frequency, intensity, duration, and timing of natural disturbances (Dale et al. 2001). For the Alps, we have to expect an increase in fire and bark beetle outbreaks if climate becomes warmer and drier (Schuhmacher and Bugmann 2006, Seidl et al. 2007), while the influence of climatic changes on other disturbances is less clear (Usbeck et al. 2010, Schneebeli et al. 1998). In an improved model, various disturbance regimes and the uncertainties related to their occurrence and impacts should thus be integrated.

Furthermore, we only considered a time period of 50 years in modeling forest ecosystem services. Alternative long-term management options that could substantially influence the provision of certain forest ecosystem services were not investigated (Schröter et al. 2005). Thus, although we did not find substantial differences in trade-offs when comparing ecosystem services values under a climate and a land-use scenario, and results showed that management of mountain forests in the next 50 years for carbon sequestration might decrease the protective capacities of forest and timber production, this might only be a short-term effect because stability might decrease in unmanaged forests over the years (Brang et al. 2006). Though harvest for production reasons alone is not profitable at the moment, a win-win situation might be generated with carbon sequestration, avalanche protection, and timber production in the longer term. In Switzerland, the Federation pays up to 70% of the costs for the maintenance of the protective forest (FOEN 2005). On the one hand, these subsidies cross-finance other sectors, for example, timber production, that would not be profitable in the steep mountain terrain, with positive effects on the regional economy. On the other hand, the potential provision of additional services that might be increasingly demanded in the future in protection forests can legitimate the high governmental investments. Further studies should thus include long-term forest planning scenarios to assess management measures required to achieve specific development objectives and their impacts on the value of ecosystem services over a longer period. Particularly the use of a BN-GIS approach can support planners exploring the implications of various future management alternatives in a spatially explicit manner (Stelzemüller et al. 2010).

Mapping uncertainties in ecosystem services assessments might furthermore help resource managers to define locations for new monitoring systems for a better understanding of changes in locally provided ecosystem services in the future. In a touristic center like Davos, recreational services are, for example, of growing importance. Suitable forests for recreation must be easily accessible and fulfill particular aesthetic criteria (Führer 2000). Dense protection forests seldom increase forest preferences, and ongoing management interventions enhance noise levels or usually go along with a cutting off of hiking trails (Frey 2002). Because both protection from avalanches and leisure activities primarily take place in areas near settlements, forests managers can profit from spatially explicit assessments identifying priority ecosystem services, related uncertainties, and their changes over time in high resolution.

Finally, in spite of considerable attention given to uncertainty visualization and first applications in ecosystem services assessments (Grêt-Regamey et al. 2013), there has been little effort to assess the impact of visual depictions of uncertainty on work with information (for a review, see MacEachren et al. 2005). Even the basic question of whether decision outcomes change in the face of an explicit depiction of uncertainty remains largely unanswered. Such knowledge would particularly be key to assess the effectiveness of the approach presented in this paper, which involves an iterative loop between expert knowledge and the mapping of ecosystem services and their related uncertainties.

CONCLUSION

There is general agreement that information uncertainty affects the outcomes of decision making (Reece and Matthew 1993, Kobus et al. 2001). Using a GIS-based BN, we show how to address uncertainty in the quantification and valuation of ecosystem services mapping using probability distributions and Bayesian rules, and how expert knowledge can be integrated into the modeling for improving spatially explicit ecosystem services values. Particularly the iterative procedure integrating expert knowledge guarantees a continuous improvement of ecosystem services value maps while opening a new way for mutual learning between scientists and stakeholders that might support adaptive resource management.

Responses to this article can be read online at:
http://www.ecologyandsociety.org/issues/responses.php/5800

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Appendix 1. Description of the Bayesian network nodes.

Table A1.1. States of the Bayesian network nodes, organized into the categories input nodes, nodes representing quantification procedures and nodes representing valuation procedures. Nodes that are updated by expert knowledge are bold.

Node	# states	Description of states	Data source
Input nodes			
Height	2	< 1800, > 1800 [m]	Digital elevation model (DEM25, Swiss Federal Office of Topography)
Temperature	3	Average June temperature: < 6.5 and > 12, 6.5 – 8 and 10.5 – 12, 8 – 10. 5 [°C]	Swiss National Weather Network
Forest cover within 500m	3	< 60, 60 – 70 , > 70 [%]	Predicted spatially explicitly by forest model described in section 'Case study'
Topography	3	Numeric values based on different terrain characteristics: < -40, (-40) – 30, > 30	Modeled according Grêt-Regamey et al. 2008
Distance to roads and settlements	4	< 30, 30 – 100, 100 – 200, > 200 [m]	Vector 25 (Swiss Federal Office of Topography)
Forest type	5	Canopy cover: 0, 0 – 20, 40 – 60, 60 – 80, 80 – 100 [%]	Predicted spatially explicitly by forest model described in section 'Case study' **Evidence: expert survey**
Harvesting method	4	From ground, mobile cable way, conventional cable way, helicopter	Modeled by Bont 2009
Modeled pressure	6	0, > 0 and <= 3, > 3 and < 10, > 10 and < 20, > 20 and < 30, > 30 [kPa]	Deterministic relations, modeled with RAMMS (Christen et al. 2010)
Building type	18	Agricultural building + garage, one-family house, multiple-family house, administration, school, hotel, industry, hospital, living + work, chair-lift, apparthotel, staff house, restaurant, trafo, reservoir, shop, church, depot	Hard labeling based on location of buildings from Communal cadastral register of Davos (unpublished data)
Nodes representing quantification procedures			
CO_2 sequestration aboveground biomass	5	0 – 8.64 [t/ha/y]	Table A2.1 and A4.1
CO_2 sequestration belowground biomass	5	0 – 2.24 [t/ha/y]	Table A2.1 and A4.1
CO_2 sequestration dead organic matter	5	0 – 2.56 [t/ha/y]	FOEN 2011
CO_2 sequestration soil	4	0 – 2.4 [t/ha/y]	FOEN 2011
Habitat suitability	6	0, 0.0625, 0.125, 0.25, 0.5, 1	Modeled based on regressions by Graf et al. 2005
Forest attractiveness for recreation	5	None, low, medium, high, very high	Based on Brändli and Ulmer 2001 and discussed with local expert
Harvestable amount of wood	5	0 – 6.72 [m^3/ha/y]	Table A2.1
People's presence in buildings	2	Yes, no	Presence "yes" = T*D/24*7 (Bart et al. 1999, p.64), where T is average presence time in hours per day, D is average presence time in days per week

House construction	6	Agricultural building, administration building, one-family house, multiple-family house, armed concrete, safety construction	Based on Bart et al. 1999 (p.125)
Persons per building	81	Numeric values: 0 – 80	Wilhelm 1997
Lethality in buildings	3	Yes, some, no	Barbolini et al. 2003 (Figure 4), added state "some lethality": 50% of lethality = "yes"
Building damage	3	Yes, some, no	For one-family and multiple-family houses: Barbolini et al. 2003 (Figure 4), otherwise Bart et al. 1999 (p. 125), added state "some damage": 50% of damage = "yes"
Nodes representing valuation procedures			
CO_2 sequestration social value	8	10, 30, 50, 75, 100, 150, 200, 250 [CHF/t]	Based on EcoSecurities 2009, Tol 2005 **Evidence: expert survey**
Habitat replacement costs	8	0, 140, 250, 360, 470, 580, 690, 800 [CHF/ha]	Based on Schweizerischer Forstverein 2004 **Evidence: expert survey**
Travel and subsistence cost	8	0, 150, 1000, 3000, 5500, 8000, 10'000, 12'000 [CHF/ha]	Prior: Beck 2008 **Evidence: expert survey**
Timber price	7	86, 96, 106, 115, 120, 150, 170 [CHF/m^3]	Based AfW GR 2008 and personal communication with forester **Evidence: expert survey**
Harvesting costs	4	90 – 160 [CHF/m^3]	Grêt-Regamey et al. 2013, personal communication with forester, AfW Gr 2008
Cost of human death	1	5 '000'000 [CHF]	Life Quality Index approach according to Merz et al. 1995
Cost of destroyed building	37	0 – 17'402'000 [CHF]	Communal cadastral register Davos (unpublished data), added state "some damage" : 50% cost of "total damage"
Indirect cost of destroyed building	37	Belongings: 24%, infrastructure: 15%, socio-economic: 10% of building value [CHF]	Wilhelm 1997 (p. 230), communal cadastral register Davos (unpublished data)

Appendix 2. Estimated characteristics of different forest types in Davos.

Table A2.1. Stock, annual growth rate and harvestable amount of timber for different forest types in Davos under a trend scenario (based on Grêt-Regamey et al. 2013). We estimated wood growth by allocating the average growth rate of the forest of Davos between 1980 and 2006, which was 4.87 m^3/ha (LFI 2008), to different forest types proportionally to their stock of wood and assuming a 50% lower growth rate in newly afforested plots (FOEN 2011). In the climate scenario, we increased these growth rates by 1.2 m^3/ha y accounting for a temperature induced upwards shift of the altitudinal vegetation zones (LFI 2008). The harvestable amount of timber is 15% less than the actual growth volume due to non-merchantable tree portions.

Forest type	**Wood stock [m^3/ha]**	**Wood growth [m^3/ha y]**			**Harvestable timber amount [m^3/ha y]**	
	2000	***1980 – 2006***	***forested areas 2000 – 2050***	***woodless areas 2000 – 2050***	***forested areas 2000 – 2050***	***woodless areas 2000 – 2050***
Small stock of wood	259.2	2.88	2.88	1.44	2.40	1.28
Medium stock of wood	388.8	4.32	4.32	2.24	3.68	1.92
Large stock of wood	529.6	5.92	5.92	2.88	4.96	2.40
Very large stock of wood	561.6	6.24	6.24	3.20	5.28	2.72

Appendix 3. Prior probability distributions for the economic valuation nodes and evidence provided by experts.

Table A3.1. Prior probability distribution of timber price and evidence provided by experts. The evidence that was fed into the Bayesian Network was calculated as the mean value of the probability estimates for each state of the node provided by the single experts.

Timber market price [CHF/m^3]	Prior probability distribution (based on Grêt-Regamey et al. 2013)	Evidence (mean (and standard deviation) of five expert opinions)
86	0.3	0.05 (0.05)
96	0.5	0.06 (0.05)
106	0.2	0.15 (0.05)
115	0	0.21 (0.15)
125	0	0.26 (0.10)
150	0	0.21 (0.19)
170	0	0.05 (0.05)

Table A3.2. Prior probability distribution of the social value of carbon sequestration and evidence provided by experts. The evidence that was fed into the Bayesian Network was calculated as the mean value of the probability estimates for each state of the node provided by the single experts.

Social value of CO_2 sequestration [CHF/t CO_2]	Prior probability distribution (based on EcoSecurities 2009, Tol 2005)	Evidence (mean (and standard deviation) of six expert opinions)
10	0	0.01 (0.02)
30	0.1	0.09 (0.08)
50	0.4	0.19 (0.10)
75	0.4	0.27 (0.14)
100	0.1	0.28 (0.10)
150	0	0.12 (0.14)
200	0	0.03 (0.05)
250	0	0.01 (0.02)

Table A3.3. Prior probability distribution of habitat replacement costs and evidence provided by experts. The evidence that was fed into the Bayesian Network was calculated as the mean value of the probability estimates for each state of the node provided by the single experts.

Habitat replacement costs [CHF/ha]	Prior probability distribution (based on Grêt-Regamey et al. 2008)	Evidence (mean (and standard deviation) of five expert opinions)
140	0.07	0.04 (0.06)
250	0.13	0.10 (0.12)
360	0.19	0.19 (0.05)
470	0.21	0.21 (0.07)
580	0.19	0.23 (0.08)
690	0.13	0.16 (0.06)
800	0.07	0.08 (0.06)

Table A3.4. Prior probability distribution of travel and subsistence costs of forests and evidence provided by experts. The evidence that was fed into the Bayesian Network was calculated as the mean value of the probability estimates for each state of the node provided by the single experts.

Travel or subsistence costs [CHF/ha]	Prior probability distribution (based on Beck 2008)	Evidence (mean (and standard deviation) of six expert opinions)
150	0.10	0.06 (0.08)
1000	0.12	0.08 (0.07)
3000	0.18	0.15 (0.11)
5000	0.21	0.18 (0.07)
8000	0.18	0.20 (0.12)
10’000	0.13	0.17 (0.12)
12’000	0.08	0.16 (0.15)

Appendix 4. Sequestration rates of carbon pools.

Table A4.1. Annual carbon sequestration rates for different carbon pools. Shown are mean values for the trend scenario. Values are higher in the climate scenario and lower on afforestation sites as described in the text.

Forest type	Growth rate [m^3 wood/ha y]	Above ground biomass [t CO_2/ha y]	Below ground biomass [t CO_2/ha y]	Dead wood [t CO_2/ha y]	Soil carbon on new afforestation sites [t CO_2/ha y]
Small stock of wood	2.88	3.27	0.78	0.96	1.6
Medium stock of wood	4.32	4.90	1.18	1.44	1.6
Large stock of wood	5.92	6.71	1.61	1.92	1.6
Very large stock of wood	6.24	7.08	1.70	2.08	1.6