Räumlich explizite Risikoanalyse zur Förderung eines integralen Risikomanagements und der Priorisierung von Massnahmen und Investitionen

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Zusammenfassung

Die zunehmenden Ansprüche der Gesellschaft an den Raum, die Siedlungs- und Infrastrukturverdichtung und eine fortschreitende Übernutzung der natürlichen Ressourcen erhöhen die Vulnerabilität des Raumes gegenüber natürlichen, technologischen und sozioökonomischen Gefahren. Nur ein ganzheitliches Management aller vorhandenen raumrelevanten Risiken kann längerfristig sichern, dass Massnahmen erarbeitet und priorisiert werden, die alle Aspekte der nachhaltigen Raumentwicklung gleichermassen berücksichtigen, und dass finanzielle Mittel risikogerecht investiert werden. Im Auftrag des Bundesamts für Umwelt (BAFU) wurde vom Fachbereich Planung von Landschaft und Urbanen Systemen (PLUS) der ETH Zürich eine Methode zur integralen Risikoanalyse erarbeitet, die verschiedene Risiken im Raum bewerten und vergleichen kann und die Möglichkeiten des risikoorientierten Planens in einem räumlich expliziten Kontext aufzeigt. Die Methode, basierend auf Bayesschen Netzwerken (BN), wurde anhand der Fallstudienregion Davos (1) auf ihr Anwendungspotential in strategischen partizipativen Entscheidungsprozessen getestet und (2) in einem räumlich expliziten Rahmen zur konkreten Landnutzungsplanung umgesetzt.

Die Resultate der Vorstudie haben gezeigt, dass sich BN für komparative Risikoanalysen eignen, weil sie in ihrem Design flexibel sind, so dass Risiken aller Arten verglichen werden können, weil sie Unsicherheiten in einem räumlichen System und der darin ablaufenden relevanten Prozesse explizit berücksichtigen und weil sie quantitative Daten mit Erfahrungswerten und Expertenwissen kombinieren können. Ausserdem fördern sie die Partizipation, den Wissenstransfer zwischen verschiedenen Sektoren und den Risikodialog, wichtige Hürden für eine erfolgreiche Umsetzung des konzeptionell vorhandenen Wissens in die Praxis. Ein landesweites Mapping verschiedener Risiken mittels BN erfordert jedoch noch erhebliche Anstrengungen, insbesondere die Verfeinerung und Weiterentwicklung der Methodik zu einem generischen Instrument und die flächendeckende Erhebung von räumlich expliziten Daten.

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1. Ausgangslage

Risiken für die Bevölkerung und ihre Lebensgrundlagen entstehen und wirken an den Schnittstellen zwischen ökologischen, ökonomischen, technologischen, politischen und sozialen Entwicklungen. In der Schweiz haben in den vergangenen Jahrzehnten insbesondere das Bevölkerungswachstum, das zunehmende Bedürfnis nach Raum, Mobilität und Kommunikation, eine Konzentration von Vermögenswerten und die schrittweise Degradation der natürlichen Ressourcen die Verletzlichkeit des Raumes gegenüber natürlichen, technologischen und sozioökonomischen Gefahren erhöht (PLANAT, 2012). Zur Sicherstellung der nachhaltigen Entwicklung ist es aus Sicht der öffentlichen Hand zunehmend wichtiger, alle Arten von Risiken zu kennen, die die Entwicklung eines räumlichen Systems, wie z. B. einer Region oder einer Gemeinde beeinflussen.

Im Bereich des Naturgefahrenschutzes ist die Schweiz mit ihren Bemühungen, den Schutz vor Naturgefahren auf der Basis des integralen Risikomanagements effizienter und effektiver zu gestalten, im internationalen Kontext zu einem BestPractice-Beispiel avanciert (Greminger, 2012). Der Paradigmenwechsel, der die Einbindung aller möglichen Schutzmassnahmen, inklusive der planerischen Aktivitäten und deren optimale Koordination propagiert, hat die Raumplanung verstärkt in den Fokus des Risikomanagements gerückt. Tatsächlich bietet die Raumplanung als interdisziplinäre und integrative Disziplin grosses Potential, das bestehende Instrumentarium im Sinne eines „all-risk“-Ansatzes[1] zu erweitern und eine ganzheitliche Planung und Bewirtschaftung von Räumen und allen damit verbundenen Risiken, aber auch Chancen, zu fördern. Bis heute jedoch stellt die praktische Nutzung des raumplanerischen Potentials eines der grössten Defizite im integralen Risikomanagement dar (Greminger & Zischg, 2011).

Die mit einem ganzheitlichen Management aller Risiken verbundenen Hindernisse sind vielfältig (Korck et al., 2011): Verschiedene fachbezogene Sektoren operieren in unterschiedlichen räumlichen Bezugseinheiten und verfolgen eigene Strategien. In einer Region z. B. können die nach Sektoren aufgeteilten Finanzflüsse und sachorientierten, voneinander unabhängigen Schutzziele dazu führen, dass Investitionen in Schutzmassnahmen fliessen, die im Kontext anderer Risiken nicht die höchste Priorität haben. Die heutigen Verfahren zur Risikoanalyse sind meist statisch und räumlich sowie zeitlich limitiert, obwohl sich Risiken schnell ändern und über institutionelle Grenzen hinaus wirken. Die lokal begrenzte Betrachtungsweise birgt die Gefahr in sich, Risiken sowie Chancen verschiedener Strategien bei Kosten/Nutzen-Analysen zu unterschätzen. Zudem werden die Unsicherheiten, die den Analysen zu Grunde liegen, noch ungenügend berücksichtigt und kommuniziert. Es fehlen Methoden, die die Vergleichbarkeit verschiedener Risiken gewährleisten. Schliesslich erschweren inkonsistente Datengrundlagen und mangelhafte partizipative und integrative Verfahren und Lernprozesse die praktische Anwendung des integralen Risikomanagements.

Eine erfolgreiche Umsetzung des bestehenden konzeptionellen Wissens in die Praxis erfordert (a) Planungsinstrumente, die vorhandenes Wissen optimal nutzen und besser zugänglich machen und den Wissenstransfer zwischen verschiedenen Sektoren fördern, (b) Methoden, die kurz-, mittel- und langfristig nicht nur Risiken von Naturgefahren, sondern auch sozio-ökonomische, technische und ökologische Risiken analysieren, bewerten und vergleichen, (c) pragmatische Problemlösungsprozesse und Ausbildungsinstrumente, die die Partizipation von Akteuren und einen verstärkten Risikodialog fördern, (d) die Berücksichtigung von Unsicherheiten bei der Analyse und beim Risikodialog, (e) Kosten-Nutzen-Analysen verschiedener Planungsalternativen für alle Sektoren auf lokaler und regionaler Ebene sowie für unterschiedliche Zeithorizonte und (f) ein langfristiges Monitoring-System, das die Entwicklung von Risiken und Chancen im Raum verfolgt und Zielkonflikte aufdeckt.

2. Ziele und Fragestellung/Auftrag des Arbeitgebers

Als Beitrag zur Weiterentwicklung der methodischen Grundlagen zur Quantifizierung und Bewertung von Risiken soll die vorliegende Studie im Rahmen eines „all-risk“-Ansatzes die Möglichkeiten des risiko-

[1] Ein „all-risk“-Ansatz berücksichtigt alle Arten von Risiken, nicht nur die Naturgefahren.

orientierten Planens und Entscheidens in einem räumlich expliziten Kontext evaluieren. Dazu soll eine Methode erarbeitet werden, welche die Vergleichbarkeit des Ausmasses von Risiken unterschiedlicher Art ermöglicht und Entscheidungsgrundlagen für risikoorientiertes Budgetieren liefert. Sie soll identifizierte Schwächen des existierenden Instrumentariums, insbesondere den mangelhaften Wissenstransfer und die ungenügende Berücksichtigung von Unsicherheiten adressieren und zu einer verbesserten Umsetzung des Risikokonzeptes in die Praxis beitragen. Ausserdem soll die Methode neben Risiken auch Chancen von Planungsalternativen abbilden und so die Vorteile einer ganzheitlichen, risikoorientierten Raumplanung aufzeigen. Diese Arbeit schliesst an Arbeiten des internationalen Projektes *Adaptalp* (Korck et al., 2012) an.

Die Resultate dieser Studie sollen dazu beitragen, folgende Fragen zu diskutieren:

- Ist ein räumlich explizites, risikoorientiertes Planen und Entscheiden zur Sicherstellung der nachhaltigen Entwicklung auf regionaler Ebene möglich und zielführend?
- Unter welchen Voraussetzungen ist das möglich?
- Welche Hindernisse gilt es zu überwinden?

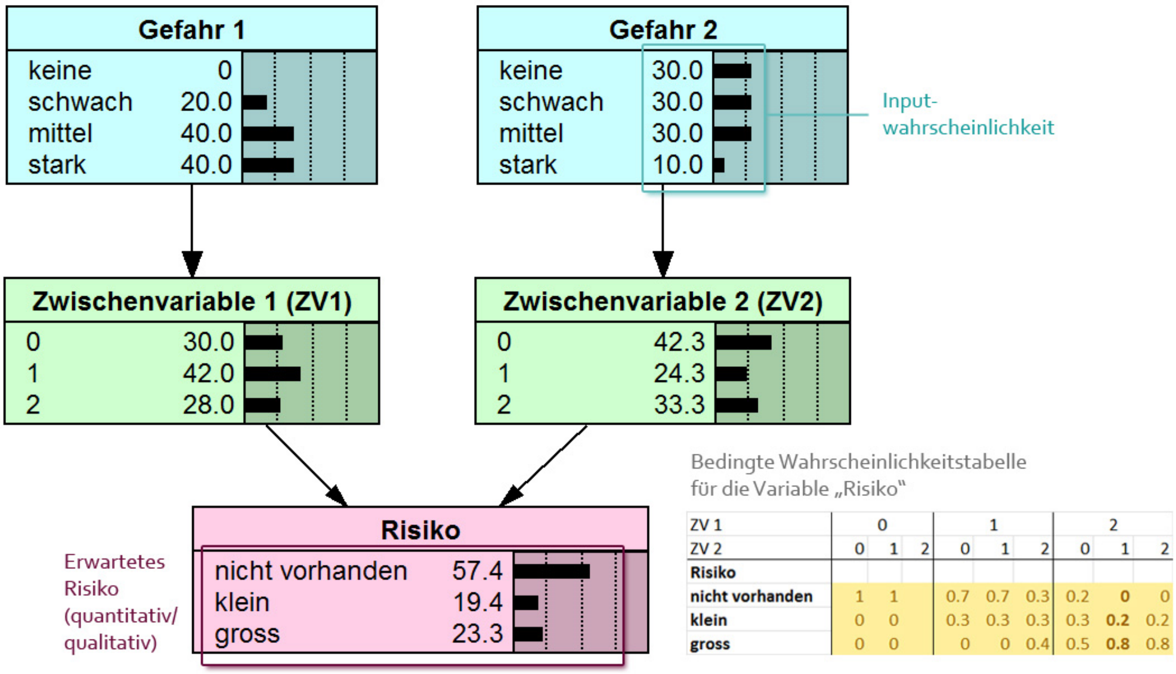
Im Rahmen dieser Vorstudie wird die entworfene Methodik auf strategischer und operativer Ebene in der Fallstudienregion Davos getestet. Die in sich geschlossene Talschaft eignet sich als Untersuchungsraum, weil sie von verschiedenen Naturgefahren betroffen, als Tourismusregion bekannt und von Landwirtschaft geprägt ist. Ihre Entwicklung wird somit von Risiken unterschiedlichster Art beeinflusst. Zudem verfügt die Region über vielfältige und räumlich explizite Datengrundlagen aus zahlreichen bereits abgeschlossenen Forschungsprojekten (z. B. Bebi et al., 2005; Grêt-Regamey et al., 2008; Grêt-Regamey et al., 2012).

3. Methodik

3.1. Bayessche Netzwerke (BN)

In der entwickelten Methode werden regionale Risiken und Chancen mit Hilfe von Bayesschen Netzwerken (BN) analysiert und verglichen. BN eignen sich dazu, Prozesse abzubilden und zu untersuchen, die Unsicherheiten unterliegen, weil Zusammenhänge im System nicht bekannt sind oder nur ungenügend verstanden werden. Ein BN ist ein Graph, der die relevanten Variablen eines Systems und ihre kausalen Beziehungen untereinander darstellt. Im Falle der Risikoanalyse vernetzt das BN die vorhandenen Gefahren in einem System über Ursache-Wirkungsketten mit Schadenspotentialen und berechnet die resultierenden Risiken. Das BN wird auf drei Grundkomponenten aufgebaut (Abbildung 1): (1) verschiedenen Systemvariablen, auch Knoten genannt, (2) Pfeilen, welche die kausalen Abhängigkeiten zwischen den Variablen illustrieren und (3) bedingten Wahrscheinlichkeitstabellen, die beschreiben, wie stark diese Abhängigkeiten sind. Ein Pfeil von Variable „Gefahr 1“ (z. B. Aufgabe von landwirtschaftlichen Flächen) zur „Zwischenvariablen ZV1“ (z. B. Siedlungsfläche) bedeutet, dass eine Aufgabe von Landwirtschaftsbetrieben eine Veränderung der Siedlungsfläche zur Folge haben kann. Der Gefahrenknoten wird als „Elternknoten“ der Zwischenvariablen bezeichnet. Knoten ohne Eltern repräsentieren Inputvariablen (in Abbildung 1 blau), die in der Risikoanalyse verschiedenen Gefahrenprozessen entsprechen. Knoten am Ende der Ursache-Wirkungsketten bezeichnen die Zielvariablen (rosa), also die verschiedenen Risiken, die es zu bewerten gilt. Für jede Systemvariable werden quantitative oder qualitative Zustände definiert, z. B. kann eine Gefahr schwach, mittel, stark oder in einer Region nicht vorhanden sein. Dabei zeigt das BN auf, mit welchen Wahrscheinlichkeiten die Variablen die verschiedenen Ausprägungen einnehmen. In Abbildung 1 z. B. beträgt die Wahrscheinlichkeit jeweils 30%, dass Gefahr 2 nicht, mit kleiner oder mit mittlerer Intensität eintritt. Die Wahrscheinlichkeit einer starken Gefahrenstufe ist mit 10% dagegen deutlich tiefer. Bei den Inputvariablen werden die Eintrittswahrscheinlichkeiten a priori festgelegt. Damit die Wahrscheinlichkeitsverteilungen von den Zwischen- und Zielvariablen berechnet werden können, müssen sogenannte „bedingte Wahrscheinlichkeitstabellen“ für jede dieser Variablen erstellt werden. Diese Tabellen zeigen, mit welcher Wahrscheinlichkeit ein bestimmter Zustand in Abhängigkeit der Zustände von den Elternknoten eingenommen wird. Wenn z. B. die Zwischenvariable 1 den Wert 2 und die

Zwischenvariable 2 den Wert 1 annehmen, dann ist das resultierende Risiko mit 20%iger Wahrscheinlichkeit klein und mit 80%iger Wahrscheinlichkeit gross (Abbildung 1).



ZV 1	0			1			2		
ZV 2	0	1	2	0	1	2	0	1	2
Risiko									
nicht vorhanden	1	1		0.7	0.7	0.3	0.2	**0**	0
klein	0	0		0.3	0.3	0.3	0.3	**0.2**	0.2
gross	0	0		0	0	0.4	0.5	**0.8**	0.8

Abbildung 1. Grundstruktur eines Bayesschen Netzwerkes: Inputvariablen (blau, Gefahrenprozesse), Zwischenvariablen (grün, Auswirkungen der Gefahren) und Zielvariablen (rosa, Risiken) sind über Ursache-Wirkungsbeziehungen miteinander verbunden. Jeder Zwischen- und Zielvariablen liegt eine bedingte Wahrscheinlichkeitstabelle zu Grunde, die beschreibt, wie die Ausprägungen der Variablen von den Zuständen ihrer Elternknoten abhängt (gelb).

Folgende Schritte werden bei einer Risikoanalyse mit BN abgewickelt:

(1) *Systemdefinition:* Festlegung des Untersuchungsperimeters und der darin relevanten Gefahrenprozesse und Parameter, welche die regionale Entwicklung steuern.
(2) *Systembild:* Erfassung der Kausalitäten innerhalb des Systems über Zwischenvariablen und Darstellung der Ursache-Wirkungsketten hin zu den Schadenspotentialen.
(3) *Gewichtung der Wirkungsbeziehungen:* Ausfüllen der bedingten Wahrscheinlichkeitstabellen. Sie beschreiben, wie stark die Schadenspotentiale von verschiedenen Gefahren beeinflusst werden und wie sensibel sie auf deren Veränderungen reagieren. Ausserdem erfassen sie Unsicherheiten, welche mit der Quantifizierung der Gefahrenprozesse und ihren Auswirkungen zusammenhängen.
(4) *Szenarien:* Aufsetzen von verschiedenen Gefährdungsszenarien mit unterschiedlichen Eintrittswahrscheinlichkeiten der relevanten Gefahren.
(5) *Modellierung:* Das BN berechnet mit Hilfe von mathematischen Algorithmen die Risiken im definierten System und bildet die mit der Risikoanalyse und –bewertung verbundenen Unsicherheiten ab[2] (Abbildung 1).

BN eignen sich auf Grund zahlreicher Eigenschaften für integrale Risikoanalysen: (1) Sie sind für Akteure intuitiv leicht verständlich, weil Beziehungen zwischen den Variablen explizit visualisiert werden. Damit wird die Transparenz der Analyse erhöht und die Nachvollziehbarkeit der Resultate verbessert. (2) Im

[2] Folgende online Tutorials liefern weiterführende Erklärungen zu BN, eine Einführung in die Bayessche Wahrscheinlichkeitsrechnung und angewandte (interaktive) Berechnungsbeispiele:
(a) auf Englisch: http://www.norsys.com/tutorials/netica/secA/tut_A1.htm
(b) auf Deutsch: http://user.cs.tu-berlin.de/~rammelt/probnet/index.html.

Sinne eines „pragmatischen Risikomanagements“[3] können bei der Risikoanalyse sowohl quantitative Daten als auch Expertenwissen verwendet werden. Dieses Vorgehen fördert den Dialog mit Betroffenen, Verantwortlichen, Fachleuten und ortskundigen Erfahrungsträgern sowie die ganzheitliche beziehungsweise integrale Sichtweise. Die Partizipation fördert aber nicht nur die Sensibilisierung der Öffentlichkeit, sondern ermöglicht auch, Prozesse zu untersuchen, für welche quantitative Datengrundlagen fehlen. (3) Das Wissen über die Ursache-Wirkungsketten sowie die Eintrittswahrscheinlichkeiten verschiedener Gefahren ist beschränkt. BN ermöglichen die Berücksichtigung und Darstellung dieser Unsicherheiten. Die Ergebnisse der Analyse gewinnen damit an Transparenz und Glaubwürdigkeit. Zudem ermöglichen die analysierten Unsicherheiten einen fundierten Risikodialog (Greminger & Zischg, 2011). (4) Alle Komponenten des BN sind veränderbar, was laufende Aktualisierungen und Ergänzungen erlaubt, sobald neue Daten oder Erkenntnisse vorliegen. Periodische Analysen mit dem BN ermöglichen zudem die Evaluation der mit dem Risikomanagement erzielten Verbesserungen. (5) Analysen können sowohl räumlich aggregiert für strategische als auch räumlich explizit für operative Entscheidungsprozesse durchgeführt werden.

Im Folgenden wird der mögliche Einsatz von BN zur Unterstützung von strategischen Entscheidungsprozessen sowie eine räumlich explizite Anwendung zur konkreten Landnutzungsplanung am Beispiel der Region Davos erläutert.

3.2. Anwendung der Bayesschen Netzwerke (BN) auf strategischer Ebene

Risikoanalysen auf strategischer Ebene bezwecken, den Handlungsbedarf festzustellen, Handlungsoptionen zu identifizieren, grob zu bewerten und entsprechende Aktivitäten zu priorisieren. Dabei kann in der Regel mit gröberen Annahmen und Daten gearbeitet werden als auf operativer Ebene (BAFU et al., 2010). Das BN dieser Vorstudie bewertet Risiken qualitativ. Im vorliegenden Beispiel wird anhand von zwei alternativen Entwicklungsszenarien untersucht, welche Risiken und Chancen für die nachhaltige Entwicklung der Region Davos relevant sind. Die Vorstudie basiert auf Resultaten von zwei Projekten, die in der Landschaft Davos durchgeführt wurden (Bebi et al., 2005; Holthausen et al., 2011)[4]. In dieser Vorstudie wurde auf die zeitintensive Mitwirkung von Akteuren verzichtet. Das Beispiel soll aufzeigen, wie eine Analyse mit BN in die Praxis umgesetzt werden kann, um Entscheidungsprozesse auf strategischer Ebene mit partizipativen Prozessen zu unterstützen.

Wie in der Einleitung beschrieben, erfolgt die Analyse schrittweise:

(1) Systemdefinition: In einem ersten Schritt werden zusammen mit Entscheidungsträgern, Akteuren und Experten die relevanten Gefahren für eine nachhaltige regionale Entwicklung ermittelt. In einer alpinen Tourismusregion wie Davos ist der Konflikt zwischen intensiver touristischer Nutzung der Region und der Erhaltung ihrer Attraktivität als Lebens- und Erholungsraum eines der wichtigsten Spannungsfelder, welches durch Chancen und Risiken geprägt ist.
Von folgenden Gefahren wird bei dieser Vorstudie ausgegangenen:
(a) Zunahme des Tourismus,
(b) Aufgabe von landwirtschaftlichen Flächen, die das Landschaftsbild prägen,
(c) Zunahme der Lawinengefahr als Beispiel für den Einfluss der Naturgefahren, da der Klimawandel die Intensität und Häufigkeit von Naturgefahrenereignissen in Berggebieten erhöhen kann.

(2) Systembild: Im Systembild werden die Gefahrenprozesse ausgehend von der Gefahr über die wirkenden Prozesse und relevanten Variablen hin zu den Schadenspotentialen aufgeführt. Die folgenden Schadenspotentiale wurden in diesem Beispiel als Zielvariablen berücksichtigt:
(a) Personen- und Sachschäden,
(b) Ästhetische Werte der Landschaft,

[3] „Der Begriff „pragmatisches Risikomanagement“ bringt zum Ausdruck, dass alles vorhandene Wissen verwendet werden kann – von mathematisch oder wissenschaftlich hergeleiteten Daten aus Statistiken, Modellierungen, Simulationen u. ä. bis Einschätzungen auf Grund von Erfahrungen oder Beurteilungen von implizitem Wissen“ (BAFU et al., 2010).
[4] Falls nicht explizit anders zitiert, basieren die Annahmen, die in der exemplarischen Risikoanalyse für die Region Davos getroffen wurden, auf Bebi et al. (2005) und Holthausen et al. (2011).

(c) Regionale Wertschöpfung,
(d) Produktivität in Land- und Waldwirtschaft,
(e) Angebot an Habitaten für Tiere.
Abbildung 2 zeigt ein Systembild, wie es aus einer Diskussion mit Akteuren resultieren könnte.

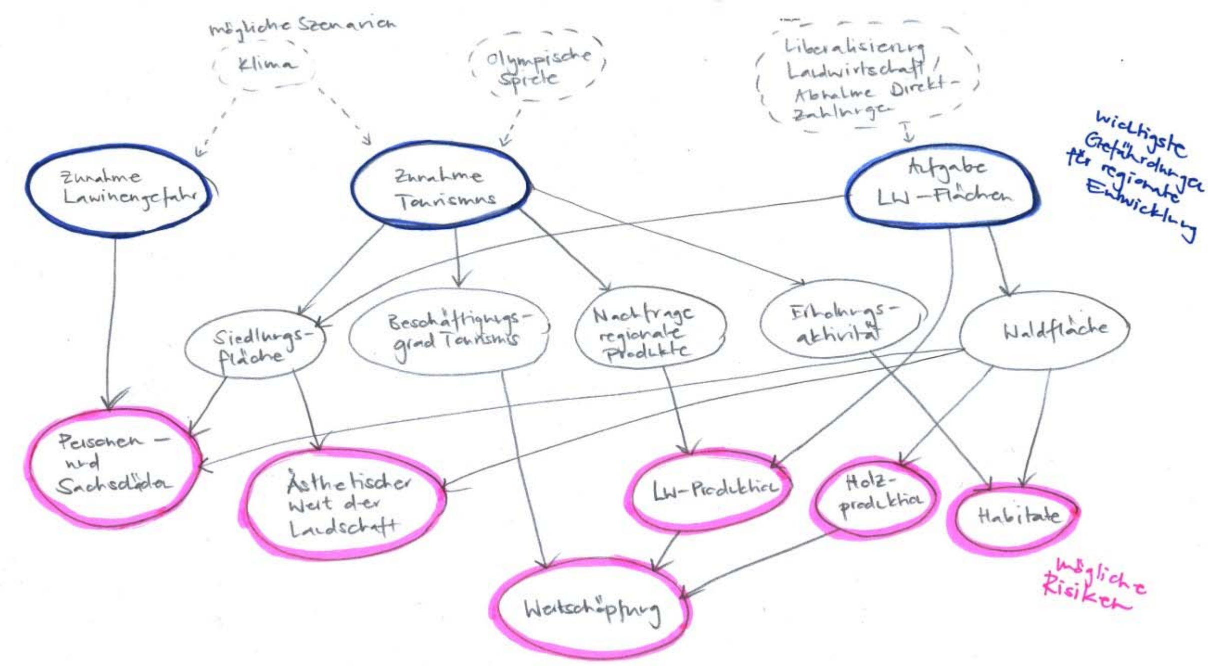


Abbildung 2. Exemplarisches Systembild für die Region Davos als mögliches Produkt einer Diskussion mit Akteuren.

(3) Gewichtung der Wirkungsbeziehungen: Im nächsten Schritt wird diskutiert, wie die kausalen Beziehungen im System ausgeprägt sind. Je grösser die Vulnerabilität der Variablen gegenüber der wirkenden Prozesse, desto stärker wirkt sich eine Veränderung der Gefahren auf die resultierenden Risiken aus. Die genauere Beschreibung der Wirkungsbeziehungen kann zunächst graphisch im aufgezeichneten Systembild erfolgen (Abbildung 3a). Anschliessend werden die Überlegungen in die BN-Umgebung implementiert[5] (Abbildung 3b). Dazu müssen als Erstes verschiedene Zustände für die Gefahren, ihre Auswirkungen und die resultierenden Risiken definiert werden. Im Beispiel Davos wurden vier mögliche Zustände für jede Gefahr gewählt: keine Gefahr, schwache, mittlere und starke Gefahr. Die Gefahren sind im skizzierten System positiv mit allen unmittelbaren Auswirkungen gekoppelt (siehe auch Abbildung 3a). Die Zwischenvariablen können deswegen in Abhängigkeit der Stärke der Gefahren drei Ausprägungen einnehmen: keine Veränderung (0), eine geringe Zunahme (1) oder eine starke Zunahme (2). Den Risiken wurden je fünf qualitative Zustände zugeschrieben: -2, -1, 0, 1, 2. Negative Werte bedeuten eine Abnahme und positive Werte eine Zunahme der Risiken. Mit dieser Skala wird gewährleistet, dass nebst den negativen auch positive Auswirkungen von Entwicklungsszenarien erfasst werden können. Sind die Zustände der Systemelemente festgelegt, muss als Zweites gewichtet werden, wie stark sie von verschiedenen Einflussfaktoren abhängen und wie sensibel sie auf deren Veränderungen reagieren. Dazu kann in der BN-Umgebung für jede Variable einzeln eine bedingte Wahrscheinlichkeitstabelle aufgerufen und ausgefüllt werden. Im vorliegenden Beispiel wurden die Resultate aus dem Projekt *Alpscape* (Bebi et al., 2005) zur Abschätzung der bedingten Wahrscheinlichkeiten beigezogen. Falls die Tabellen mit Hilfe von Experten ausgefüllt werden, ist dieser Schritt besonders zeitintensiv und bedarf einer überlegten Herangehensweise, da bedingte Wahrscheinlichkeiten intuitiv schwer abschätzbar sind. Sobald eine Variable von drei oder mehr Elementen beeinflusst wird, sind verlässliche Schätzungen äusserst anspruchsvoll (z. B. O'Hagan et al., 2006).

[5] Es existieren verschiedene Programme zur Modellierung von BN. In dieser Vorstudie wurde mit dem Programm Netica der Firma Norsys gearbeitet. Eine Demoversion des Programms steht auf http://www.norsys.com/netica.html zum Download bereit.

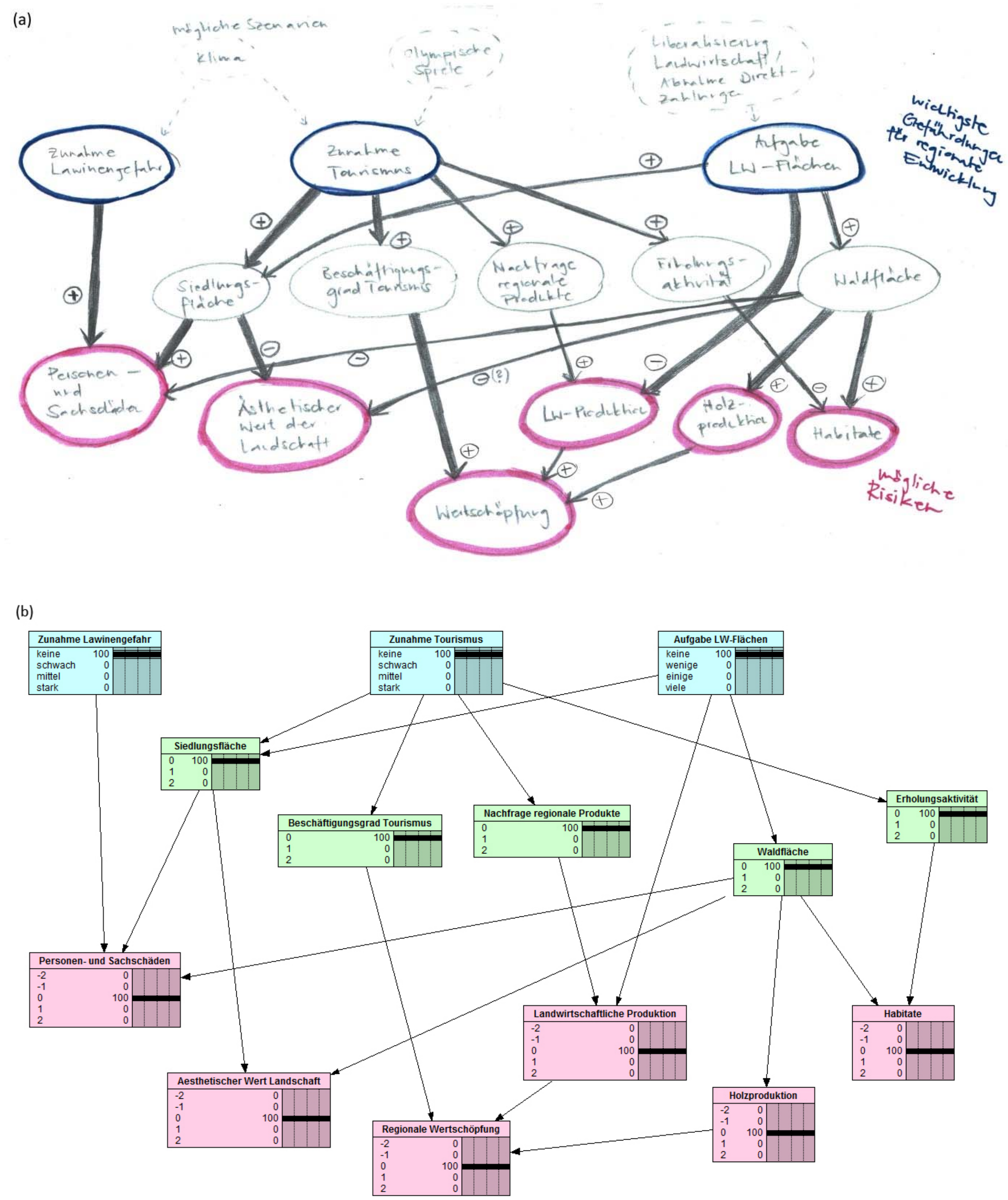


Abbildung 3a. Bestimmung der Wirkungsbeziehungen im Systembild: dicke Pfeile symbolisieren einen starken Einfluss, wobei die Operatoren +/- anzeigen, ob eine Zunahme der Ursprungsvariable zu einer Zu- oder Abnahme der Zielvariablen führt. 3b. Implementierung der Kausalketten in die BN-Umgebung. Die bedingten Wahrscheinlichkeitstabellen sind nicht dargestellt.

(4) Szenarien: Für die Region Davos wurden zwei Szenarien gewählt:
Szenario 1 „Landwirtschaft“: Die Subventionen für die Landwirtschaft werden auf Grund der zunehmenden Liberalisierung der Landwirtschaft gestrichen. In der Folge werden im Raum Davos viele landwirtschaftliche Flächen aufgegeben. Die Besucherzahlen steigen nur leicht an. Die Nachfrage nach lokalen, qualitativ hochwertigen landwirtschaftlichen Bergprodukten nimmt aber dank einer positiven Kaufeinstellung der Bevölkerung gegenüber regionalen Spezialitäten trotzdem zu.

Szenario 2 „Klima“: Die Klimaveränderung führt vermehrt zu kritischen Lawinensituationen. Auf Grund der schneesicheren Lage und eines vielseitigen Winter- und Sommerangebots steigt die Zahl der Touristen und Logiernächte erheblich.
Die Szenarien werden über die Eintrittswahrscheinlichkeiten der verschiedenen Gefahren im BN berücksichtigt (Abbildung 4).

(5) Modellierung: Abbildung 4 zeigt die Risiken und Chancen, die unter Szenario 2 („Klima“) in Davos zu erwarten sind. Als Folge einer erhöhten Nachfrage nach regionalen Produkten steigt die landwirtschaftliche Produktion schwach an. Diese Produktionszunahme und die Ankurbelung der Tourismusbranche steigern die regionale Wertschöpfung erheblich. Im Gegensatz zu den ökonomischen Chancen, die sich durch die Klimaerwärmung auftun, vergrössert sich das Risiko, wertvolle Habitate durch erhöhte Erholungsaktivität zu verlieren. Eine Erweiterung der Siedlungsfläche führt zudem zu einem Verlust des ästhetischen Wertes der Landschaft und einer beachtlichen Zunahme an potentiellen Personen- und Sachschäden. Diese Kausalitäten werden explizit in der BN Umgebung dargestellt. Ausserdem können die Akteure unmittelbar die Unsicherheiten, die mit den einzelnen Risiken und Chancen verbunden sind, erkennen.

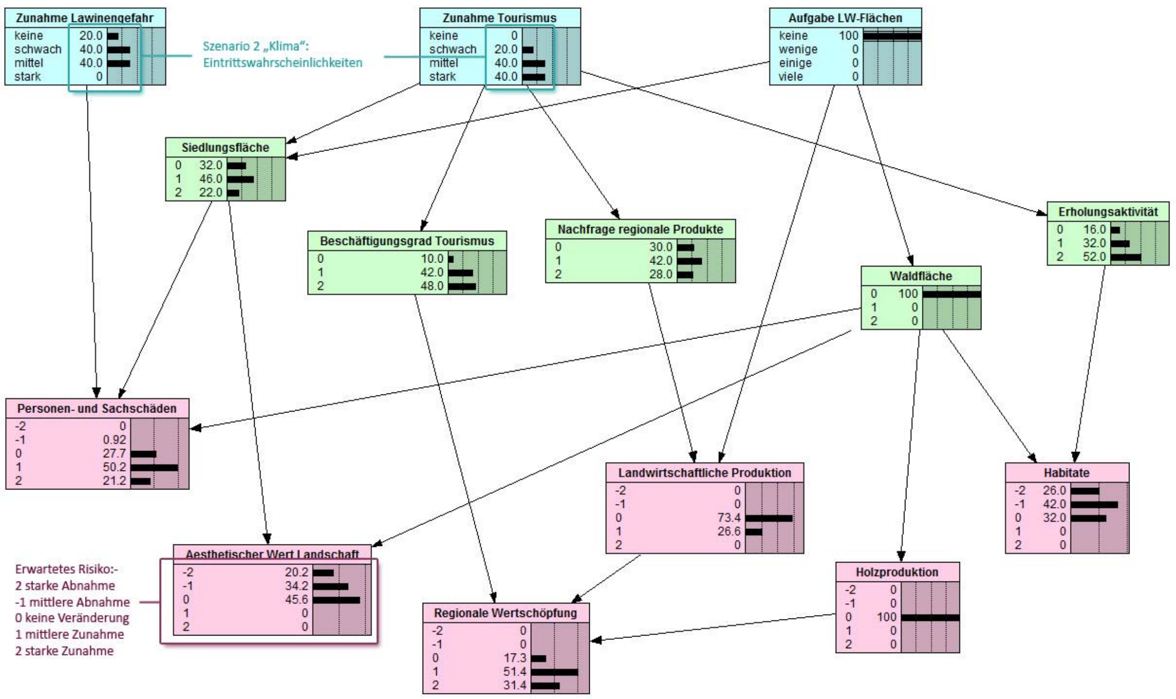


Abbildung 4. Risiken und Chancen (rosa) für die Region Davos unter einem gewählten Szenario (implementiert durch die Eintrittswahrscheinlichkeiten der blauen Gefahrenprozesse). Die Wahrscheinlichkeitsverteilungen der Variablen zeigen die Unsicherheiten der Analyse.

Die Resultate der Analyse können für einen Vergleich der Chancen und Risiken unter alternativen Szenarien auch aggregiert werden. Eine aggregierte Darstellung verdeutlicht das Ausmass der zu erwartenden Risiken und zeigt Handlungsfelder auf, die priorisiert werden müssen (Abbildung 5). Zeichnet sich z. B. eine Streichung der landwirtschaftlichen Subventionen ab (Szenario 1), ist nicht nur die landwirtschaftliche Produktion stark betroffen, sondern es besteht ein erhebliches Risiko, dass der ästhetische Wert der Landschaft Davos abnimmt. Um diesem Risiko entgegenzuwirken, könnte die öffentliche Hand vermehrt in Massnahmen zur Landschaftspflege investieren. Das vorliegende BN kann in einem weiteren Schritt auch mit ebensolchen Massnahmenvariablen, die politische Entscheidungen und daraus abgeleitete Massnahmen repräsentieren, erweitert werden. Die Resultate des ergänzten BN zeigen dann, wie mögliche Handlungsalternativen die Risikolandschaft im System in qualitativer Hinsicht verändern. Die Resultate einer Risikoanalyse mit BN ermöglichen Entscheidungsträgern also, Risiken und Chancen verschiedener Szenarien gegeneinander abzuwägen und mittels zielgerichteter Investitionen Chancen zu maximieren und Risiken zu minimieren.

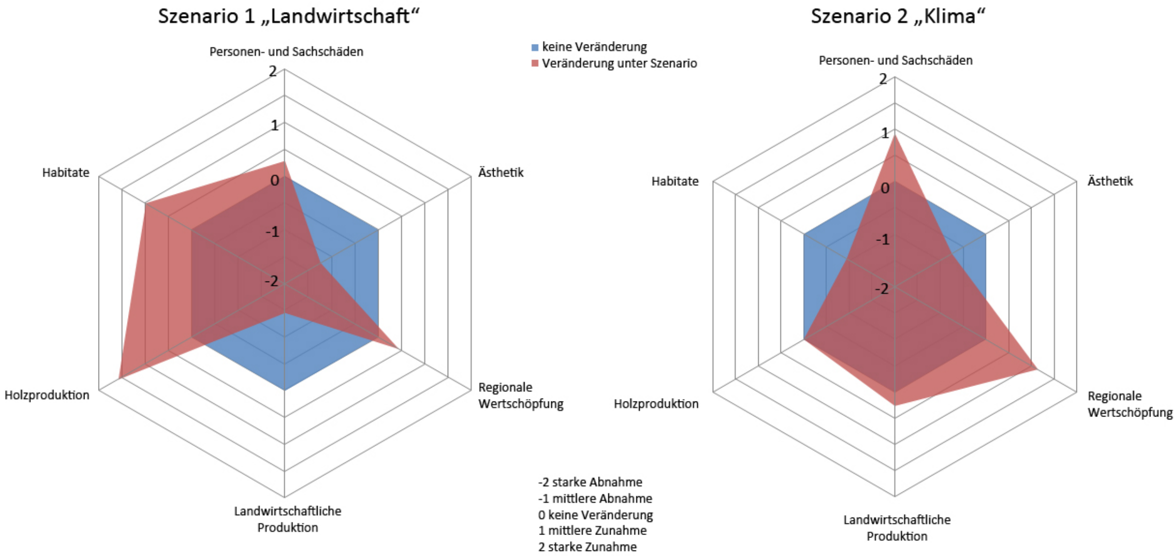


Abbildung 5. Vergleich des zu erwartenden Ausmasses von Risiken und Chancen für die Region Davos unter zwei Szenarien.

3.3. Räumlich explizite Anwendung von Bayesschen Netzwerken (BN) am Beispiel Davos

Für die konkrete Planung und Realisierung von Massnahmen sind möglichst präzise und detaillierte Entscheidungsgrundlagen nötig (BAFU et al., 2011). In der Landschaftsplanung haben sich mit der Einführung von Geoinformationssystemen neue Möglichkeiten für räumlich explizite Analysen eröffnet (Leitao & Anhern, 2002). Im vorliegenden Beispiel werden verschiedene raumrelevante Risiken quantifiziert, bewertet und kartiert, um räumlich differenzierte Handlungsoptionen in der Landnutzungsplanung aufzuzeigen und so die Priorisierung von Investitionen in Schutzbemühungen zu vereinfachen. Die im Rahmen der Vorstudie durchgeführte Analyse zeigt die räumlich expliziten Risiken in der Talschaft Davos, die auf Grund von Lawinengefährdung und Landnutzungsveränderungen bei fünf verschiedenen sozio-ökonomischen Szenarien zu erwarten sind. Ein umfassender wissenschaftlicher Bericht über die Einzelheiten der Methodik mit detaillierten Resultaten ist diesem Bericht angehängt (Anhang A). Die nachfolgenden Ausführungen sollen zusammenfassend aufzeigen, wie BN im räumlich expliziten Rahmen zur Abbildung einer integralen Risikolandschaft angewendet werden können.

(1) Systemdefinition: Für die räumlich explizite Analyse wurde die Landnutzung als steuernde Systemvariable, das heisst im Sinne der Systematik der Risikoanalyse als „Gefahr“ festgelegt. Sie wird einerseits durch politische Rahmenbedingungen und planerische Handlungen beeinflusst, so dass verschiedene Szenarien simuliert werden können. Andererseits verändern Änderungen in der Landnutzung die Vulnerabilität der Landschaft gegenüber Naturgefahren und ihr Potential, verschiedene Ökosystemleistungen[6] zur Verfügung zu stellen. Da Verluste von Ökosystemleistungen Risiken für die gesellschaftliche Wohlfahrt und für die Multifunktionalität einer Landschaft bedeuten, eignen sie sich als Indikatoren, um Risiken und Chancen für die Regionalentwicklung unter Landnutzungsveränderungen abzubilden. Folgende Ökosystemleistungen wurden als Zielvariablen gewählt:
(a) Landwirtschaftliche Produktion,
(b) Holzproduktion,
(c) CO_2-Speicherung und -Verminderung,
(d) Lawinenschutz und -Vorbeugung,

[6] Als Ökosystemleistungen werden die direkten und indirekten Beiträge von Ökosystemen zur gesellschaftlichen Wohlfahrt bezeichnet. Damit eignet sich das Konzept zur Kommunikation des Wertes von Ökosystemen (Farley, 2008).

(e) Erholung.
Zusätzlich wurden
(f) Personen- und Sachschäden durch Lawinen als Zielvariable festgelegt.
Um später Kosten und Nutzen von Handlungsalternativen abzuwägen, wurden ausserdem die wichtigsten Kosten für die Landnutzung und Landschaftspflege ermittelt:
(g) Produktionskosten in der Landwirtschaft,
(h) Produktionskosten in der Forstwirtschaft,
(i) Kosten für den Lawinenschutz.

(2) Systembild: Die Landnutzungsvariable wurde über die wirkenden Prozesse mit den Schadenspotentialen Ökosystemleistungen und Sach- und Personenschäden in Verbindung gebracht. Dabei wurden die Prozesse, die für die jeweiligen Leistungen relevant sind, in Variablen des BN transformiert (Abbildung 6). Der Einbezug von Experten half, die Prozesse so genau wie nötig, gleichzeitig aber möglichst vereinfacht abzubilden. Um die Vergleichbarkeit der einzelnen Risiken sicherzustellen, wurden ökonomische Bewertungsmethoden ins BN integriert (Abbildung 6, grüne Variablen). Sie versuchen, das Ausmass der Veränderung von Ökosystemleistungen in Geldeinheiten zu erfassen. Holzproduktion und landwirtschaftliche Produktion wurden anhand des Marktpreises bewertet, die CO_2-Speicherung anhand des Preises von CO_2-Äquivalenten und die Erholungsleistung mittels eines Reisekostenansatzes, das heisst anhand des Betrages, den Reisende zahlen, um in ein Erholungsgebiet zu gelangen. Die Lawinenschutzleistungen und die Personen- und Sachschäden wurden mit Hilfe von räumlich expliziten Häuserdaten in einer klassischen Risikoanalyse monetarisiert.

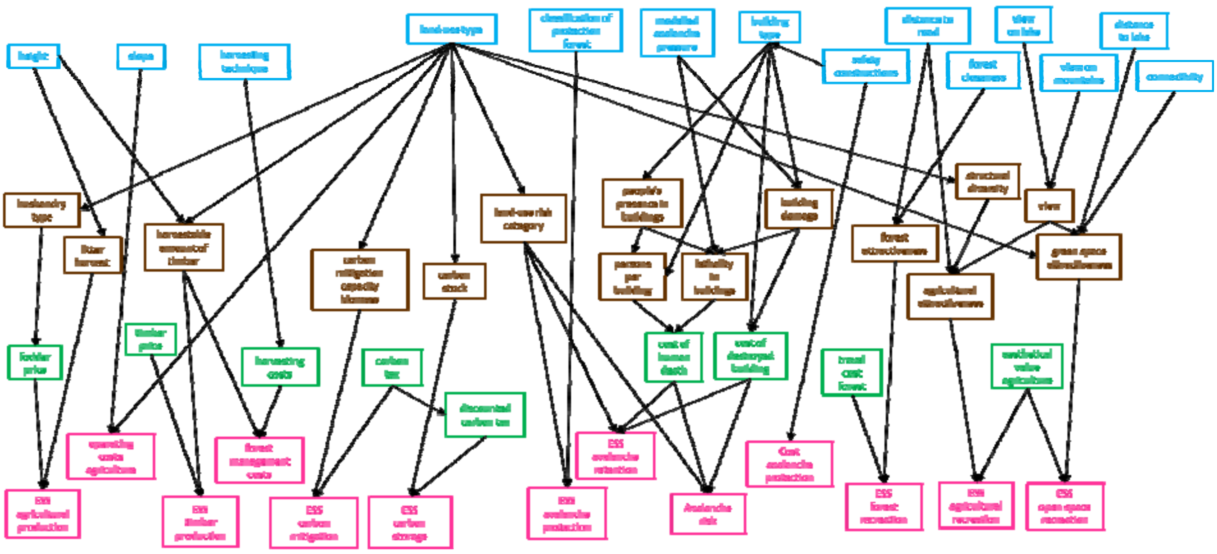


Abbildung 6. Bayessches Netzwerk für die Bewertung von Risiken (rosa) in der Landschaft Davos auf Grund von Landnutzungsänderungen. Blau dargestellt sind räumlich explizite Inputvariablen, braune Variablen repräsentieren Prozesse zur Quantifizierung und grüne Variablen zur Monetarisierung der Risiken.

(3) Gewichtung der Wirkungsbeziehungen: Die bedingten Wahrscheinlichkeitstabellen wurden basierend auf aktueller wissenschaftlicher Literatur ausgefüllt und teilweise mit Hilfe von Expertenwissen angepasst. Dabei wurden die mit den verschiedenen Prozessmodellen und Bewertungsmethoden verbundenen Unsicherheiten berücksichtigt (Details im Anhang A).

(4) Szenarien: Die Landnutzungsveränderungen und ihr Einfluss auf die Risikolandschaft Davos wurden anhand von fünf verschiedenen Szenarien für das Jahr 2021 modelliert. Die angewendeten Szenarien wurden basierend auf bereits existierenden regionalen Szenarien verschiedener Projekte entwickelt (z. B. Bebi et al., 2005; Grêt-Regamey et al., 2008; ARE GR, 2009; Mountland, 2011) und sind normativ, das heisst, regionale Investitionen und die Planungspolitik verfolgen bestimmte Ziele:
(a) „Null-Risiko-Toleranz" (Sach- und Personenschäden durch Naturgefahren werden nicht toleriert, Lawinenverbauungen werden errichtet),

(b) „Präventive Raumplanung“ (keine Siedlungserweiterung in Gefahrenzonen, Akzeptanz der bestehenden Risiken),
(c) „Maximierung der Ökosystemleistungen“ (Intensive Waldpflege und Subvention der Landwirtschaft als landschaftspflegender Sektor, Baustopp),
(d) „Grosser Sportanlass“ (Siedlungserweiterung, wenig Naturschutz),
(e) „Sanfter, nachhaltiger Tourismus“ (Wertschätzung und Pflege der Kulturlandschaft, gemässigte Siedlungserweiterung).
In einem separaten Landnutzungsmodell wurde für jedes Szenario und jede einzelne Rasterzelle berechnet, wie gross die Wahrscheinlichkeit für verschiedene Landnutzungen im Jahr 2021 ist (Abbildung 7). Diese Wahrscheinlichkeiten wurden dann im Modellierungsschritt ins BN eingespiesen.

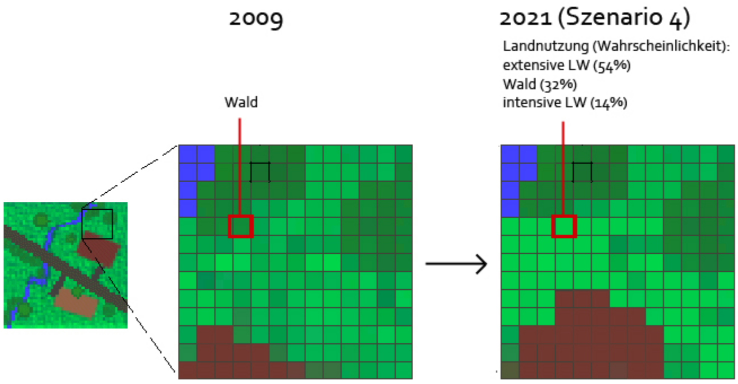


Abbildung 7. In einem Landnutzungsmodell wurden für jedes Szenario Wahrscheinlichkeiten der Landnutzungsveränderungen modelliert.

(5) Modellierung: In der räumlich expliziten Risikoanalyse wird das BN für jede Zelle einzeln modelliert (Abbildung 8).

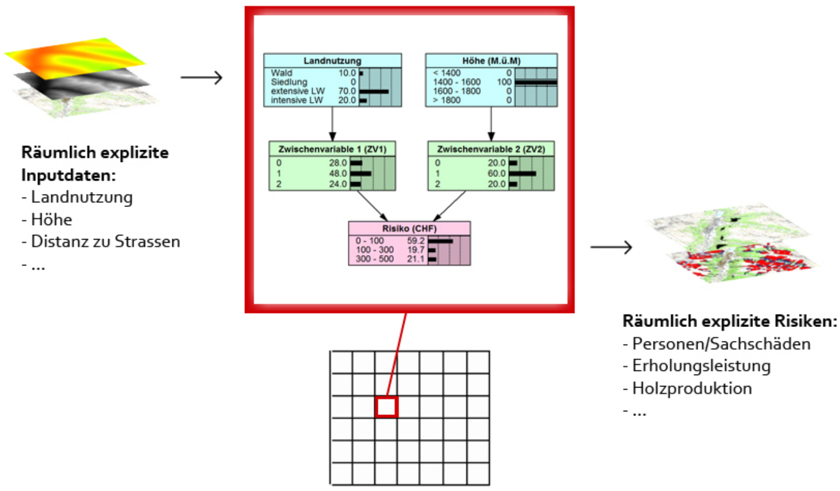


Abbildung 8. Räumlich explizite Modellierung von Risiken: das BN wird mit Hilfe von räumlichen Inputdaten in jeder Zelle berechnet.

Zur Darstellung in Karten werden die Erwartungswerte der verschiedenen Risiken basierend auf einer traditionellen Risiko-Gleichung berechnet:

In jeder Rasterzelle werden die Wahrscheinlichkeiten, mit welchen verschiedene Landnutzungstypen zukünftig auftreten, $P(LU_i)$, mit den jeweils verbundenen Schäden, Kosten oder Leistungen der entsprechenden Landnutzung, $C(LU_i)$, multipliziert und für jedes Risiko einzeln aufsummiert. Um die Unsicherheit zu illustrieren wird für jeden Wert die Standardabweichung berechnet.

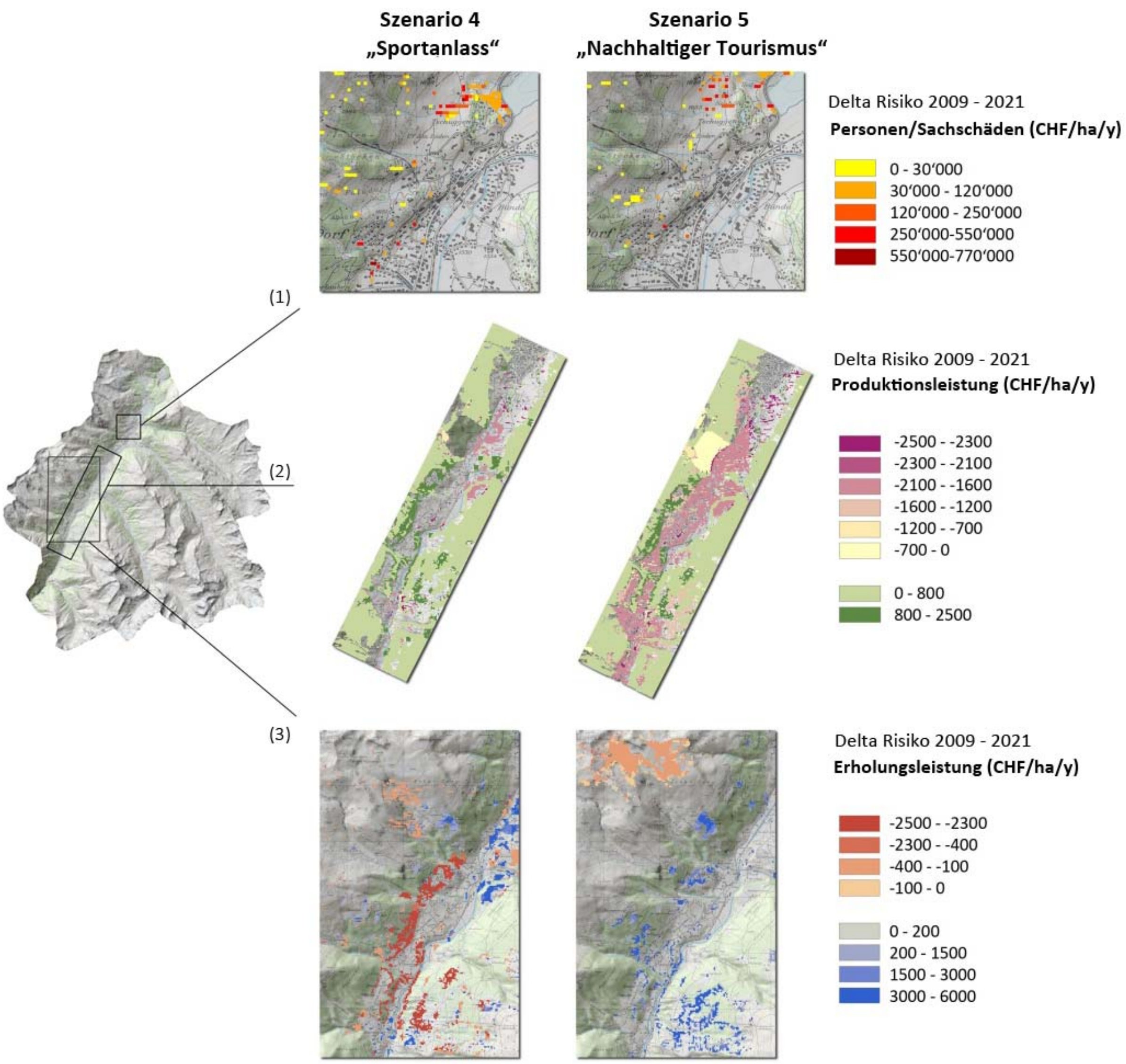


Abbildung 9. Räumlich explizite Auswirkungen von zwei alternativen Landnutzungsszenarien auf Personen-/Sachschäden durch Lawinen und in der Bereitstellung von Ökosystemleistungen. Die Kartenausschnitte zeigen, wo in der Region mit einer Zunahme von Risiken gerechnet werden muss.

Abbildung 9 zeigt eine kartographische Darstellung der Resultate zur Identifizierung und Lokalisierung von verschiedenen Risiken und Chancen, die sich auf Grund von zwei unterschiedlichen Szenarien ergeben. Die Lawinenrisiken nehmen vor allem am Dorfrand zu. Hier ist der Siedlungsdruck in beiden Szenarien am grössten. Im Szenario „Grosser Sportanlass“ sind die Lawinenrisiken höher, da zusätzliche touristische Infrastruktur und Sportlersiedlungen gebaut werden müssen (Tabelle 1). Abnahmen (Risiken) und Zunahmen (Chancen) von Ökosystemleistungen sind in beiden Entwicklungsoptionen vor allem im Talboden, ausserhalb des Dorfkerns sehr ausgeprägt. Während Landnutzungsveränderungen unter Annahme eines Sportevents zu höheren Produktionsleistungen führen, nehmen dieselben unter dem Szenario „Nachhaltiger Tourismus“ deutlich ab, da intensive Landwirtschaftsflächen zunehmend extensiviert werden. Durch die Extensivierung und die Förderung der regionalgerechten Bewirtschaftung steigt hingegen die Erholungsleistung im Talboden und in spezifischen Waldflächen. Die Karten zeigen in hoher Auflösung, welche Gebiete der Region Davos von Lawinen bedroht sind und das grösste Risiko hinsichtlich eines möglichen Verlustes an Ökosystemleistungen aufweisen.

Um die Nutzen und Kosten verschiedener Planungsalternativen zu vergleichen, können zusätzlich zu dem Ökosystemleistungen und erwarteten Lawinenschäden die jährlichen Kosten für das Landschaftsmanagement berechnet werden (Tabelle 1). Mit Ausnahme der einmaligen Investitionskosten in den Ausbau der Infrastruktur im Szenario „Sportanlass“ sind die laufenden Landmanagementkosten deutlich höher im Szenario „Nachhaltiger Tourismus“. Die Extensivierung der landwirtschaftlichen Produktion und die Pflege der Kulturlandschaft sind ausschlaggebend für die nötigen Investitionen. Der Vergleich von Szenarien verdeutlicht also, welche Risiken und Chancen zu welchen Kosten unter alternativen Planungsoptionen in einer Region gegeneinander abgewogen werden müssen. Die räumliche Darstellung in Karten kann Planern und Entscheidungsträgern helfen, Massnahmen zu priorisieren und den Ressourceneinsatz zur Prävention auf besonders risikoreiche Gebiete zu konzentrieren. Weitere Resultate und zusätzliche Darstellungsmöglichkeiten sind dem wissenschaftlichen Bericht zu entnehmen (Anhang A).

Tabelle 1. Erwartete Chancen (Zunahme von Ökosystemleistungen), Risiken (Verlust von Ökosystemleistungen und zu erwartende Lawinenschäden) sowie Landmanagementkosten in der Region Davos unter zwei Landnutzungsszenarien.

Szenario	Delta Lawinenschäden 2009 - 2021 (CHF/y) Ausschnitt 1 (Abbildung 9)	Delta Produktionsleistung 2009 - 2021 (CHF/y) Ausschnitt 2 (Abbildung 9)	Delta Erholungsleistung 2009 – 2021 (CHF/y) Ausschnitt 3 (Abbildung 9)	Delta Kosten 2009 – 2021 (CHF/y) Gesamte Landschaft Davos
Sportanlass	+ 14’800’000	+ 3’700’000 - 1’900’000	+ 3’100’000 - 5’200’000	+ 418‘000
Nachhaltiger Tourismus	+ 10’300’000	+2’800’000 - 9’800’000	+ 5’000’000 - 200’000	+ 18‘800‘000

4. Diskussion

Nur ein ganzheitliches Risikomanagement kann längerfristig sichern, dass finanzielle Mittel risikogerecht und nach Prioritäten geordnet eingesetzt und Massnahmen getroffen werden, die ökologisch verträglich, sozial gerecht und wirtschaftlich effizient sind. In der Schweiz sind erste Ansätze einer flächendeckenden, integralen Betrachtung aller Risiken auf Stufen der Gemeinden, von Regionen und Kantonen vorhanden (z. B. Greminger & Zischg, 2012; Greminger, 2012). Um das sektorenübergreifende Management aller Risikoarten zu etablieren, sind allerdings noch grosse Anstrengungen nötig. Diese Studie liefert einen Beitrag zur Weiterentwicklung der methodischen Grundlagen, die nötig sind, um verschiedene Risiken in einem festgelegten System (Raum) integral zu bewerten und zu vergleichen. Die erarbeitete Methode zur integralen Risikoanalyse, basierend auf Bayesschen Netzwerken (BN), wurde auf ihr Potential zur Unterstützung von strategischen partizipativen Entscheidungsprozessen getestet sowie in einem räumlich expliziten Rahmen umgesetzt. Ziel dieser Studie war es insbesondere zu prüfen, ob ein solch räumlich expliziter Ansatz für eine risikoorientierte Planung zielführend und umsetzbar ist und eine nachhaltige Regionalentwicklung unterstützen kann.

Die qualitative Bewertung von raumrelevanten Risiken mittels BN birgt ein vielfältiges Potential, risikoorientiertes Denken, Planen und Handeln zu fördern und strategische Entscheidungsprozesse zu unterstützen. Der frühe Einbezug unterschiedlicher Akteure in den Entwurf des Systembilds sichert die Erfassung aller relevanten Gefahren und Risiken, fördert den Wissensaustausch und Dialog zwischen Interessengruppen und Sektoren und motiviert Beteiligte zur gemeinsamen Problemlösungssuche. Die in allen Schritten des Prozesses notwendige Diskussion (Risikodialog) trägt zu einem tieferen Verständnis des Systems und seiner Sensitivitäten bei. Die BN-Umgebung bietet ideale Voraussetzungen dafür, das Risikokonzept sowie die Unsicherheiten der unterschiedlichen, auf Annahmen beruhenden Szenarien besser zu verstehen. Der Einfluss einer Veränderung der Gefahrenprozesse auf das Risikoausmass kann ebenso illustriert werden wie der Einfluss der gesteigerten Verletzlichkeit der Systemelemente (über eine veränderte Gewichtung der Wirkungsprozesse, respektive Veränderungen der bedingten Wahrscheinlichkeitstabellen). Das Verstehen der Vulnerabilität eines betrachteten Raumes ist dabei von besonderer Bedeutung, da die Verletzlichkeit von Landschaften und darin bereits vorhandenen Objekten durch die steigenden Nutzungskonflikte und die Verdichtung in zunehmendem Ausmasse die Risiken bestimmen (Greminger & Zischg, 2011). Die Resultate der Analyse mit BN zeigen auf, welche Risiken und Chancen unter verschiedenen Entwicklungsstrategien gegeneinander abgewogen werden müssen. Damit werden die vorhandenen Interessenkonflikte abgebildet, für die mit Hilfe des Risikodialogs Lösungen gesucht werden müssen. Zudem unterstützen Visualisierungen der Risikolandschaft die Diskussion über die Prioritätenfolge von und risikogerechte Investitionen in präventive Massnahmen. Ein solcher Entscheidungsprozess weist ein hohes Mass an Transparenz und Transdisziplinarität auf, was die Akzeptanz der priorisierten Handlungsfelder erheblich erhöhen kann.

Die vorgestellte Methodik eignet sich zum Einsatz auf allen politischen Ebenen, in Gemeinden, Regionen, Kantonen oder dem Bund. Der Aufwand der Risikoanalyse variiert mit dem Detailgrad des aufgestellten BN, der Anzahl der beteiligten Diskussionspartner und der berücksichtigten Gefahren und Risiken. Besonders zeitaufwändig ist die Gewichtung der Wirkungsbeziehungen im BN. Für jede Variable müssen die bedingten Wahrscheinlichkeitstabellen eingefüllt, verhandelt und ihre Wirkung auf die Risiken getestet werden. Da die Resultate sehr sensitiv auf die gewählten Wahrscheinlichkeitsverteilungen reagieren, empfehlen Celio et al. (2012) einen zusätzlichen Validierungsschritt, der die Robustheit des BN sowie das Vertrauen der Akteure in das Modell erhöht.

Risiken haben immer eine räumliche Komponente: zum Beispiel beschränken sich gravitative Naturgefahrenereignisse auf Berggebiete mit spezifischen topografischen Eigenschaften oder technische Risiken sind vermehrt in industriellen Gebieten anzutreffen. Die Übernutzung und Zersiedelung von Landschaften ist im Mittelland ausgeprägter als in den Alpen und Voralpen und stark von lokalen Standortfaktoren abhängig. In einer Region variieren Risiken also in ihrem Ausmass stark zwischen verschiedenen Gebieten und sind oft lokal konzentriert. Eine räumlich explizite Analyse, Bewertung und Darstellung der Risiken ist deswegen äusserst sinnvoll und angebracht. Insbesondere auch deshalb, weil ein hundertprozentiger Schutz vor allen Risiken auf Grund der begrenzten Mittel und des begrenzten Raumes nicht möglich ist und Restrisiken in gewissen Gebieten toleriert werden müssen (BAFU et al., 2010). Resultate dieser Studie zeigen, dass Risikokarten eine hervorragende Grundlage zur Förderung der nachhaltigen risikoorientierten Raumplanung bieten. Die räumlich explizite Darstellung kann helfen, Risikohotspots zu identifizieren, um so sicherzustellen, dass Investitionen der öffentlichen Hand am richtigen Ort und in kostenwirksame Massnahmen erfolgen. Insbesondere zeigt ein lokaler Vergleich von Risiken, Chancen und Kosten von Planungsstrategien, wo Massnahmen kosteneffizient sind und die grössten ökonomischen, sozialen und ökologischen Nutzen bringen. So kann sichergestellt werden, dass mit limitiertem Budget ein Maximum an Risikoreduktion erzielt und die Chancen einer nachhaltigen Raumentwicklung optimal gefördert werden können. Visualisierungen von verschiedenen Szenarien ermöglichen eine lokale Abwägung von Chancen und Risiken und unterstützen die Entwicklung von räumlich differenzierten Strategien und Massnahmen. Zusätzlich können Risikokarten das Bewusstsein der Bevölkerung und ihre Motivation, das integrale Risikomanagement zu fördern, erhöhen, weil sie die Betroffenheit der Bevölkerung explizit abbilden.

Die Vorstudie hat allerdings auch gezeigt, dass räumlich explizite Risikoanalysen mit BN mit einem grossen Zeitaufwand, fundiertem Expertenwissen und hohen Datenanforderungen verbunden sind. In der Fallstudienregion Davos sind dank zahlreicher abgeschlossener Forschungsprojekte Daten unterschiedlichster Art, z. B. partizipativ erarbeitete Szenarien der regionalen Entwicklung oder Lawinenmodellierungen, verfügbar. Viele der für die Risikoanalyse verwendeten Informationen existieren nur spezifisch für die Talschaft. Insbesondere räumliche Daten sind in grossen Teilen der Schweiz nicht flächendeckend erhoben. Das bedeutet, dass die Aufbereitung der Daten für Risikoanalysen in anderen Regionen sehr viel Zeit kostet und Erfahrung im Bereich der Geoinformation und Modellierung benötigt. Um repräsentative Analysen zu generieren, muss das Wissen verschiedenster Experten gebündelt und für das Erstellen des Systembilds sowie das Gewichten der Wirkungsbeziehungen genutzt werden. Diese Vorgehensweise fördert einerseits den Austausch und Lernprozess zwischen Wissenschaftlern und Akteuren, erfordert andererseits aber auch ein grosses Netzwerk an Kontakten, die Bereitschaft verschiedener Experten zur Mitwirkung und genügend Zeit für wiederholte Feedbackrunden.

5. Empfehlungen und Ausblick

Die im Rahmen dieser Studie entwickelte Methode, die mittels Bayesschen Netzwerken (BN) Risiken und Chancen von Planungsalternativen vergleicht und abbildet, ist ein erster Schritt in Richtung einer ganzheitlichen, risikoorientierten Raumplanung. Die Methode kann vielen der einleitend identifizierten Lücken in der Umsetzung des integralen Risikomanagements begegnen. Insbesondere fördern BN die Partizipation, den Wissenstransfer und den Risikodialog, integrieren Unsicherheiten und sind in ihrem Design flexibel, so dass neben Risiken von Naturgefahren auch sozio-ökonomische, technische und ökologische Risiken erhoben werden können. Dennoch haben die Erfahrungen aus dieser Vorstudie gezeigt, dass die Methode zur räumlich expliziten Analyse von Risiken und Chancen einer Region in ihrer derzeitigen Form noch nicht als praxistaugliches Instrument eingesetzt werden kann. Ein grosses Hindernis stellen fehlende oder nicht verfügbare flächendeckende räumlich explizite Daten dar.

Wir empfehlen deshalb, die Methode vorab auf strategischer Ebene zur risikoorientierten Entscheidungsfindung in Gemeinden, Regionen oder Kantonen einzusetzen. Zum Beispiel kann in Workshops mit Gemeinden ein Mindmap zur Risikolandschaft auf dem Gemeindegebiet erstellt werden. Das Wissen und die Erfahrung von unterschiedlichen Experten und Betroffenen fliessen dabei in die Erstellung eines Kausalitätsbaumes, den man in eine BN-Umgebung implementieren kann. Sowohl die pragmatische Darstellung in einem Mindmap als auch die Modellierung der Risikolandschaft in einem BN eignen sich als Diskussionsgrundlage zur Entwicklung einer gemeinsamen Strategie zur Reduktion von Risiken und zur Erhöhung von Chancen. Feedback von Workshopteilnehmern sollte zur Verbesserung des Ablaufs genützt werden und in einen Leitfaden zur Anwendung der Methodik in partizipativen Prozessen einfliessen. In einem weiteren Schritt empfiehlt sich die Integration der verfeinerten Methode in eine interaktive Plattform.

Eine solche Plattform zur Unterstützung der risikoorientierten Entscheidungsfindung auf strategischer Ebene könnte in einem weiteren Schritt und bei vorhandenen Datengrundlagen für räumlich explizite Anwendungen erweitert werden. Deswegen sollten gleichzeitig die Erhebung von fehlenden räumlichen Daten vorangetrieben sowie bestehende behördliche Schranken zu existierenden, aber nicht öffentlich verfügbaren Daten abgebaut werden. Nur so kann ein landesweites Mapping von Risiken auch in die Praxis umgesetzt werden und ein risikoorientiertes, nachhaltiges Landnutzungsmanagement gewährleisten.

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ANHANG A

Integrated spatially explicit risk assessment for prioritizing regional investments

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Abstract

The increasing scarcity of space, the growing vulnerability of the landscape and the densification of economic assets not only enhance conflicting uses of the landscape but also ecological, social, technical and natural hazard risks. Integrating all of these risks into management and planning decisions is most pressing for a sustainable regional development and the maintenance of a socially demanded security. Building upon existing tools and concepts for risk management that go beyond natural hazard assessment, we introduce a participatory framework for quantifying and valuing different risks in a spatially explicit matter and mapping associated trade-offs under different socio-economic scenarios accounting for related uncertainty. In a case study in Davos, we test our approach by assessing risks from future avalanche damages and in the flow of ecosystem services (ESS) related to a set of planning options and compare them to the landscape management costs under these alternative strategies. In a first step, the policy scenarios are translated into land-use changes by a transition-matrix based land-use model. In a second step, current and future spatial risks are mapped by a Bayesian network interlinked within a GIS platform. Such maps help (1) identifying and localizing different kind of risks, thus framing regional problems, (2) outlining the value of an ecosystem and its services to stakeholders, (3) comparing different risks, evaluating suitable policy options and targeting related measures, and (4) quantifying and communicating uncertainties in a spatially explicit manner. Set up as a pre-study, we extensively discuss limitations, preconditions and challenges related to our approach and outline its contribution to the advancement of methods for holistic risk-oriented planning methods in Switzerland.

Contents

1. Introduction

1.1. Risk-based planning

The natural and built environment and society's spatial demands are changing at an accelerating rate challenging traditional natural hazard and risk management practices and spatial planning instruments insufficiently adapted to such a dynamic context. The concentration of economic assets, an increased vulnerability of the landscape, society's insatiate demand for mobility and communication and global change have enhanced the extent of damages from natural hazards in the last years (PLANAT, 2003). Thus, the security of people, a fundamental human need and a basic requirement for a prosperous society is increasingly jeopardized. In addition, technical and socio-economic developments have altered and will substantially alter society's livelihood in future (BABS, 2010).

The concentration of risks in connection with the scarcity of space and limited resources has resulted in a fundamental shift in paradigm for dealing with natural hazards away from a reactive defense against these hazards triggered by catastrophic events towards a preventive holistic approach including risk mitigation and tolerating residual risks (PLANAT, 2003). Such a risk culture facilitates precautionary measures to reduce the dangers and consequences from natural hazards. At the same time, overall protection is no longer aimed at, but certain risks are consciously tolerated. In other words, within this culture security does not denote that no damage occurs, but that damages can be handled. In Switzerland, the institution of the national platform for natural hazards (PLANAT) in 1997 substantially reinforced the change in paradigm.

In order to push the establishment of a risk culture considering a broader risk portfolio, including technical and social risks, the national government has launched different programs and projects. *KATARISK* and the follow-up activity *Risks Switzerland* led by the Federal Office for Civil Protection (BABS) aim at: (1) establishing a comprehensive and flexible catalogue of different hazards, (2) systematically analyzing and documenting each hazard by a uniform dossier (3) comparing risks related to the hazards (probabilities of occurrence and impacts) under different scenarios and (4) deriving recommendations for an integral management of catastrophic events in Switzerland (BABS, 2003; BABS, 2010). Based on *KATARISK*, the BABS has published guidelines for hazard analysis and prevention at cantonal level (*KATAPLAN,* BABS, 2008).

The institution of PLANAT and these national institutional efforts initiated the development of different risk-based planning instruments and tools. Most of them solely deal with or primarily concentrate on natural hazard risks. For example, the concept of integral risk management coordinates the implementation of a broad catalogue of measures against natural hazards and comprehensive hazard maps established for built areas in most of the cantons are implemented in communal land-use planning. The tool *Econome* evaluates the cost-efficiency of technical measures and planned projects targeting economic risk reduction from natural hazards following a traditional risk analysis, where the monetary risk is calculated as the function of the probabilities of all potential events and the expected damages under these events (BAFU, 2007). *Riskplan* assesses a broader risk portfolio and draws on the newly developed method of “pragmatic risk management” that allows a systematic and transparent assessment of risks, the cost efficiency of measures and the identification and prioritization of planning alternatives. The tool allows integrating at the same time scientific data from statistics or models as well as knowledge from experts and stakeholders, thus lying fundamentals for integrative and participative planning (BAFU et al., 2010).

However, despite an existing knowledge base improvements in the implementation of integrated risk management in practice embedding a broader risk landscape are still required (Korck et al., 2011). Current planning practice is often still initiated by hazard events instead of being prospective and management-oriented and diverse stakeholders with differing priorities hamper a clear goal definition and the prioritization of measures. Cost-benefit analyses are predominantly performed at local scale despite the fact that interventions for risk reduction positively affect whole catchment areas or regions thus, benefits are often undervalued. Further obstacles to the implementation of integral risk management result from the lack of countrywide consistent data, uncertainties related to the spatial and temporal dimension of scenarios and missing participative and integrative concepts.

The discrepancy between conceptual knowledge and practical application calls for (a) planning instruments that make existing information available and institutionalize knowledge transfer between different planning disciplines, (b) further participation of relevant stakeholders and their level of awareness through a comprehensive risk dialogue, (c) integrating and communicating uncertainty related to natural hazard events and risk management, (d) assessing costs and benefits of planning alternatives or measures at different spatial and temporal scales, and (e) viewing threats of natural hazards in the context of socio-economic, technical and ecological risks (Korck et al., 2011). Such system-oriented decision-support tools could facilitate the implementation of risk-appropriate and cost-effective solutions and the prioritization of public investments while guaranteeing a targeted level of security. Acknowledging the increasing scarcity of space, the growing vulnerability of the landscape, the spatial densification of economic assets and related conflicting uses and in order to contribute towards an advancement of existing risk-oriented decision-support tools, the aim of this study is to pack the fundamental ideas from existing instruments such as *Riskplan* into a spatially explicit approach.

The establishment of an integrative risk management including and balancing natural hazard, socio-economic, technical and environmental risks in Switzerland could further a sustainable planning practice that includes all three dimensions of sustainability equally. While being comprehensive, such an integrative approach helps prioritizing investments and measures by comparing different risks and assessing trade-offs at different spatial scales. Participation in combination with a conscious advancement of a risk dialogue supports the risk awareness within society, the acceptance of measures, the ability to deal with and balance risk and thus the identification of socially demanded levels of security and the three sustainability criteria. Since natural, technical and societal hazards are changing continuously and financial resources for damage prevention are limited, a 100% level of security cannot be reached. Risk management helps evaluating which security can be sustainably guaranteed at which price.

1.2. Research questions

Regarding natural hazard management, Switzerland plays a pioneering role in the international context and serves as a best practice example across Europe. While first efforts towards an integrative planning and management of landscapes and regions and risks therein have been made, it is most pressing to operationalize conceptual ideas and to design decision support tools that assess natural hazard risks in the context of other prevailing risks. Only if such tools are understood, used and discussed by decision-makers in transdisciplinary processes, a risk culture can be anchored within the planning practice and attitude of society. Building upon existing methods, concepts and data, e.g. from the project *AdaptAlp* (Korck et al., 2011) or from the tool *Riskplan* (BAFU et al., 2011) the aim of this study is to contribute towards an advancement of integrative risk-oriented decision support tools in Switzerland by developing a spatially explicit approach for quantifying, valuing and mapping different spatial risks like those from natural and technical hazards or ecological risks for prioritizing regional investments. In this pre-study, we sketch a methodology for mapping risks from natural hazards and ecological risks under different socio-economic scenarios and test it in the case study region Davos. The framework is set up in a flexible way allowing to integrate other risks, e.g. from technical hazards in a later step. Accounting for uncertainties in future land-use changes related to five alternative regional development options the maps can make risk trade-offs evident allowing stakeholders to compare different investment policies and target their financial resources. The preliminary results help evaluating the approach regarding its suitability for aiding spatial planning decisions and formulating recommendations for the establishment of a generic instrument.

This study will thus specifically address the following overarching research questions:

- Does spatially explicit risk-oriented planning support sustainable development of a region?
- How does our approach contribute to an integrative risk management in Switzerland?
- Which limits and shortcomings can we identify in the approach?

The report is structured into three parts: In Chapter 2 we introduce the framework including a description of the case study, the different scenarios and the specific models. We then present modeling results and different maps for outlining the potential applications of the method (Chapter 3). In a last step we discuss the methodology regarding its strengths and weaknesses and in the context of the research questions, evaluate the potential for improvement and outline further research questions and fields of action (Chapter 4 and 5).

2. Methodology

2.1. Overall framework

We apply a risk approach that allows for a spatially explicit assessment of risks from natural hazards and changes in the provision of ecosystem services (ESS) based on the aerial statistics of Switzerland (Figure 1). The idea is that different land uses have different vulnerability to natural hazards and different potentials to provide ESS defined as goods and services provided by the ecosystem that are useful to people. The concept of ESS is increasingly used as a support for natural resource management decisions and, bridging human welfare and the natural environment, is suitable for communicating the value of ecosystems to stakeholders (Farley, 2008; Daily et al., 2009; Sutton and Constanza, 2002). Moreover, the ability to supply various ESS characterizes resilient multifunctional landscapes, thus, major losses in ESS denote ecological risks that can be compared to risks from natural hazards.

In a first step, we model land-use change under different socio-economic scenarios reflecting planning and investment options based on transition matrixes of past land-use changes (Chapter 2.3). As an output of this module we get probabilities of different future land-use types in each grid cell (Figure 1). In a second step, we map the potential damages from avalanches, the provision of different ESS and the investment and management costs related to the planning scenarios now and in future by a Bayesian network (BN) linked within a Geographic Information System (GIS) platform (Chapter 2.4). A BN is a probabilistic graphical model used to simulate systems characterized by some degree of uncertainty caused by imperfect understanding or incomplete knowledge of the system dynamics. The network pictures how variables interact with each other and assesses the state of target variables and associated uncertainty based on these causal relationships (see Figure 3, Chapter 2.4). In our case study, the BN propagates the probabilities of different land-use changes and calculates the related potential avalanche damage, ESS and costs by a traditional risk equation where risk R is defined as the function of the probabilities $P(A_i)$ of all potential events A_i and the expected consequences under these events $C(A_i)$ (e.g. Einstein, 1988):

$$R = \sum_i P(A_i) \cdot C(A_i) \quad (1)$$

Here, risk corresponds to the sum of all probabilities of occurrence of a particular land use $P(LU_i)$ and the consequences in the potential avalanche damage $AD(LU_i)$, in the flow of ESS $ESS(LU_i)$ and in the investment and management costs $Cost(LU_i)$ given this land use (see Figure 1). A small number of experts is integrated into scenario development (module 1) and the design of the BN (module 2) allowing for testing the participative potential of the method.

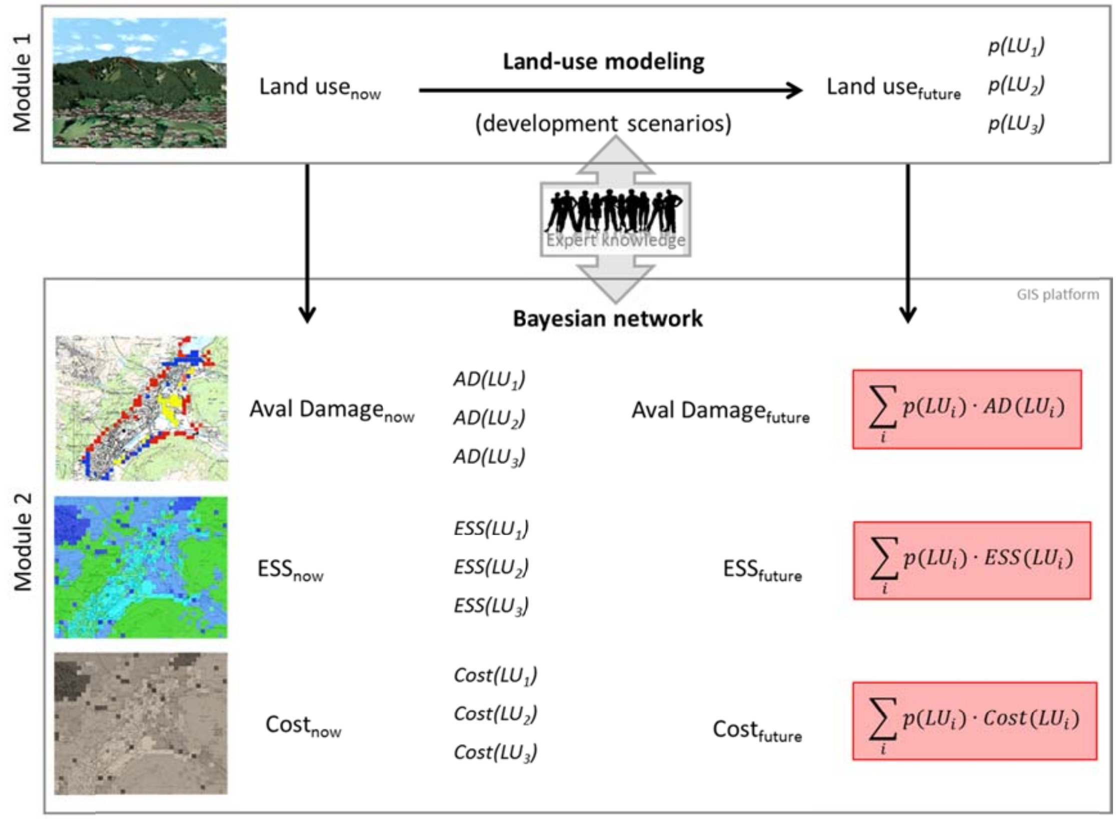

Figure 1. Risk approach for mapping risks of avalanche damages, in the flow of ecosystem services (ESS) and of investment and management costs under socio-economic scenarios.

2.2. Case study region

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 (Figure 2). 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. While 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. The farming activities in the region have constantly decreased as of the end of the 19th century, while the forest has gradually expanded, currently occupying an area of 22% of the total landscape. Most of the 90 farms in the area obtain a secondary income from tourism and around 80% of the resident population works in tourism-dependent sectors. Davos accommodates different sanatoriums, is location of international congresses and conferences (e.g. the World Economic Forum) and offers around 24'000 beds to visitors (5'200 beds in hotels and pensions, 16'100 in holiday flats or private rooms, 2'200 in group accommodations and 550 in hospitals or sanatoriums (Holthausen et al., 2011)). Despite being known as a famous wellness town for decades and a potential growing interest in the popular skiing area due to snow security under expected increase of temperature, future growth of settlement area for accommodation of touristic infrastructure has recently been restricted by the accepted initiative on secondary residences that foresees to limit the contingent of secondary residences in a municipality to 20% of all dwellings.

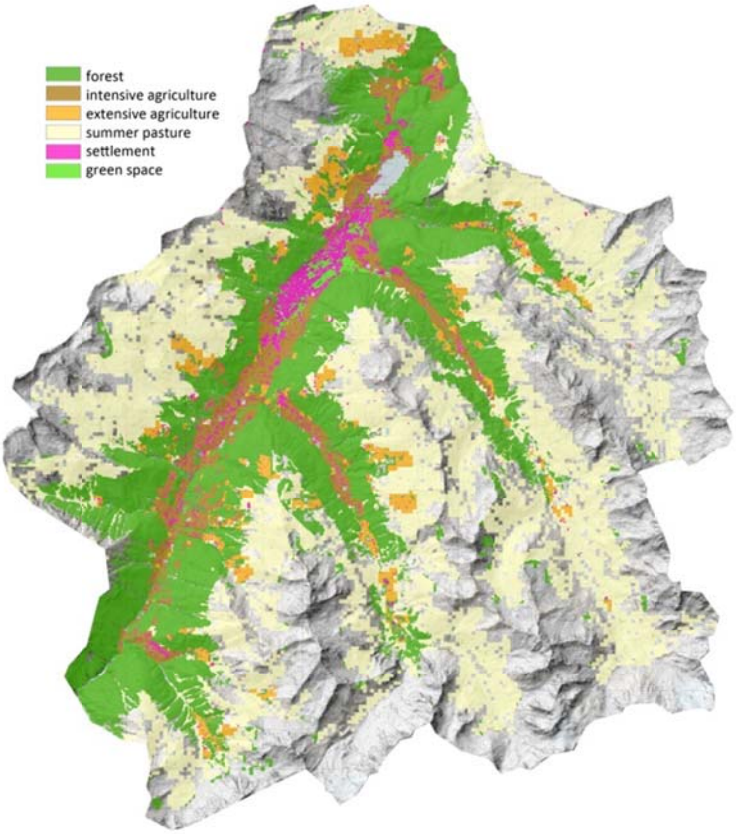

Figure 2. Map of the case study region Davos showing the land-use types in 2009.

2.3. Land-use modeling

In order to generate and analyze future land-use scenarios, it is first necessary to model the probability of land-use change based on historical data. To this end, we use data sets of land-use change and their determinants collected in two time periods: 1985 and 1997. Maps of land use are obtained from the aerial statistics of Switzerland at a 100m resolution. In order to focus the analysis on the most important land use-types in the study area, we aggregate and reclassify the original 74 different land-use categories into the following eight categories: forest, intensive agriculture, extensive agriculture, summer pasture, settlement area, open green space, water bodies and unproductive area, at a resolution of 25m. We perform this land use reclassification based on other spatially explicit data sets, such as the forest border, the cadastral map of the community or past pixel maps of the region. Finally, we use a multilogistic regression technique to derive the land-use probabilities for each grid-cell with a resolution of 25m. Variables used in the logit function are given in Table 1. This regression technique allows the estimation of land-use conversion probabilities for multiple land-use types. The land-use model labels each grid cell with an expected land-use type and a cell-specific so called transition probability matrix that informs on how likely a cell converts to the different land-use types considered. Extrapolating observed past land-use change into the future forecasts land use change under the business as usual scenario. In order to generate scenario-specific transition probability matrices, we re-run the regression based on land-use constraints defined by stakeholders for each scenario in the year 2021.

Table 1. Variables of the logit function.

Variable	Data source
Land-use change	Aerial statistics (swisstopo)
Neighborhood composition	Aerial statistics (swisstopo)
Distance to city center	Vector 25 (swisstopo)
Distance to lake	Vector 25 (swisstopo)
Distance to train station	Vector 25 (swisstopo)
Distance to roads and paths	Vector 25 (swisstopo)
Distance to major roads	Vector 25 (swisstopo)
Distance to skiing facilities	Vector 25 (swisstopo)
Yearly precipitation	Norm values (MeteoSchweiz)
Average duration of sunshine	Norm values (MeteoSchweiz)
Temperature	Norm values (MeteoSchweiz)
Elevation	Digital elevation model (swisstopo)
Slope	Digital elevation model (swisstopo)
Soil type	Soil capability map (BWL)
View on summit	SwissNames (swisstopo)
Visibility of lakes	Vector 25 (swisstopo)
Agricultural subsidies	Calculated based on information of BWL

2.3.1. Scenarios

Scenarios are developed for the year 2021, a medium time horizon which is sufficiently short term that climate change effects would not need to be explored yet and sufficiently long term that it allows enough time for some ecological and landscape changes to become visible, while it is still in the life span of most stakeholders and relevant for current long-term planning and policy decisions (Solvia et al., 2008). With the exception of the business as usual scenario, the scenarios developed can be regarded as rather 'extreme' as they are understood as imaginative pictures of potential futures rather than prognoses or realistic forecasts (Penker and Wytrzens, 2005). Scenarios are derived by combining national (e.g. MOUNTLAND, 2011; Bolliger et al., 2007), regional (e.g. ARE GR, 2009) and local (e.g. Grêt-Regamey et al., 2008; Holthausen et al., 2011; Bebi et al., 2005) existing scenarios and discussing and adjusting them with experts. The scenarios elaborated in this study are normative scenarios, in that regional investments and planning policy pursue specific goals. Resulting constraints for the land-use model for each scenario are summarized in Table 2.

Table 2. Total area of land-use types in 1985, 1997 and 2009 and under different scenarios. The bold numbers indicate the extent of those land-use types that have been set as modeling output goals in the normative scenarios.

	1985 [ha]	1997 [ha]	2009 [ha]	2021 [ha]					
Land-use				BAU	Zero risk toleranc e	Preventive planning	ESS max	Sport event	Soft touris m
Forest	4821	5591	5975	699	6907	6973	7006	**6325**	6972
Intensive	1122	1029	1017	0	1001	937	**467**	**1233**	**637**
agriculture	970	889	741	994	613	718	**1153**	**516**	**1014**
Extensive	7735	7384	7130	626	6907	6804	6805	7035	6804
agriculture	439	463	485	6891	**497**	**498 (spat. expl.)**	**485**	**506**	**497**
Summer pasture	89	90	111	508	112	110	119	105	**115**
Settlement	193	180	180	128	180	180	180	180	180
Open green space	1006	9625	9798	180	9220	9217	9223	9539	9218
Water bodies	7			9120					
Unproductive areas									

Business as Usual (BAU)

Key structural, policy and socio-economic trends and related trends in land-use changes will continue into the future as observed for the recent past. Decreasing market interventions will lead to more farm amalgamations, a moderate increase in abandoned marginal land and slightly lower agricultural product prices gradually approaching EU-level (Bolliger et al., 2007; Grêt-Regamey et al., 2008). Forest management practice focuses on small scaled intervention in order to maintain a sustainable protection against natural hazards and forest growth exceeds harvest (Brang et al., 2006). The settlement area continues growing predominantly in Davos Platz and Dorf due to increasing touristic visits and a stable resident population profiting of work in tourism-related sectors (Holthausen et al., 2011). The concentration and expansion of economic assets results in an increase of risk from natural hazards. Despite the concentration of population and infrastructure in the village center the pressure on the landscape and on agricultural areas at the border of settlements and accordingly on related ESS continuously grows (ARE GR, 2009).

Scenario 1: Zero risk tolerance

The public authorities of Davos are following a zero risk tolerance policy investing in technical measures to reduce the avalanche risk in the valley to zero. Due to costly technical constructions, this scenario is associated with high investment and management costs. Land-use change in agricultural areas is assumed as in the business as usual scenario. Due to the implementation of the initiative on restricted secondary residences, the growth of settlement is restricted (half growth rate of BAU).

Scenario 2: Preventive spatial planning

Being aware of the prevalent threats from natural hazards the authorities support preventive land-use planning and biological measures for natural disaster reduction. Forest growth is furthered above existing endangered dwellings that have been erected before the building ban in hazard zones has been implemented. To prevent from any increase in regional damage potential, spatial planning is very restrictive in all danger zones, with no development of settlements in neither red (high risk) or blue (medium risk) zones (Fuchs et al., 2004). Due to the implementation of the initiative on restricted secondary residences, the growth of settlement is restricted (as in scenario 1, but spatially explicitly). In contrast to a zero risk policy, in such a planning scenario residual risks from avalanches are tolerated but minimized.

Scenario 3: Ecosystem services maximization

Society and government subsidizes conservation and extensive and sustainable forms of agriculture. Conservation outweighs production of wood and food products. Forest area grows continuously and management focuses on the provision of a multitude of services. Ecological direct payments tied to tight agricultural regulations and contributions for individual conservation contracts are increased. Agriculture continues to be an important form of land management, but it is regarded primarily as a tool of conservation management rather than of production (Solvia et al., 2008). Land is increasingly managed by farmers focusing on the provision of ESS rather than by traditional farmers. Growth of settlement and touristic expansion is kept to a minimum. This scenario is related to an increase of the value of diverse ESS while risks from natural hazards are tolerated. However, since no additional buildings are constructed, damage potential and correspondingly the regional risk is not growing further.

Scenario 4: Large sport event

Davos is elected as the scene of Winter Olympic Games in 2022. Settlement area grows within and outside the village centers, since new apartments for athletes need to be established, and touristic infrastructure is utilized to its capacity maximum (Bebi et al., 2005). In this scenario, the village is growing at the expense of agricultural areas in the valley bottom. Environmental awareness focuses on technical solutions and efforts in nature conservation are reduced (MOUNTLAND, 2011). Agriculture is intensified while prices of agricultural products are low. Forest management practice focuses on timber harvest which is used to support local construction companies for building work. Associated with these land-use changes is a decrease of the value of ESS provided by the landscape.

Scenario 5: Soft sustainable tourism

Regional authorities invest in local solutions to economic, social and environmental sustainability and promote local identity while furthering a green tourism culture (MOUNTLAND, 2011). Tourism becomes more regional rooted and spatial planning policy is rather restrictive, thus, settlement areas expand only moderately while recreational green space within the town is maintained. Green production is supported and ecological direct payments and income from conservation contracts are higher since society increasingly demands semi-natural landscapes (Bolliger et al., 2007). Efforts in nature conservation are extended and prices for agricultural and timber products increase while mainly regionally produced goods are consumed. Thus, ESS in agricultural systems as well as on green areas within the village gain in value while risks from natural hazards are tolerated.

2.4. Ecosystem services quantification and valuation models

We embed the quantification and valuation of potential avalanche damages and of different ESS and related management costs into a Bayesian network (BN). In the BN, the variables of the system are represented by nodes characterized by different states and related probabilities and connected through arcs showing causal relationships among these variables. The model propagates the uncertainties associated with the future land-use change and other spatially-explicit input variables within the network and fills the final nodes with probabilistic distributions. Thus, BN have the advantages that (1) they account for uncertainty allowing to link them within a risk analysis framework, (2) they picture the explicit relationships between the variables of the model, thus, results can be presented to stakeholders in a concise matter, (3) quantitative data and expert knowledge can be taken into account simultaneously allowing for participative planning processes. Figure 3 illustrates the BN representing the causal relations among the factors that influence the risk of avalanche damage, in the flow of ESS and in management costs in our case study. Part of the network and specific nodes have been discussed with experts (as indicated in Figure 3) in order to evaluate the potential of integrating stakeholders into the process of modeling. Details on the states of the nodes are given in Table 3. We quantify the provision of selected ESS by state-of-the art GIS-based process models and assign monetary units to the the quantified services by using suitable and ESS-specific valuation methods (Chapter 2.4.1 – 2.4.4).

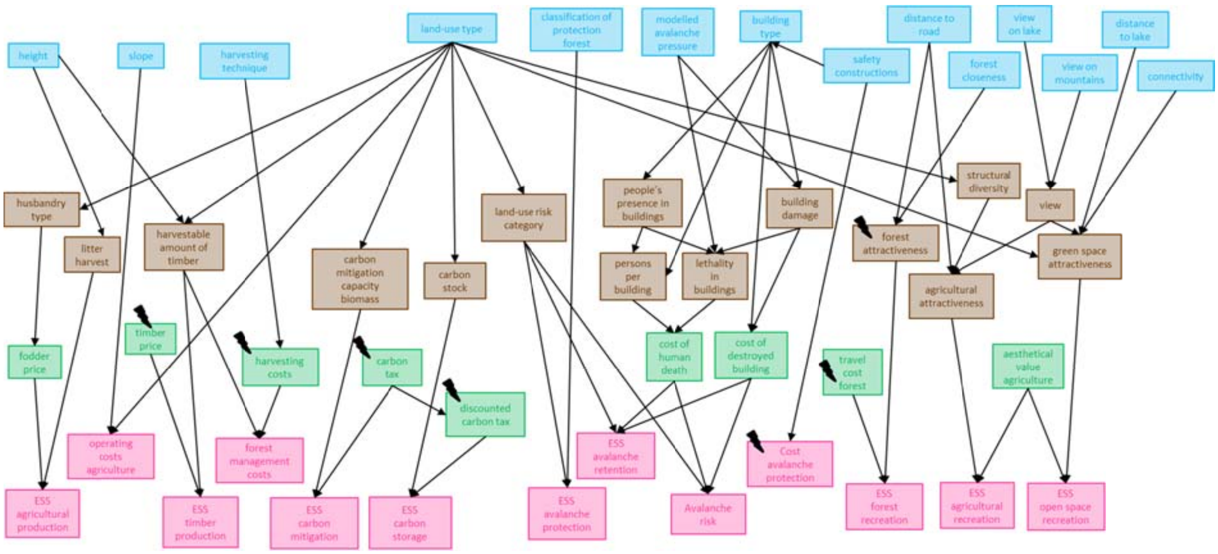

Figure 3. Bayesian network of the valuation of ecosystem services (ESS), the avalanche risk and management costs in Davos. The blue nodes are spatially explicit input variables, the brown and green nodes are variables of the quantification and valuation models, respectively, and the pink nodes are the utilities in terms of changes of services, costs and risks. Nodes tagged with a black blizzard integrate stakeholder knowledge.

Table 3. States of the Bayesian network nodes, organized into the categories input nodes, nodes representing quantification procedures and nodes representing valuation procedures.

Node	# discrete states of node	Description of states	Source of probability distribution
Input nodes			
Height	4	< 1400, 1400-1600, 1600-1800, >1800 [m]	Digital elevation model (DEM25, Swiss Federal Office of Topography)
Slope	5	<18, 18-25, 25-35, 35-50. 50-80 [°]	Digital elevation model (DEM25, Swiss Federal Office of Topography)
Harvesting technique	4	From ground, mobile cable way, conventional cable way, helicopter	Bont, 2009
Land-use type	7	Forest, intensive agriculture, extensive agriculture, summer pasture, settlement, open green space, unproductive areas	Aerial statistics (swisstopo), predicted spatially explicitly by land-use model described in Chapter 2.3
Protection forest classification	9	No, marginal, very small, small, medium, high, very high, extremely high, highest damages	Grêt-Regamey et al. (in review)
Modeled pressure	6	0, > 0 and <= 3, > 3 and < 10, > 10 and < 20, > 20 and < 30, > 30 [kPa]	Calculated with RAMMS (Christen et al., 2011)
Building type	5	Agricultural buildings, one/multiple family houses, public buildings, industrial buildings, hotels + restaurants	Hard labeling based on location of buildings from Communal cadastral register of Davos (unpublished data)
Protective measures	2	Yes, no	Geodata from the Office of Forest and Natural Hazards GR
Distance to road	4	<30, 30-100, 100-200, >200 [m]	Vector 25 (swisstopo)
Forest closeness within 2.5km	4	0-25, 25-50, 50-75, 75-100 [%]	Calculated based on land-use data
View on lake	3	0, <50, >50 [number of visible shorelines]	Calculated based on land-use data and vector25 (swisstopo)
View on mountains	4	<10, 10-20, 20-30, >30 [number of visible summits]	Calculated based on land-use data and vector25 (swisstopo)
Distance to lake	4	<50, 50-100, 100-1000, >1000	Vector 25(swisstopo)
Connectivity	2	Isolated, connected	Calculated based on land-use data
Nodes representing quantification procedures			
Husbandry type	4	Intensive, extensive, summer pasture, none	Based on land-use type (intermediate node)
Litter harvest	11	0 – 79 [100kg/ha/y]	AGRIDEA Lindau, 2012
Harvestable amount of timber	6	0 – 42 [CHF/100kg]	WSL, 2010
Carbon stock	8	0 – 843 [tCO_2/ha]	BAFU, 2011
Carbon mitigation capacity biomass	4	0 – 6.2 [tCO_2/ha]	BAFU, 2011
People's presence in buildings	2	Yes, no	Presence "yes" = T*D/24*7 (Borter, 1999, p.64), where T is average presence time in hours per day, D is average presence time in days per week
Persons per building	9	0 – 80	Mean based on Wilhelm (1997), variance proportional to mean (normal distributed variance)
Lethality in buildings	2	Death, not death	Barbolini et al. (2004, Figure 5), for the category "some damage": assumed 50% lethality of "total damage"
Building damage	3	Yes, some, no	For one-family and multiple-family houses: Barbolini et al. (2004, Figure 4), otherwise Borter (1999, p. 125), added state "some damage" (50% of damage = "yes")
Land-use risk category	3	At avalanche risk, avalanche risk retention, avalanche protection	Based on land-use type (intermediate node)
Forest attractiveness	5	None, low, medium, high, very high	Assumed based on Brändli and Ulmer (1999) and Bernasconi and Schroff (2003)
Structural diversity	3	None, low, high	Based on land-use type (intermediate node)
View	4	Low, medium, high, very high	Based on view lake/mountains

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Agricultural attractiveness	5	None, low, medium, high, very high	Assumed based on Grêt-Regamey et al. (2012)
Open space attractiveness	5	None, low medium, high, very high	Assumed
Nodes representing valuation procedures			
Roughage price	6	0 - 42 [CHF/100kg]	SBV, 2012
Timber price	8	0 – 170 [CHF/m^3]	Estimated by regional and local foresters
Operating costs agriculture	8	0 – 7200 [CHF/ha]	Grêt-Regamey et al., 2012
Carbon tax	8	0 – 250 [CHF/tCO2]	Estimated by environmental economists
Discounted carbon tax	8	0 – 8.9 [CHF/tCO2]	Based on carbon tax
Harvesting cost	4	90 – 160 [CHF/m^3]	Estimated by local foresters
Cost of human death	9	1 – 400'000'000 [CHF]	Life Quality Index approach according to Merz et al. (1995)
Cost of destroyed building	13	0 – 144'000'000 [CHF]	Communal cadastral register Davos (unpublished data), for the category "some damage" assumed 50% cost of "total damage"
Travel cost forest	7	0 – 12'000 [CHF]	Estimated by scientists working with forest ESS
Aesthetical value agriculture	6	0 – 1000 [CHF]	Grêt-Regamey et al. (2012)

2.4.1. Production services

Production services are relevant for the land-use categories forest, extensive and intensive agriculture and to a smaller degree for summer pastures.

Agricultural litter production depends primarily on the husbandry type and on the altitude of the farmlands (AGRIDEA Lindau, 2012). In Davos, there are no acres, all fields are managed as intensive or extensive pastures or, at higher elevations, as summer pastures with cattle grazing during summer time. The litter is either cut as hay or directly grazed by the cattle. While additional factors (e.g. exposition, dryness in summer, rain regime over the year, soil composition, …) also influence the biomass production, we did not include them in our model due to temporal variability and associated lack of spatially explicit data. We base our model on averaged data collected over several years in the Wirz Handbuch for agriculture: plants and animals (AGRIDEA Lindau, 2012). The uncertainty included in the amount of litter harvest from intensive and extensive fields results from incomplete knowledge on whether single pastures are cut (higher harvest) or grazed (lower harvest, Table 4). Values of yearly fodder production and consumption on summer pastures are based on the assumption, that cattle stay on alps during four months and farmers do not cut the meadows.

Table 4. Conditional probabilities for litter harvest depending on husbandry type and elevation.

		Probability Litter harvest (100kg/ha/y)									
Husbandry type	Height (masl)	3	5	10	16	26	32	41	52	62	79
Intensive	< 1400	0	0	0	0	0	0	0	0	**0.5**	**0.5**
	1400-1600	0	0	0	0	0	0	0	**0.5**	0	**0.5**
	1600-1800	0	0	0	0	0	0	**0.5**	0	**0.5**	0
	>1800	0	0	0	0	**0.5**	0	0	**0.5**	0	0
Extensive	< 1400	0	0	0	**0.5**	0	0	**0.5**	0	0	0
	1400-1600	0	0	0	**0.5**	0	**0.5**	0	0	0	0
	1600-1800	0	0	**0.5**	0	**0.5**	0	0	0	0	0
	>1800	0	0	**0.**	**0.**	0	0	0	0	0	0

				5	5						
Summer pasture	< 1400	0	**1**	0	0	0	0	0	0	0	0
	1400-1600	0	**1**	0	0	0	0	0	0	0	0
	1600-1800	**1**	0	0	0	0	0	0	0	0	0
	>1800	**1**	0	0	0	0	0	0	0	0	0

In yearly surveys, the Swiss Association of Farmers (SBV) collects market prices for different fodder products (SBV, 2012). We monetize the production service of intensive pastures by modeling a normal distribution over market prices reported for normal hay, while prices for Ecohay are used to model the probability distribution of the value of fodder production on extensive and summer pastures (Table 5).

Table 5. Probability distributions for market prices of roughage harvested from different pasture types.

	Probability	
Roughage price (CHF/100kg)	Intensive pastures	Extensive and summer pastures
22	0	**0.18**
27	0	**0.65**
32	**0.25**	**0.17**
37	**0.45**	0
42	**0.30**	0

We quantify timber production based on the observed yearly amount of harvested timber between 1995 and 2006 in the canton Grison (WSL, 2010), thus accounting for uncertainty related to annual fluctuations. The harvestable amount of timber is dependent on and therefore modeled for different altitudinal belts as a normal distribution over the yearly harvest in these belts as reported between 1995 and 2006 (Table 6).

Table 6. Conditional probabilities for timber harvest from forest at different altitudes.

	Probability Harvestable amount of timber (m3/ha/y)							
Height (masl)	0.5	0.7	0.9	2.2	2.7	3.1	3.8	4.6
< 1400	0	0	0	0	0	**0.3**	**0.44**	**0.26**
1400-1600	0	0	0	**0.26**	**0.43**	**0.31**	0	0
1600-1800	0	0	0	**0.26**	**0.43**	**0.31**	0	0
>1800	**0.27**	**0.45**	**0.28**	0	0	0	0	0

The timber harvest is then monetized by an average price for different timber products in the region of Davos, i.e. construction timber, pulpwood and firewood. The current regional average timber price fluctuates around 96 CHF/m3 (77% construction timber à 100 CHF/m3, 8% pulpwood à 55 CHF/m3, 15% firewood à 30 CHF/m3) and is used to value the service in 2009. Local and regional foresters provided their opinion on the future development of the timber price (and thus the future value of the ESS) forecasting an increasing market value of the resource (Table 7).

Table 7. Probability distribution for current and future average timber price.

Timber price (CHF/m3)	**Probability**	(in 2009)
86	**0.048**	0.3
96	**0.062**	0.5
106	**0.154**	0.2
115	**0.216**	0
125	**0.258**	0
150	**0.214**	0
170	**0.048**	0

2.4.2. Carbon sequestration services

The carbon sequestration service is a regulating ESS and defined as the storage of carbon dioxide through aboveground and belowground growing and existing biomass in soils (BAFU, 2011). In this study, we distinguish between a carbon storage and a carbon mitigation service. Carbon is stored in all non-built land-use types, thus, relevant to agricultural fields, forests and to a smaller degree also to open space green areas. The carbon storage service is understood as a stock constant over the time considered, since the CO2 that is taken up each year by the vegetation is released again through decomposition of biomass, thus, carbon is not accumulatively sequestered. The carbon stock is understood similar to an economic asset and its annual value calculated as a yearly interest of the total value of this stock. By contrast, the forest in Davos is continuously growing and mitigating CO2 for longer periods through densification and expansion. Thus, the yearly amount of growing timber is fully accounted as a carbon sink.

We quantify the carbon storage service based on carbon stocks reported for different land-use types in Switzerland's Greenhouse Gas Inventory (BAFU, 2011). The amount of carbon stored thereby depends on the altitudinal zone, the NFI region and the vegetation type. However, since Davos is located in the high Alps, these variables are uniform in the whole region and the carbon stock in the model only depends on the land-use type. We account for carbon stocks in living aboveground biomass and roots as well as for carbon stored in soils modeling normal distributions over yearly data measured between 1990 and 2009 in alpine regions above 1200 masl (Table 8).

Table 8. Conditional probabilities of carbon in biomass/soils on different land-use types.

	Probability CO2 stock in biomass/soils (tCO2/ha)						
Land-use type	210	224	280	317	697	770	843
Forest	0	0	0	0	**0.32**	**0.36**	**0.32**
Intensive, extensive and summer pastures	0	**0.17**	**0.46**	**0.37**	0	0	0
Green areas	**0.06**	**0.76**	**0.18**	0	0	0	0

We quantify the carbon mitigation service of the forest based on the yearly growth rate of the forest in Davos (WSL, 2010). In order to account for yearly fluctuations, we model a normal distribution over the observed annual growth of forest between 1983 and 2007 and calculate the corresponding carbon mitigation capacity (Table 9) following Thürig and Schmid (2008):

$$CO_2[t/hay] = G[m^3/hay] \cdot \rho \left[\frac{kg}{m^3}\right] \cdot BEF \cdot C/biomass[kg/kg] \cdot C_1 \cdot C_2 \qquad (2)$$

G is the growth rate of the forest, ρ the density of coniferous wood (394 kg/m3), BMF the biomass expansion factor of 1.57, C/biomass is 0.5 kg/kg and C1 and C2 the conversion factors to CO2 (44/12) and tons (0.001), respectively.

Table 9. Probability distribution of the carbon mitigation capacity of the forest in Davos.

Carbon mitigation capacity (t/ha/y)	**Probability**
4.8	**0.25**
5.4	**0.44**
6.1	**0.31**

Carbon sequestration services are commonly valued by the carbon tax which fluctuates currently around 30 CHF/tCO2. While the current carbon tax is used to monetize the ESS in 2009, environmental economists were asked to predict future prices for CO2 equivalents (Table 10) for valuing the service in 2021. We monetize the carbon mitigation capacity of the forest by the full carbon tax. By contrast, the annual value of the landscape as a carbon storage is understood as an interest of a valuable constant asset and calculated using the compound interest formula:

$$C_n = C_0(1 + \frac{p}{100})^n \qquad (3)$$

where Co and Cn are the capital's value at present and after n years, respectively, and p is the annual interest rate. We assume an interest rate of 3% according to the convention of the German National Environmental Office (Schwermer, 2007) and a time span of 12 years, starting from 2009 to 2021 resulting in an average yearly interest of 3.5% and values for the discounted carbon tax as given in Table 10.

Table 10. Probability distribution of carbon tax estimated by experts and related interests.

Carbon tax (CHF/tCO2)	Interest of carbon tax (CHF/tCO2)	**Probability** (in 2009)

30	1.1	**0.1**	0.85
50	1.8	**0.194**	0.15
75	2.7	**0.268**	0
100	3.5	**0.276**	0
150	5.3	**0.122**	0
200	7.1	**0.03**	0
250	8.9	**0.01**	0

2.4.3. Avalanche risk and avalanche protection services

In Alpine environments such as Davos, avalanches are the most severe natural hazard posing a threat to settlements, infrastructure and people. Even though damage is usually on a smaller scale than from other natural hazards such as flooding events, avalanches pose a high level of threat locally, because Alpine settlements are concentrated in confined areas (Fuchs et al., 2004). Beside technical constructions and organizational measures, mountain forests provide effective low-cost protection against triggering and propagation of avalanches. In fact, protection against avalanches was found to be the key ESS in half of the forest in Davos (Grêt-Regamey et al., in review). In this study, we quantify in addition to the avalanche protection service of forests, an avalanche prevention service of non-built land-use types in hazard zones. The idea behind this ESS is that the construction of new dwellings in these areas would increase the economic risks from avalanches. Thus, natural landscapes in hazard zones have an intrinsic value for preventing additional risks in a region, an important service in the context of an integral, comprehensive and prospective risk management.

We quantify the avalanche risk using the numerical two-dimensional avalanche model RAMMS (Christen et al., 2011). In a first step, RAMMS identifies 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 predicts the run-out distances, flow velocities and associated impact pressures in a spatially explicit manner.

Table 11. Density of different building types in settlement areas and total costs of destroyed buildings in case of complete damage.

Settlement category	Density of buildings (houses/ha)	**Probabilities** of total costs of destroyed buildings in different settlement area (CHF/ha) in case of complete damage
Agricultural buildings	1	800'000 (**0.31**), 1'500'000 (**0.36**), 1'800'000 (**0.33**)
One/multiple family houses	12	18'000 (**0.3**), 36'000'000 (**0.41**), 54'000'000 (**0.29**)
Public buildings	8	80'000'000 (**0.32**), 112'000'000 (**0.37**), 144'000'000 (**0.31**)
Industrial buildings	8	24'000'000 (**0.24**), 36'000'000 (**0.33**), 48'000'000 (**0.43**)
Hotels and restaurants	8	48'000'000 (**0.25**), 64'000'000 (**0.34**), 80'000'000 (**0.41**)

We then identify the potentially endangered settlement areas by overlaying the run-out zones with the Vector 25 data and price damages to buildings and fatalities using a traditional risk-analysis approach. In order to obtain a raster-based risk value we categorize grid cells by their dominant building type assuming different density of houses in different settlement categories (calculated as locally averaged values based on the aerial statistics and vector 25 maps, Table 11) and compute direct and indirect costs of the potentially destroyed dwellings therein. The total costs in each settlement category are calculated by a normal distribution over reported values for the category-specific housing type in Davos (Communal cadastral register) and accounting for damages of belongings (24% of building value) and infrastructure (15% of building value) as well as for socio-economic losses (10% of building value). Table 11 shows the resulting probability distribution of these costs for each settlement category in case of complete damage. In order to account for uncertainty, we add a state "some damage" where 50% of the total values of a building are destroyed. The severity of the damage itself is dependent on the building type and the intensity of the avalanches (Barbolini et al., 2004; Borter, 1999; Table 12).

Table 12. Conditional probabilities for building damage in different settlement categories in dependence of the avalanche pressure.

Settlement category	Avalanche pressure (kPa)	**Probabilities** Building damage: Yes	Some	No
Agricultural buildings	0-3	**0.05**	**0.05**	**0.9**
	3-10	**0.25**	**0.25**	**0.5**
	10-20	**0.25**	**0.25**	**0.5**
	20-30	**0.5**	**0.5**	0
	>30	**0.5**	**0.5**	0
One/multiple family houses and hotels and restaurants	0-3	**0.02**	**0.02**	**0.96**
	3-10	**0.1**	**0.1**	**0.8**
	10-20	**0.22**	**0.22**	**0.56**
	20-30	**0.37**	**0.37**	**0.26**
	>30	**0.5**	**0.5**	0
Public buildings and Industrial buildings	0-3	**0.05**	**0.05**	**0.9**
	3-10	**0.35**	**0.35**	**0.3**
	10-20	**0.35**	**0.35**	**0.3**
	20-30	**0.5**	**0.5**	0
	>30	**0.5**	**0.5**	0

The costs of potential fatalities are determined by the number of people present in buildings and the lethality within the houses: each person in a building is valued in case of death with 5'000'000 CHF following the life quality approach of Merz et al. (2005). We use local data on hotel beds and values by Wilhelm (1997) to model probabilities for the number of people present in different building types (Table 13). The lethality depends on the average presence time of people in houses (Borter, 1999, Table 13), the intensity of the avalanche and the severity of the building damage (Table 14).

Table 13. People's presence in buildings and related number of persons per building.

Building category	People's presence in buildings (**probability**)	**Probabilities** of number of persons per building
Agricultural buildings	**0**	0 (**1**)
One/multiple family houses	**0.68**	2 (**0.28**), 4 (**0.48**), 5 (**0.24**)
Public buildings	**0.27**	20 (**0.24**), 30 (**0.37**), 4 (**0.31**)
Industrial buildings	**0.27**	2 (**0.38**), 4 (**0.38**), 5 (**0.24**)
Hotels and restaurants	**0.54**	40 (**0.3**), 60 (**0.35**), 80 (**0.35**)

Table 14. Conditional probabilities for lethality depending on the avalanche pressure and the building damage.

Building damage	Avalanche pressure (kPa)	**Probabilities** lethality: Death	No death
yes	0-3	0	**1**
	3-10	**0.01**	**0.99**
	10-20	**0.09**	**0.91**
	20-30	**0.18**	**0.82**
	>30	**0.27**	**0.73**
some	0-3	0	**1**
	3-10	**0.005**	**0.995**
	10-20	**0.045**	**0.955**
	20-30	**0.09**	**0.91**
	>30	**0.135**	**0.865**

In this study, we do not include costs resulting from the damage of railways or streets, people present in open space or due to economic losses from interrupted activity of the industry. However, the flexible framework and existing risk analysis methods (Borter, 1999) allow to integrate these risks with moderate effort if data from traffic counts and operating data from local industry are available.

We calculate the avalanche prevention service of non-built landscape in hazard zones similar to the avalanche risk, assuming that these grid cells would be overbuilt. Since at the moment there are no real dwellings on such areas, we have to hypothesize which housing types are built in case of settlement expansion. We only consider areas below the timber line for future settlement development and differentiate two strata with different probabilities regarding the type of potential future dwellings: in grid cells below 1600 masl we assume a settlement mix of 20% of each building type, whereas between 1600 and 1900 masl we assume an expansion entailing to 50% agricultural buildings and to 25% one/multiple family houses and hotels/restaurants, respectively. To value the service, we run a risk analysis for these potential future dwellings (and people within).

We use results from a previous study in the landscape of Davos to locate and value the protection service of forests. Based on the findings of Grêt-Regamey et al. (in review), we categorize and monetize forest patches according to the value of the assets they protect from avalanches (Table 15).

Table 15. Protection forest categories and associated values of the ecosystem service (ESS) avalanche protection.

Protection forest category (extent of damage)	Value ESS avalanche protection (CHF/ha/y)
No	0
Marginal	50
Very small	1000
Small	8000
Medium	20'000
High	32'000
Very high	60'000
Extremely high	200'000
Highest	500'000

2.4.4. Recreation services

Beside the protection of human settlements against natural hazards, recreational and aesthetic values of the landscape are particularly important in alpine valleys that depend to a large part on tourism (Schönenberger, 2001; Grêt-Regamey et al., in review). In Davos, where skiing, hiking and biking are amongst the most popular sports, we account for leisure opportunities in the forest, on agricultural land and on open green space. For example, the community runs a golf court which is intensively used in summer by residents and tourists (Holthausen, 2011).

We assess the recreation service of forests by assigning a qualitative degree of forest attractiveness to each forest grid cell (Table 16). The attractiveness of forests increases with proximity to roads, tracks and infrastructure where tourists mostly carry out their sport activities (Brändli and Ulmer, 1999) and with increasing closeness of the forest. Several studies have shown that people appraise the calm and protective character of the forest which is only perceived if the forest patch is of a certain size and density (e.g. Bernasconi and Schroff, 2003; Scarpa et al., 2000).

Table 16. Attractiveness of a forest stand depending on the distance to road and the forest closeness.

	Attractiveness for recreation			
	Forest closeness within 2.5km (%)			
Distance to road (m)	0 – 25	25 – 50	50 – 75	75 - 100
<30	medium	high	very high	very high
30 - 100	low	medium	high	very high
100 - 200	none	low	medium	high
> 200	none	none	low	medium

We monetize the forest recreation service based on a discussion with experts on literature values from studies on travel and subsistence costs of different forest stands in Switzerland (Beck, 2008). We have asked different experts to assign monetary values to a forest stand of "very high attractiveness" (Table 17). We then use 75%, 50% and 25% of the full value for monetizing forest patches of high, medium and low attractiveness, respectively.

Table 17. Average probability distribution of the value of a forest stand of "very high attractiveness" estimated by experts.

Travel cost forest (CHF/ha/y)	**Probability**
500	**0.14**
1000	**0.15**
3000	**0.18**
8000	**0.20**
10'000	**0.17**
12'000	**0.16**

Similar to the forest, the attractiveness of agricultural landscapes for recreation depends on their accessibility, that is, on the roads and tracks within. In addition, analyses on landscape aesthetics normally include attractiveness at local scale (i.e. of the land-use type), in the proximate surroundings (for example the number and combination of typical structural elements) and in the background (Nohl, 2000). In this study, we include local attractiveness by distinguishing the structural diversity of different agricultural land-use types and the background view, since the unique panorama with many summits and a pure mountain lake is one of the key features of the alpine valley. Regarding local attractiveness, different studies in Switzerland have shown that people prefer landscapes that are of structural diversity over homogeneous fields (for an overview on studies: Grêt-Regamey et al., 2012). Furthermore, we assume that the attractiveness of an area increases with the number of summits that can be seen at the horizon and whether a glimpse on the lake is possible at a site (Table 18). These factors determine the qualitative degree of attractiveness that is assigned to each agricultural grid cell (Table 19).

Table 18. Background view depending on view on lake and view on mountains.

	View		
	View on lake (number of visible shorelines)		
View on mountains (number of summits)	0	<50	>50
<10	low	low	low
10 - 20	low	medium	high
20 - 30	medium	high	very high
>30	high	very high	very high

Table 19. Attractiveness of agricultural land-use types depending on distance to road, structural diversity and view.

	Attractiveness for recreation							
	View							
	Low		*Medium*		*High*		*Very high*	
Structural Diversity	Low	High	Low	High	Low	High	Low	high
Distance to road (m)								
<30	medium	high	high	very high	high	very high	high	very high
30 - 100	low	medium	medium	high	high	very high	high	very high
100 - 200	none	low	low	medium	medium	high	high	very high
> 200	none	low	none	low	low	medium	medium	high

In order to monetize the agricultural recreation service, we model a normal distribution over values collected for different agricultural land-use types by Grêt-Regamey et al. (2012, Table 20) and assign the full or part of the values to different attractiveness categories similar to the valuation of the forest recreation service (very attractive = 100% of value, high = 75%, medium = 50%, low = 25%).

Table 20. Probability distribution of recreational value of agricultural landscapes..

Recreational value for category "very attractive" landscape (CHF/ha/y)	**Probability**
500	**0.02**
650	**0.12**
750	**0.26**
850	**0.35**
1000	**0.25**

Community open green space offers a lot of possibilities for leisure activities, e.g. walking dogs, reading, playing games or golfing. Moreover the lake of Davos provides additional opportunity for diverse water sports, such as surfing, swimming or bathing. The attractiveness of high-quality green space has been shown to depend on its distance to water bodies as well as on its size (Mahon and Miller, 2003). Connected open areas at the border or close to the lake are of most value to visitors and locals. In this study, we include in addition the view (Table 18) as an important determinant of the quality of public green space. The combined influence of these three variables on the attractiveness of this land-use type is shown in Table 21. Due to lack of adequate studies, we value the service according to the recreation on agricultural land (see above).

Table 21. Attractiveness of an open green space depending on distance to lake, connectivity and view.

	Attractiveness for recreation							
	View							
	Low		*Medium*		*High*		*Very high*	
Connectivity Distance to lake (m)	Isolated	Connected	Isolated	Connected	Isolated	Connected	Isolated	Connected
<50	medium	high	high	very high	high	very high	high	very high
50 - 100	low	medium	medium	high	high	very high	high	very high
100 - 1000	none	low	low	medium	medium	high	high	very high
> 1000	none	low	none	low	low	medium	medium	high

2.4.5. Management and investment costs

In order to guarantee the provision of terrestrial ESS, the landscape has to be maintained and managed in a sustainable way. Thus, the benefits we obtain from ESS are related to management costs. Agricultural land-use types only exist as such due to human cultivation. Here, the management is mostly driven by the production service. However, when weighing costs against benefits, other services such as carbon sequestration or recreation that are provided as a side-benefit of such a management need to be included in the balance. Similarly, in forest management strategies production services have traditionally been prioritized, however the objectives of silivculture and accordingly the management objectives have changed within the last 30 years towards a multifunctional use of forests (e.g. Fürst et al., 2007). Management techniques for supporting multifunctional forests range from no or minimal intervention to technical constructions depending on the favored ESS, thus, related costs vary substantially (Schönenberger, 2001). In mountain areas as Davos, the maintenance of protective forest is a key management issue and foresters target a stable forest structure enabling a controlled timber harvest while guaranteeing resilience towards hazards (personal communication with forester). In this study, we calculate costs of the provision of ESS assuming a maximum sustainable harvest, that is, the yearly growing biomass (fodder or timber) is harvested from the ecosystem. In addition, we account for running costs of existing and investment costs of new technical avalanche constructions.

Operating costs for meadows depend on many micro-scale spatially explicit factors, e.g. sunshine in certain months, exposition or pest plants and animals, which cannot be included in the model due to lack of data. We calculate the costs for agricultural management depending on two macro scale factors, the slope of a field and the husbandry type, based on values reported in Grêt-Regamey et al. (2012). On extensive pastures, the costs amount with increasing slope while those on intensive pastures are not dependent on the slope due to lack of adequate data. However, in general, intensive meadows are generally not located in steep terrain, since such a terrain is difficult to access with machines. Due to higher working loads it is much more expensive to cultivate intensive than extensive fields (Table 22). Summer pastures are by definition not cultivated, but only grazed by cattle which are not accounted as direct economic investments in this study.

Table 22. Costs for managing intensive and extensive pastures depending on the slope.

	Management costs CHF/ha (**probability**) Husbandry type	
Slope (°)	Intensive	extensive
<18	3700 (**0.27**), 5430 (**0.46**), 7200 (**0.27**)	1592 (**0.80**), 1605 (**0.10**), 1684 (**0.10**)
18- 25	3700 (**0.27**), 5430 (**0.46**), 7200 (**0.27**)	1605 (**0.10**), 1684 (**0.80**), 2751 (**0.10**)
25 - 35	3700 (**0.27**), 5430 (**0.46**), 7200 (**0.27**)	1605 (**0.10**), 1684 (**0.80**), 2751 (**0.10**)
35 - 50	3700 (**0.27**), 5430 (**0.46**), 7200 (**0.27**)	1592 (**0.10**), 1605 (**0.80**), 1684 (**0.10**)
50 - 80	3700 (**0.27**), 5430 (**0.46**), 7200 (**0.27**)	1605 (**0.10**), 1684 (**0.10**), 2751 (**0.80**)

Harvesting costs within the forest are calculated based on a spatially explicit assessment of adequate harvesting methods in Davos (Bont, 2009). Depending on soil texture, infrastructure and slope, timber can be taken out of the forest from the ground, with a mobile cable way, with a conventional cable way and by helicopter. Each technique is given a price based on knowledge from local foresters (Table 23). The final forest management costs are assessed by the harvestable amount of timber and the harvesting technique foresters apply at each site.

Table 23. Harvesting costs for timber depending on the harvesting technique.

	Probability Harvesting costs (CHF/m3)			
Harvesting technique	90	105	115	160
From ground	**0.8**	**0.2**	0	0
Mobile cable way	**0.05**	**0.9**	**0.05**	0
Conventional cable way	0	**0.05**	**0.9**	**0.05**
helicopter	0	0	**0.1**	**0.9**

In Davos, most technical avalanche constructions are of the type “retaining constructions”. The building costs of these preventive measures amount to 1’000’000 CHF/ha while operating costs generally make up about 0.5% of the investment costs (personal communication with SLF/WSL). We thus assume annual costs of 5000 CHF/ha for existing constructions. In scenario 2, where new technical constructions are planned, we discount the price for such new constructions over a period of 12 years starting from 2009 until 2021. The resulting 3.5% of this discounting correspond to investments of 35’000 CHF/ha/y.

3. Results

Going one step further than existing tools for integral risk management, our approach assesses risks in a spatially explicit way at high resolution. Thus, the result section predominantly shows a selection of different possibilities of maps we can draw and present to stakeholders based on our calculations. Amending the maps with some aggregated assessments will outline the full potential of the approach.

3.1. Risk identification and localization

Land-use change alters threats from natural hazards and the flow of ESS as indicated in Figure 4 for the scenarios “sport event” and “sustainable tourism”. Even though under these two scenarios, only 4.6% and 3.8%, respectively, of the total area of Davos will experience a transformation of the current land use until 2021, the related changes of economic and ecological risks are substantial. The avalanche risk maps locate the highest increase of potential damage from avalanches in Davos Dorf next to the existing housings where settlement expansion is most probable. Since in case of a large sport event, more infrastructure needs to be established, the risk in the presented cutout is higher than under a policy supporting a sustainable regional tourism (Table 24). Gains and losses in the flow of ESS occur primarily in the main valley bottom outside the village center. While in scenario 4 the value of the production service increases in future, a considerable value loss of the service has to be expected under scenario 5. This results from the fact that assuming a sustainable tourism in Davos entails a change from intensive to extensive agricultural practice on many meadows. In our model, such a change of husbandry type yields less fodder with a lower market price (SBV, 2012). However, if increasing demand for local biologically produced products was included in the valuation of the service, these values could change substantially. Negative and positive impacts of the two development options on the recreation service are observed mainly near forest treeline and on agricultural areas in the valleys. A sustainable use of the meadows and growth of forest above treeline in scenario 5 increase the attractiveness of the landscape and thus its recreational value. By contrast, settlement expansion and intensification of agriculture substantially lowers the recreational value of the landscape in scenario 4, especially in near-walk distance from the current village border and in the plain of the main valley.

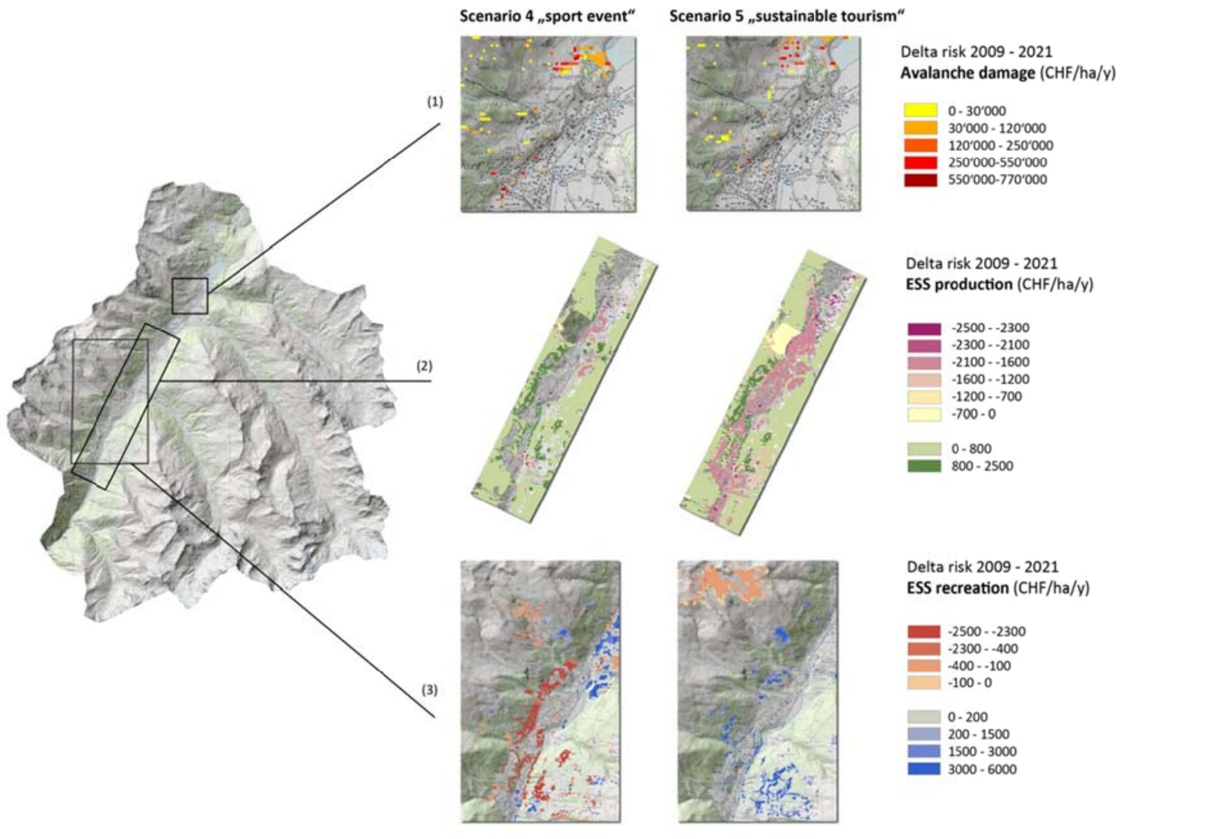

Figure 4. Location of most pronounced changes in the risks from avalanches and in the flow of ecosystem services (ESS) under the scenarios "sport event" and "sustainable tourism".

Table 24. Changing risks under two scenarios at different locations in the region.

Scenario	Delta avalanche risk 2009 - 2021 (CHF/y) Cutout 1	Delta risk production services 2009 - 2021 (CHF/y) Cutout 2	Delta risk recreation services 2009 – 2021 (CHF/y) Cutout 3
Sport event	+ 14'800'000	+ 3'700'000 - 1'900'000	+ 3'100'000 - 5'200'000
Sustainable tourism	+ 10'300'000	+2'800'000 - 9'800'000	+ 5'000'000 - 200'000

3.2. Ecosystem services maps

So far, ecological risks have not been included in risk assessment tools, even though the protection of the integral resilience of a landscape and its services is most pressing in view of a sustainable development of space. Valuing ESS in Davos illustrates the various benefits the mountain area provides to residents and tourists (Table 25). Expected values of the selected ESS range from around 500 Mio. CHF/year for the avalanche prevention service to 1 to 3 Mio. CHF/year for production services. The entire landscape will provide recreation opportunities of a value of 20 Mio. CHF/year and generate additional services of around 25 Mio. CHF/year and 9 Mio. CHF/year as a carbon sink and storage, respectively. Depending on the expected land-use change related to the different scenarios and on the considered service, the ESS value change considerably from now until 2012.

In all scenarios despite scenario 4, in which agricultural area is conserved and intensified, several alpine meadows above treeline are abandoned and others in the valley bottom are taken over by settlement expansion. Thus, the regional amount of harvested agricultural products and thus the aggregated value of the related service will decrease in future. By contrast, the forest will further expand and enhance the amount of timber harvest and the revenue from sale of timber products, thus, the regional value of the timber production service. For the same reason, the carbon mitigation capacity of the forest and its value as a carbon sink in 2021 are larger than today. An additional cause of the increasing value of both the carbon mitigation and the carbon storage service is the changing price of carbon equivalents that is used to monetize the two services. Due to climate change and expected political resolutions restricting further greenhouse gas emissions, experts forecast a substantial raise of the carbon tax until 2021, tripling the value of the landscape as a carbon storage. However, this valuation procedure does not consider the very local demand but rather expresses how much value such landscapes dominated by forest and natural land-use types have at global scale for sequestering greenhouse gases. The value of the recreation service remains more or less constant, as the valley located within a beautiful scenery, equipped with hiking trails and various touristic infrastructure, already attracts large visitor crowds today. Since settlement growth is assumed to be limited by the implementation of the initiative on restricted secondary residences, the local demand for recreation will not grow substantially. Similarly, the avalanche protection service of the forest has a comparable value now and in future, since young forest stands growing at treeline do not substantially expand downstream endangered areas that are protected by the forest. The slight value loss of the avalanche prevention service results from conversion of agricultural area in endangered zones either to settlement, to forest or to unproductive land. In case of land-use change to settlement this loss is accompanied by an increase of risk from avalanches as observed for example in scenario 5. On the other hand, if a transformation to forest occurs the service of the underlying grid cell changes from an indirect retention to a direct protection service. It has to be noted that the extraordinarily high value of the avalanche prevention service has to be treated very carefully. Since damages to dwellings and fatalities pose large economic losses, the model assigns high values to all regions in endangered zones that are not turned into settlement, but could possibly be threatened by such a conversion. However, it remains a point of discussion, which areas are potentially endangered by settlement expansion or establishment of new infrastructure. For example, if the potential settlement growth is restricted to regions below 1600 masl, the total value of the retention service in the landscape of Davos will be cut by 75%. Nevertheless, it remains a very crucial ESS of the region.

Table 25. Annual benefits from selected ecosystem services, related management costs and risks from avalanches in the region Davos under different scenarios.

		Scenario (CHF/y)					
	2009 (CHF/y)	BAU	Scenario 1: Zero risk tolerance	Scenario2: Preventive planning	Scenario 3: ESS max	Scenario 4: Sport event	Scenario 5: Soft tourism
Agricultural production	3'078'000	2'275'000	2'858'000	2'830'000	1'984'000	3'197'000	2'148'00
Timber production	925'000	1'325'000	1'233'000	1'294'000	1'399'000	1'224'000	1'343'000
Carbon mitigation	1'100'000	3'198'000	2'935'000	3'272'000	3'455'000	3'059'000	3'462'000
Carbon storage	8'530'000	25'336'000	23'500'000	25'524'000	26'265'000	24'364'000	26'397'000
Recreation	20'682'000	21'411'000	20'905'000	21'765'000	22'289'000	21'276'000	22'294'000
Avalanche protection	191'665'000	193'570'000	189'570'000	193'703'000	194'400'000	192'609'000	194'502'000
Avalanche prevention	527'556'000	487'319'000	420'753'000	500'122'000	466'781'000	510'838'000	465'754'000
Management costs	5'633'000	5'230'000	45'638'000	5'754'000	4'953'000	6'051'000	24'458'000
Avalanche risk	16'101'000	16'171'000	0	16'101'000	16'306'000	16'274'000	17'450'000

In order to maintain the potential to provide all these services, the landscape needs to be managed. In scenarios where agriculture is in tendency intensified these management costs generally increase while a more extensive use of meadows reduces the costs. Forest expansion on expense of agricultural land-use types reduces the regional management costs since the cultivation of fields is on average more work-intense and costly than forest interventions. Running costs for avalanche protection measures remain constant in all scenarios, but investments in new safety constructions substantially enhance the total management costs in scenario 3 where no risks from avalanches are tolerated in future.

The development of the avalanche risk until 2021 depends substantially on where the land-use model allocates new settlement areas. Since in all scenarios at maximum only 12 ha of the landscape are converted to settlement, the change of the avalanche risk at regional scale is not substantial despite in scenario 5 where current agricultural land in the valley bottom is conserved and new settlement has to be established at higher locations that are generally more hazard-prone.

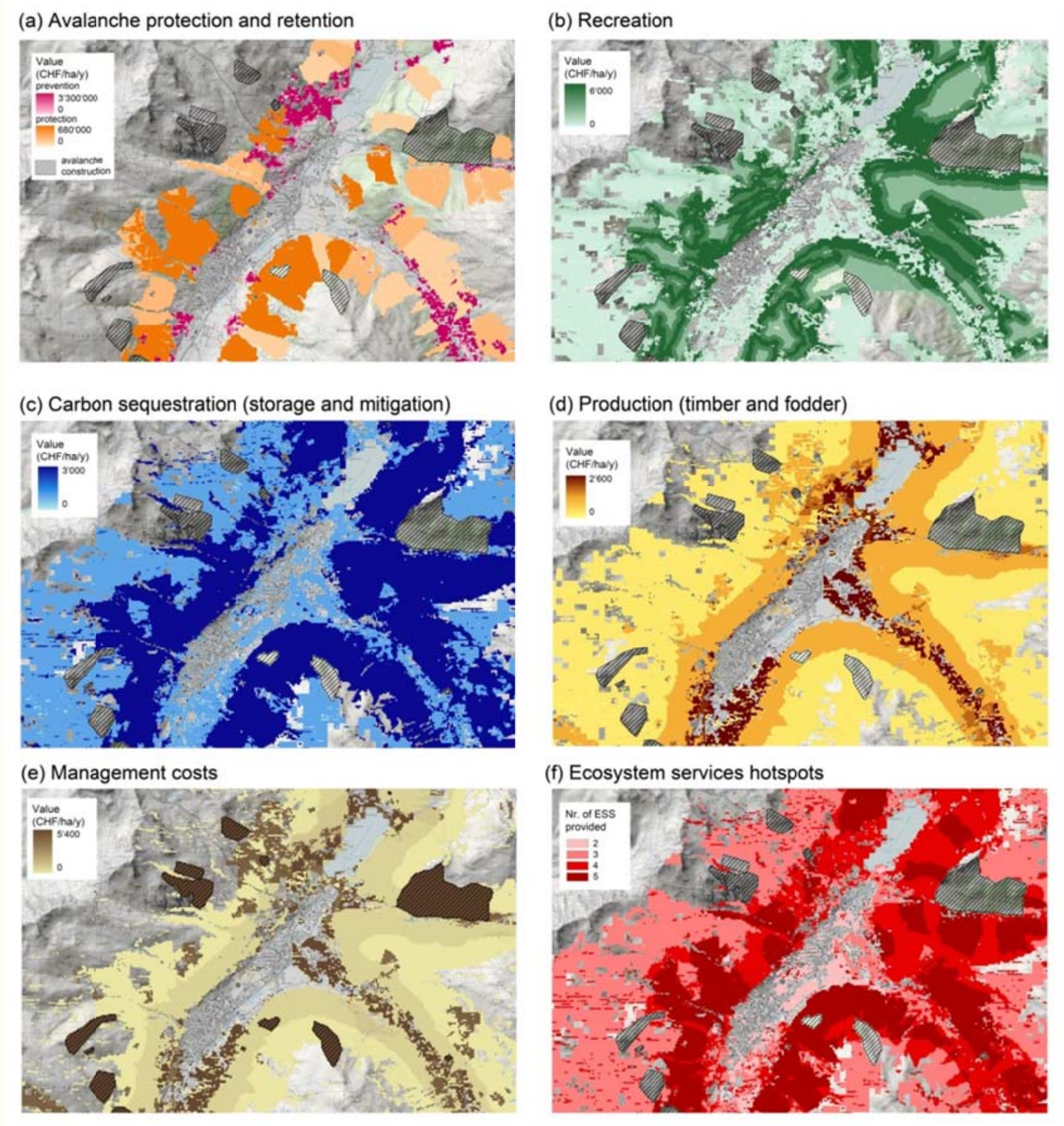

Figure 5. Potential of the landscape Davos to provide different ecosystem services (ESS) under an ESS maximization scenario: (a) avalanche protection and retention, (b) recreation, (c) carbon mitigation and storage, (d) timber and fodder production, and (e) associated management costs and (f) resulting ESS hotspots.

The spatial patterns of the ESS and related management costs are exemplarily presented for the scenario “ESS maximization” in Figure 5. Contrary to other considered services that are supplied by all non-built land-use areas, the avalanche protection and prevention services are provided by specific forest stands and agricultural retention areas, respectively. The avalanche protection service is located at hazard-prone, steep slopes where the forest protects dwelling against natural hazards. Around 50% of the forest has a protective function and the 2900 ha protective forest stands provide benefits of 68’000 CHF/ha on average, ranging from 3 CHF/ha to 680’000 CHF/ha. Meadows providing a prevention service are found in potential avalanche run-out zones, on the one hand in the valley bottom where protective forest has not enough strength to provide a full security from the power of the snow masses and on the other hand in areas within the forest belt where no trees grow. For evaluating planning strategies of the municipality the prior regions are of high importance, since settlement expansion near existing dwellings is rather in discussion, while at more elevated sites construction activities are mostly restricted to single buildings, e.g. agricultural buildings, skiing infrastructure or in particular cases hotels or sanatoriums. In Davos, the most valuable agricultural retention areas with a maximum value of 3.3 Mio. CHF/ha, are located at the borders of the village in Davos Dorf and Platz as well as in the side valleys, especially in the Dischma, where avalanches recur often and almost always reach the valley bottom.

The forest is the most valuable land-use type for recreation. Belts around settlements and hiking trails provide optimal recreational opportunities of a maximum value of 6800 CHF/ha while remote areas are of lower value for leisure activities. Of highest recreational value is also open green space at the lakeside where tourists and residents enjoy a lot of different sports in near-walking distance to the village center. The value of the carbon sequestration service (here presented as a sum of carbon mitigation and storage) increases from 5 CHF/ha on remote summer pastures to 3000 CHF/ha in close forest stands. Most valuable in terms of production services are the valley bottoms where farmers can cultivate intensive meadows. Here revenues from product sale mount up to 2600 CHF/ha. If valued by the current market price, extensive pastures are of lower value, however this may change if local preferences for regional products were included in the valuation (see above). Forests generate additional market income from sale of timber which is predominantly harvested in lower forest belts, where trees grow faster and accessibility is better than at higher elevations.

Since in our model management costs are tightly connected to production services (see section 2.4.5), the spatial pattern of the costs is similar to the map of the production services. The most significant cost factor with 5000 CHF/ha is the maintenance of avalanche constructions for guaranteeing safety for houses and people in the village. Overlying the single maps identifies ESS hotspots. 60% of the whole landscape provides 3 or more ESS. Hotspots where 4 or 5 services are provided simultaneously are predominantly located in specific protective forest stands or extensive agricultural land important for the avalanche prevention service.

3.3. Policy scenario comparison

Existing tools such as *Econome* evaluate efficiency of technical measures by cost-benefit analysis where benefits are restricted to economic gains in terms of dwellings that can be protected by additional measures. Despite still being controversial the valuation of ESS allows including ecological risks in such a balance between costs and benefits. The monetary units of the ESS can be compared to avalanche risks and management costs enabling an evaluation of different planning options. Aggregated regional values of these risks and costs (Table 25) help evaluating different policy options from an overall perspective. For example, the ESS values are highest in the “sustainable tourism” and the “ESS maximization” scenario. While agricultural and cultural landscape is conserved in case of a sustainable tourism policy, higher avalanche risks have to be taken into account since new dwellings are built in hazard-prone regions. On contrary, even though settlement expansion is higher in the “sport event” scenario due to additional infrastructure for tourists and athletes, avalanche risk is lower than in scenario 5. Here, the village is growing at the expense of extensive meadows in the valley bottom which is not endangered by avalanches. At the same time, such a strategy maintains the avalanche prevention service of the landscape. However, we have to expect losses in the recreational attractiveness of the landscape as well as in its potential as a carbon sink if comparing with other planning options.

Aggregated values alone can help getting an overview on different policy options, but for targeting limited resources it is most pressing to map where these policy options have most influence in terms of benefits and ESS losses. Figure 6 and 7 compare consequences of the two scenarios “zero risk tolerance” and “preventive spatial planning” for the areas Davos Dorf and Davos Platz, respectively. In order to guarantee full protection against snow masses in Davos Dorf, investment and management costs mount up to 5 Mio. CHF/year as compared to 700’000 CHF/year for landscape management under preventive spatial planning (Figure 6). In addition, the total value of ESS that are provided near the village is substantially lower (around 20 Mio. CHF/year) due to numerous new safety constructions that destroy the natural landscape and its provisional, aesthetical and regulating services. On the other hand, these constructions will guarantee safety in the village, while society tolerates an avalanche risk of nearly 4 Mio. CHF/year in scenario 2. In Davos Platz, this residual risk is spatially more concentrated and less constructive measures are necessary for cutting down the potential future avalanche damage. Investments of 630’000 CHF/year can prevent from an avalanche risk of 2.7 Mio CHF/year while related losses in the flow of ESS are minor.

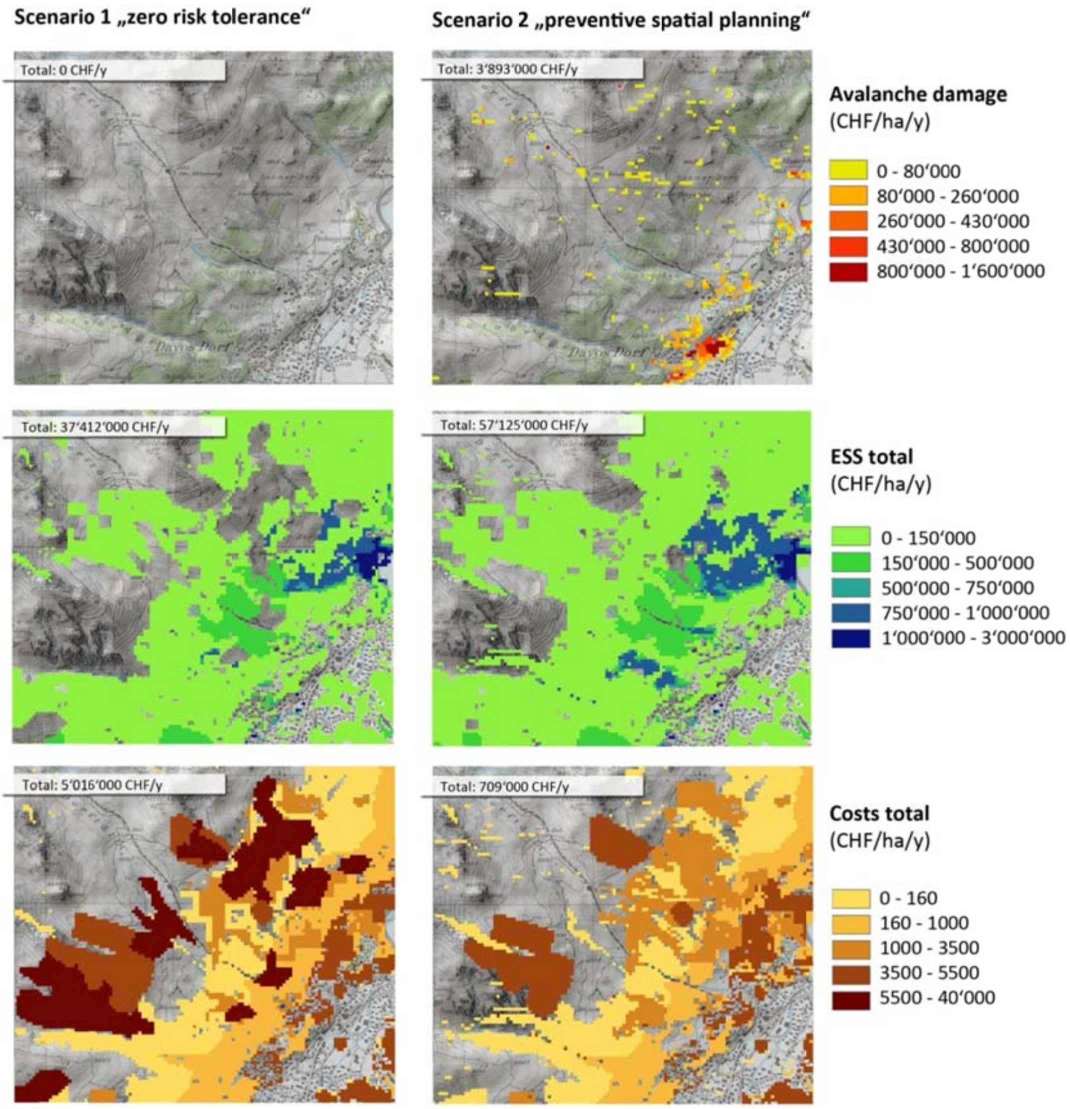

Figure 6. Comparison of future potential avalanche damage, ESS benefits and landscape management costs under different scenarios in Davos Dorf.

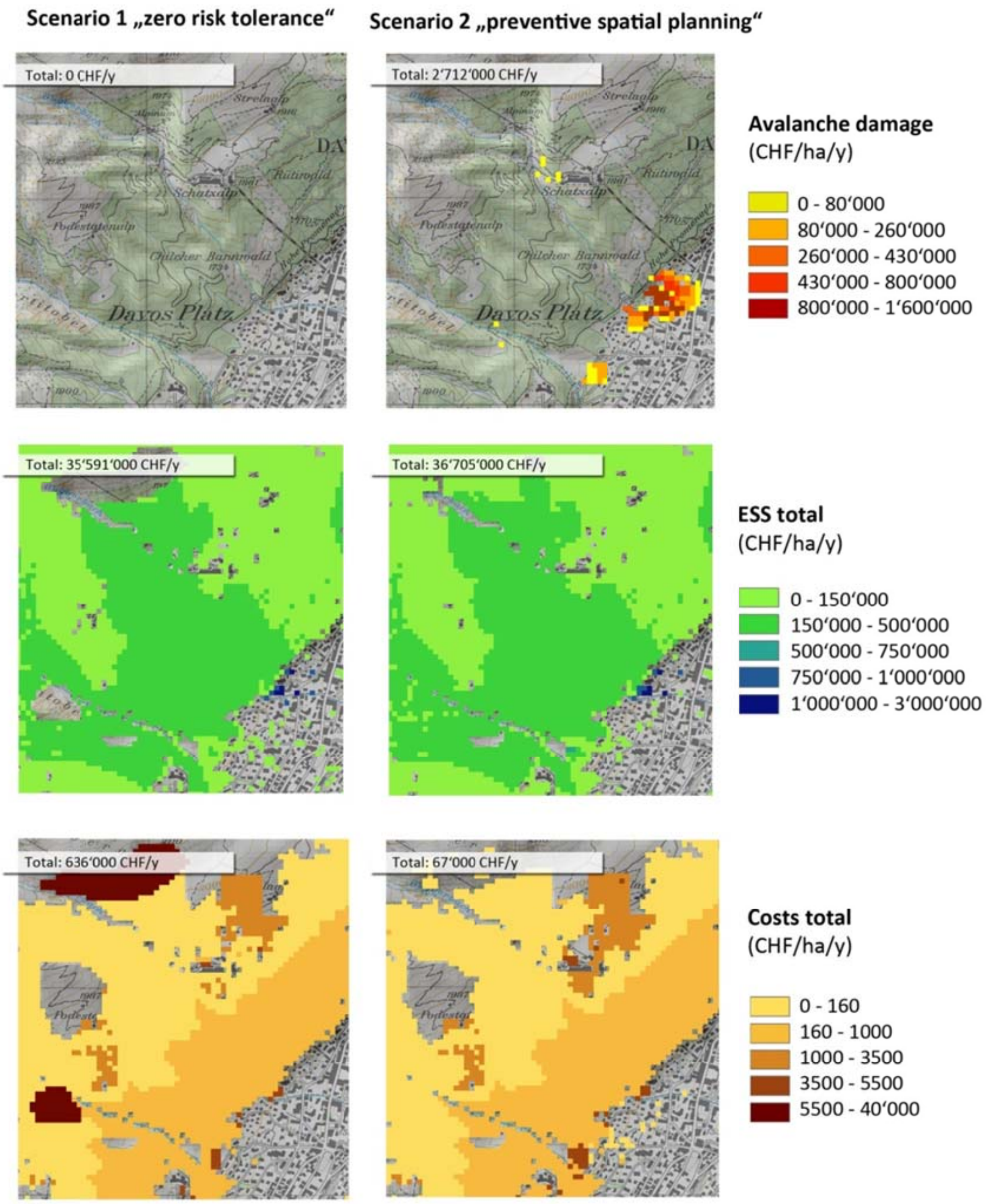

Figure 7. Comparison of future potential avalanche damage, ESS benefits and landscape management costs under different scenarios in Davos Platz.

3.4. Uncertainty map

Integrating a probabilistic approach such as a BN into a GIS offers the possibility to quantify uncertainties related to the calculated avalanche risks and ESS flows in a spatially explicit manner. Figure 8 visualizes such an uncertainty map for the carbon storage service under scenario 1. In addition to the color range that shows the expected value, we introduce a shading as a measure for the uncertainty of each value (following Grêt-Regamey et al., accepted b). Grid cells with dark shading have a large standard deviation as compared to their expected value, pointing to the large uncertainties in the estimation of the benefit of the service at these locations. Such zones predominantly lie at the border of the village where a variety of political and locational factors influence the expansion of settlement and the location of new infrastructure. In addition, uncertainties are enhanced near the current treeline where the extent of forest expansion is difficult to predict since biophysical as well as anthropogenic drivers interact and influence land-use change in these areas. In remote areas predominantly used as summer pastures and within close forest patches, land-use change is very unlikely and thus, uncertainties are lowest.

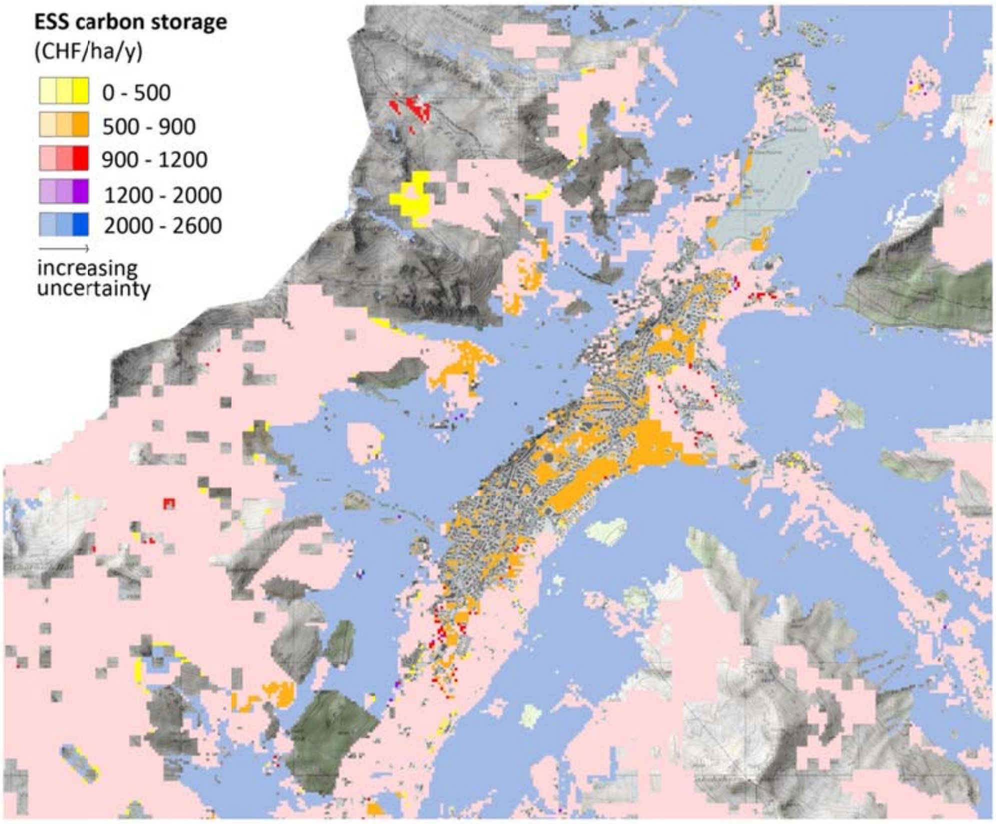

Figure 8. Map of the ecosystem service carbon storage including uncertainty visualization. The darker shading indicates high uncertainties in the model results.

4. Discussion

4.1. Data requirements and model set-up

Mapping a bundle of ESS, related management costs and potential damages from natural hazards in a region using a risk approach provides an overview on the integral risk landscape to decision-makers accounting for uncertainty in land-use changes. As a novel contribution to risk assessment tools our method presents results in a spatially explicit way at high resolution. The approach we present is at this stage relatively time consuming, involves manually performed tasks, needs expertise in modeling and in the use of geoinformation tools and is very data intense. Since spatially-explicit data are scarce, especially if needed as time series, both modules of our model rely on several assumptions that have to be kept in mind and discussed critically when interpreting the outcomes.

4.1.1. Land-use model

It is worth pointing out that the accuracy of future generated scenarios relies mostly on three factors: (1) the resolution of data, (2) the number of land-use categories, and (3) the spatial variability of land-use drivers. From a purely statistical perspective, higher data resolution leads necessarily to more accurate results. Higher data resolution also produces less smooth and therefore less uniform maps of predicted land use and ESS. Uniform maps are recommendable for representing global spatial trends, but not so much for performing local spatial analysis. As already mentioned, spatial data with high resolution is unfortunately not always easy to collect. In addition, this type of data usually makes the analysis computationally intensive and time-consuming. Concerning the land-use categories, there is no consensus about the ideal number of categories to be used in the analysis. Similarly to the data resolution analysis, the higher the number of land-use categories, the more accurate the results are. However, it may occur that some categories contain only a few numbers of observations yielding therefore misleading results. Finally, the spatial variability of land-use drivers is a key factor for the reliability of future scenarios. In order to generate realistic scenarios the explaining variables need to be significant for explaining the observed land-use transitions which is not always given in our case study. For example the subsidies variable exhibits low spatial variability over the study area. As a consequence, the effects of subsidies on land-use change can be poorly investigated in a spatially explicit manner. Since in Switzerland, the level of subsidies is an important driver to steer land-use changes into a desired direction, the generation of some future scenarios, especially those in which large extensions of lands are expected to be converted, may be difficult to explain. This however might also be typical for a touristic alpine district as Davos, where most farmers have a second income from tourism and where decisions on how to cultivate the meadows and whether or not to abandon them are not so much dependent on subsidies. In more remote areas where agriculture is the main income of population subsidies may serve as a good spatially explicit driving variable.

The development and analysis of land-use scenarios on landscape properties is an effective method of evaluating possible alternative futures (Francis and Hamm, 2011). In our case study, scenario analysis sketches a spectrum of potential future landscapes and related economic, ecological and social risks and benefits. In the context of regional planning and an advancement of a risk dialogue, participative scenario development requires stakeholders to clearly state assumptions and desired outcomes, leading to greater clarity and understanding of interests of different stakeholder groups and to a negotiation process on which planning options are of relevance for a region. Our approach offers great potential to involve stakeholders and policy-makers early in the modeling process for setting up scenarios and rules for the land-use model. However, projections of future land use and environmental conditions are uncertain and it is probable that the scenario assumptions stakeholder set up may not be valid in the future due to changing economic conditions and policy decisions. Using a special regression technique we can derive land-use conversion probabilities for multiple land-use types, thus, accounting for the uncertainty inherent to each scenario.

4.1.2. Ecosystem services models

Despite being acknowledged as a concept that bridges human welfare to services provided by ecosystems (Daily, 1997; MA, 2005), ESS modeling (especially including valuation schemes) is still a controversial topic (e.g. Ghazoul, 2008; Sagloff, 2010) and the concept is at risk of dying of misuse (Grêt-Regamey et al., 2012b). Nevertheless, in light of the increased vulnerability of and pressure on the landscape, the concept that frames the idea of conservation in light of economical benefits can help supporting decision-makers in balancing risks from natural hazards and technical and societal risks against flows of ESS and thus contribute to a sustainable landscape management.

Impact of alternative land-use or climate scenarios on the future provision of ESS has been modeled and mapped at different scale (e.g. Scholze 2006 at global scale, Schröter et al. 2005 at continental scale or Nelson et al. at landscape scale) with different modeling techniques. In order to potentially be applicable as a generic approach and practical tool, we have chosen a pragmatic method based on simple models representing ecosystem dynamics. Since uncertainties concerning the long-term development of ecosystems are manifold and more pronounced for such simplified approaches, we account for uncertainty following an approach of Grêt-Regamey et al. (accepted b). The risk approach based on BN integrated within a GIS platform allows propagating parameter uncertainty and results can be understood as an expected value similar to results from a traditional risk analysis. However, in order to be understood as such, adequate maps have to be designed that allow communicating this uncertainty to stakeholders (see next section).

The quantification and valuation of ESS that we applied in this study comes along with many simplifying assumptions. For example, we reduced the set of variables influencing the considered services to a minimum and only included elements which have been discussed before in other studies. Especially regarding cultural ESS, such as recreation, quantitative assessments are scarce and it is difficult to define biophysical properties representing a recreational value of ecosystems. BN however offer a great potential to refine these models for local circumstances as they allow the integration of stakeholders. Celio et al. (2012) showed that including stakeholder knowledge in BN can make land-use modeling more accurate. A positive side effect of the participation is the broader acceptance of the results and models within the stakeholder group and a deeper understanding of the functioning of the ecosystem. In this pre-study, we included expert knowledge only in very few input nodes mainly representing valuation procedures while it is most pressing to also discuss the model structure and refine conditional probability tables with local experts. For example, we used Swiss average values in order to determine the amount of fodder that can be harvested from intensive and extensive meadows. However, a local survey amongst farmers may reveal that in Davos the production is much higher or lower than we assumed. Another example is the attractiveness of green spaces that has been estimated depending on view, distance to lake and connectivity. Locals and visitors could provide important input in whether additional factors are relevant and how much priority they have for their perception of attractiveness.

Appropriate economic valuation methods are crucial for valuing and mapping ESS benefits. To monetize production services we use the direct market price of agricultural products and timber. Long-term estimates of values related to these services thus depend on future price development. We asked local experts to forecast future timber prices in the region and included them in the valuation of the future forest production service. Due to lack of time we were not able to conduct such a query amongst farmers and assumed the same fodder prices now and in future. Such different procedure is also reflected in the results: the value of timber production increases in future in all scenarios even if the forest area only grows slightly (scenario 4), since experts expect higher product prices than at the moment, while the agricultural production service loses in value until 2021 (however, also as a consequence of decreasing agricultural area). The impact of changing prices is most pronounced for carbon sequestration services. Economic experts expect a substantial increase of the carbon tax which enhances the value of the globally traded service accordingly. Valuing cultural services is even more difficult. We base our valuation on other studies in Switzerland which have been conducted to elicit the value of recreation using willingness-to-pay or travel-cost methods. Thus, the modeled value distribution is only a rough proxy for how recreation is perceived and appreciated at local scale in Davos. Here, visitors and residents could contribute crucially in describing the local demand for the service. Despite these limitations, valuation of ESS is crucial for comparing benefits from different services, thus, indispensable for evaluating cost-efficiency of alternative measures in the context of an integral risk management.

Scenarios have been implemented in the first module of the approach by examining plausible options of land-use change (see above). In addition, we have the possibility to adjust probability distributions in our BN depending on the different policy assumptions underlying each scenario. On the one hand, we could alter probability distributions of input variables, for example vary the future market prices or carbon tax depending on the scenario. On the other hand, we could assume that certain variables have less influence on specific services in future by adjusting conditional probability tables. However, due to lack of adequate quantitative information and a detailed and comprehensive elaboration of all scenarios, we used the same BN for modeling ESS in all future scenarios. This furthermore eases the interpretation of the results when comparing scenarios, since effects on the provision of ESS or the development of the avalanche risk in the region are a consequence of changing land-use policy and not due to a different valuation system.

In summary, the BN applied in this study is very preliminary. However, due to its flexibility the approach offers a lot of possibilities for improvement. BN can be updated as soon as new information is available, thus, results can continuously be improved and management strategies be adapted. In addition, they can easily be extended by other risks, for example technical risks that have not been considered so far in this assessment. Most importantly, they allow or even call for a participation of stakeholders and experts which is most pressing if results should support practical decision-making and anchoring a risk culture within society.

4.2. Practical implementation

4.2.1. The potential of maps

One of the key research questions of this study was whether the presented approach can help support sustainable development of a region. We have demonstrated different maps that have the potential to visualize various aspects of our modeling results and that are suitable for aiding spatial decision-making at local to regional scale.

Maps localizing areas of highest avalanche risks and regions where flows of ESS are most threatened by policy scenarios (Chapter 3.1) are useful for problem identification and framing. For example, the two planning strategies “large sport event” and “sustainable tourism” will alter preliminarily ESS provided in the main valley bottom of the landscape Davos. While in case of a sport event production services gain in importance, recreation services are under pressure and vice versa if sustainable tourism is pushed in the region. Thus, beside identifying sensitive regions that should be especially regarded when discussing planning strategies, maps can visualize trade-offs decision-makers have to consider in these regions.

ESS maps (Chapter 3.2) outlining the value of different ESS now or in future are a valuable communication tool helping to explain the relevance of ESS to stakeholders. Together with the BN illustrating causal dependence among the variables they can enhance system understanding and insight in ecological processes underlying the services. Moreover, such maps provide a monetary value of beneficiaries from ecosystems that can help decision-makers to understand the ecological value of a landscape and that can be used in cost-benefit analysis. Overlying the maps reveals ESS hotspots localizing ecologically valuable areas that should be considered and preserved when discussing and implementing planning strategies. In Davos, the forest at lower altitudinal belts provides a variety of services and should be managed accordingly. Preserving such forest patches not only maintains a level of ESS, but also guarantees a protection from avalanches in the valley bottom. Moreover, we have identified some extensively cultivated meadows as important avalanche retention areas supplying multiple additional ESS. Following an integral risk management and in light of a sustainable development, such areas should be preserved and prevented from being transformed to settlement area.

Maps comparing risks from avalanches, in the flow of ESS and of management costs under different scenarios (Chapter 3.3) can be helpful to identify suitable policy options and to better target related measures. At regional scale, a policy pushing a “sustainable tourism” increases potential avalanche damages but will maintain and enhance the value of ESS of the landscape. On the other hand, if Davos hosted a “large sport event” most ESS would suffer, but additional risks from avalanches could be prevented even though the village would further grow. Such assessments make the trade-off situation explicit and can support decision-makers in selecting a range of ESS at a targeted value and prioritizing planning strategies accordingly. Comparing the costs and benefits of the two strategies “zero risk tolerance” and “preventive spatial planning” with differing underlying assumptions regarding how and where to expand settlement areas reveals that in certain areas residual avalanche risks probably need to be tolerated, since measures to prevent from potential damages are very costly and will threaten many ESS. On the other hand, in areas, where risk from avalanches is very concentrated, single safety constructions, only diminishing ESS to a minor degree, can help reducing avalanche risks without large trade-offs. Thus, contrary to overall regional assessments, our approach can evaluate the efficiency of policy scenarios at very local scale and distinguish between areas where investments will result in minor changes from such where they result in major benefits for society in terms of economic, social and ecological revenues.

Integrating a probabilistic approach such as a risk approach related to BN into a GIS allows quantifying uncertainties in a spatially explicit manner (Chapter 3.4). Uncertainty maps visualize the geographical variation of uncertainties and can thereby increase the confidence in modeling results. Such maps can foster the credibility and acceptance of scientific studies in society and can show where policy measures have uncertain consequences. However, ways to communicate uncertainties related to ESS quantification and valuation in a useful manner to decision-makers remain largely unstudied. Thus, an ambitious effort is needed to go beyond just modeling ESS and related uncertainty and to develop appropriate methods for risk communication in ESS research.

Despite offering various potentials for supporting regional planning the presented results must be very carefully interpreted and the produced maps have to be used with a high degree of responsibility. Most critical in terms of credibility are the lack of adequate spatial data and the preliminary set-up of ESS process models. Especially, finding appropriate valuation techniques for different services remains a very difficult task while having a huge influence on the outcomes. We thus recommend a careful handling and communication of aggregated absolute values of different ESS but argue in favor of a spatially explicit representation of the values in maps which is not so much affected by the valuation procedure.

4.2.2. Recommendations for a generic approach

The methodology applied in this report has been developed as a pre-test for checking the possibility of establishing a generic approach for assessing a broad risk portfolio at local to regional or even national scale in a spatially explicit way for supporting sustainable development. In order to potentially serve as a generic tool, the following major challenges have to be addressed: (1) Data requirements are very high. Especially spatial data are often not available and if they are, they are not always available with the appropriate resolution. In Davos, we could profit from many previous studies, conducted modeling efforts and processed data. For example, we used avalanche run-out areas modeled for a study by Grêt-Regamey et al. (in review) in the avalanche risk BN, since hazard maps for the region are not available. Such simulations are time-consuming and need specific knowledge of underlying processes and modeling tools. (2) Drivers of land-use change have to be identified prior to the land-use modeling. These drivers may vary considerably amongst regions. Thus, in a first step, a set of possible variables need to be collected and processed to spatially explicit layers. Then, for each region independently, an analysis checking for explaining variables has to be conducted before starting the land-use model. (3) This as well as some subsequent steps, e.g. the land-use modeling itself or the preparation of certain input data to the ESS process models, currently rely on procedures involving many manual aspects and are not yet elaborate enough to be programmed in a generic way. For example, the calculation of the avalanche protection service in an automatic way remains a challenge ahead.

If these shortcomings can be overcome, we recommend establishing an interactive platform similar to the *Riskplan* platform for tapping the full potential of our approach. Such a platform should include some specific features: (1) Users need to have the possibility to add other risks, such as technical risks, or to choose in a risk catalogue among those risks that are most relevant for their analysis. (2) Stakeholders should be able to set up and design their own scenarios depending on their planning scope. One option is to predefine several determinants and related characteristic states for selection, e.g. the price for agricultural products, the amount of subsidies or the general attitude towards conservation of landscape and ESS. (3) ESS quantification and valuation models should be programmed in a flexible way. That is, users are allowed to change input probabilities and conditional probability tables of the BN refining the model for special local conditions. This also includes the possibility of implementing adjustment regarding the preferences for valuation in future. (4) A module for performing sensitivity analysis should be integrated in order to check the credibility of the results and as a possibility for gaining a deeper understanding of system functioning and its most sensitive elements. Maps generated on such a platform can than be used as an interactive exercise when negotiating with stakeholders about different land-use and investment options.

The aim of this study was to contribute to an advancement of methods for integrative risk management in Switzerland. Building on existing tools, our approach features particularly the following novelties: (1) Working with risk landscapes and efficiently implementing an integral risk management requires the comparability of different risks. The concept of ESS can help integrating ecological values and risks in a holistic management strategy. Set up as an utilitarian approach, the risk of ESS losses are valued from the perspective of the society, thus, are comparable to other risks such as those from natural hazards which are calculated as economic damages to society. (2) Municipalities still are the key players in managing risk landscapes, responsible for the security of people and infrastructure within the municipal boundaries (Greminger, 2012). The spatially explicit representation of risks at high resolution can aid targeting investments and risk-oriented decision-making at very local scale, thus, serving as a suitable decision support at the level of municipalities. (3) Uncertainties are integrated into the assessment of scenarios and can be communicated in a comprehensible way to stakeholders.

5. Outlook

In order to serve as a practical tool for supporting integral risk management in Switzerland, it remains a most pressing task to apply and improve the approach presented here to move beyond these preliminary and illustrative analyses. From a scientific point of view, establishing a blueprint for mapping ESS at national or even international level could help setting up more elaborate ESS models and improve the integration of ecological risks in the presented approach and in risk management in general as well as the acceptance of the concept amongst scientists and stakeholders. Applying the method country-wide and realizing it as an interactive platform and decision-support tool requires an easy access free of charge to data bases of cantons and municipalities. Beside the continuous improvement of methodological fundaments, an ambitious effort is needed to develop appropriate methods for risk communication. Only if risks and uncertainties are understood by affected stakeholders and decision-makers, integral risk management can be anchored in society and measures to reduce different risks will be efficiently implemented and broadly accepted. This requires that scientific analyses and results are processed and presented to non-scientists in an easy and understandable manner (Greminger, 2012), thus, the science-policy interface has to be strongly fostered. We thus recommend to further develop and improve our method in a transdisciplinary team of experts that can help designing the tool according to the needs of planners and decision-makers. While the approach presented in this study focuses on spatially-explicit management support important at local to regional scale, it is an additional major task to establish more aggregate instruments for risk-oriented planning at a strategic level at local to national scale. Greminger (2012) summarizes the current state of integral risk management in Switzerland, and associated limitations, challenges and requirements from a broader perspective.

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