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Panarchy and sustainable risk prevention by managing protection forests in mountain areas

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ABSTRACT: Mountain forests can prevent or reduce the risk posed by rockfall and avalanches, but to provide this service continuously most forests need to be managed. This paper explains the Panarchy theory and applies it to the management of a mountain forests that protect against rockfall. Using this theory in a simulation model helps to understand the interactions between protection forests, rockfall and forest organisations that have to take decisions on managing rockfall risks. We show that simulations based on the Panarchy theory, in which these different actors are linked, provide insight in the effects of different risk and forest management strategies and their costs on the long term. In many cases, innovative forest management could be sufficient to reach an acceptable level of safety. In the remaining cases, where technical protective measures are needed, an existing forest cover still has a mitigating effect meaning that less expensive protective constructions would suffice.

1 INTRODUCTION

The risk posed by natural hazards in the European Alps, such as rockfall (the fall of individual rocks smaller than 5 m^3) and snow avalanches, is quite small when expressed in terms of loss of human lives, especially when compared to other well-known threats and natural hazards in the world. However, some risks could locally be quite large, the financial ones in particular, mainly due to the obstruction of important traffic ways and due to the destruction of housing and infrastructure. These risks can be significantly reduced or sometimes prevented by forests, as they can stop falling rocks (Gsteiger 1993, Berger et al. 2002) or prevent the release of snow avalanches (Berger, 1996, Weir, 2002). Individual trees and groups of trees, also called forest stands, can thus save lives and money. Forests that explicitly provide protection against natural hazards are called protection forests (Brang et al. 2001).

Mountain forests in the European Alps and the protection they provide have a long and distinguished history (Schönenberger 2000, Dorren et al. 2004a). Without these forests, the costs of building and maintaining technical protective constructions would be unaffordable. This is recalled in the first paragraph of the Mountain Forest Protocol of the Alpine Convention: 'Mountain forests provide the most effective, the least expensive and the most aesthetic protection against natural hazards.' In Austria and Switzerland alone, approximately 50 million Euros are spent yearly to maintain or improve the protective effect of mountain forests (European Observatory of Mountain Forests 2000, Swiss Federal Statistical Office 2002). In spite of the huge amounts spent, the protection a forest can provide is difficult to quantify, since empirical data on the mitigating effect of forests on natural hazards are sparse. Therefore, we are trying to quantify the protective effect of forests, primarily against rockfall, but also against snow avalanches. To achieve this, we use real-size field experiments (Dorren et al. in press) and we developed 3D rockfall simulation models that explicitly take the role of protection forests into account (Dorren et al. 2004b).

The available scientific data show that existing forests in mountain areas protect for a large part against rockfall (Jahn 1988, Gsteiger 1993, Dorren et al. in press), of course depending on the state of the forest cover and the site conditions. The hazard posed by rockfall, the rockfall velocities and the rebound heights significantly decrease on forested slopes compared to similar non-forested slopes. Currently, we also know the relationship between the diameter of different tree species and the maximum amount of energy that can be dissipated by different tree species (Dorren & Berger in press). This is an important step as it enables us to quantify the energy that can be dissipated by forest stands and compare them with technical measures such as rockfall nets or other kinds of barriers. We argue that protection forests can provide effective and sustainable basic protection against rockfall, if the potential, which means a good combination between stand density and stem diameters with regards to the rockfall magnitude (cf. http://www.rockfor.net) is present at the site. In cases where forests cannot provide sufficient protection, because slopes are too steep or too short, or the forest is degraded and its structure is not dense enough, protection must be provided by technical measures such as rockfall dams, nets, tunnels, etc. Even then the mitigating effect of the existing forest cover should not be neglected. In this paper, we will give background information on protection forests. We will also explain the Panarchy theory (Gunderson & Holling 2002) and use it in a first simulation experiment to understand the interactions between protection forests, rockfall and a forestry organisation that has to take decisions on managing rockfall risks. In the simulation experiment we tested different cases of investments in protection forest management and in civil engineering and their effects on the rockfall risk over time.

2 THE PANARCHY THEORY

2.1 *Panarchy*

A Panarchy is a structure in which systems (e.g., natural, human, as well as combined human-natural systems) are interlinked in continual adaptive cycles (Holling 2000, Gunderson & Holling 2002). In an adaptive cycle, four distinct stages have been identified: (i) exploitation or growth, (ii) conservation, (iii) release or collapse and (iv) reorganisation (Fig. 1). Many systems (human and natural) can be represented by such a cycle. It exhibits two major transitions. The first, from exploitation to conservation, is the slow, incremental phase of growth and accumulation. The other, from release to reorganisation, is the rapid phase of reorganisation leading to renewal. The first is predictable with higher degrees of certainty. The consequences of the second phase are unpredictable and highly uncertain. An important consequence of the adaptive cycle is that the resilience of a system changes throughout an adaptive cycle. Resilience is high during the growth phase and it shrinks as the cycle moves towards the conservation phase, where the system becomes more fragile. Resilience expands again as the cycle shifts rapidly into a back-loop in which system resources are organized for a new initiation of the cycle.

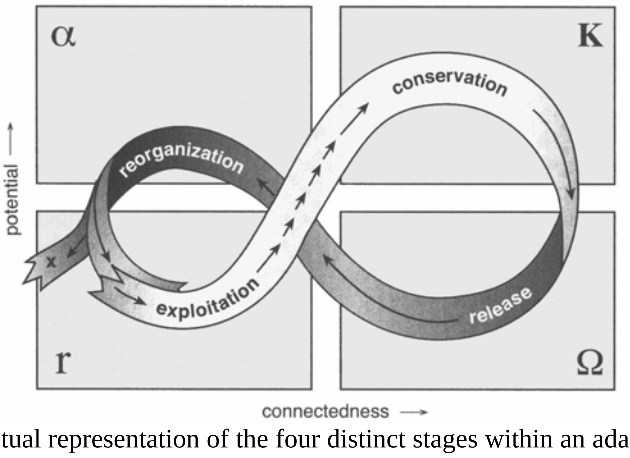

Figure 1. A conceptual representation of the four distinct stages within an adaptive cycle (from Gunderson & Holling 2002).

Panarchy has evolved from hierarchy theory, firstly applied in geo-ecosystem research by Allen & Starr (1982) and O'Neill et al. (1986). They initiated an increase of theoretical understanding by viewing the landscape as a multi-scale dynamic system in which biotic and abiotic processes interact. However, both the adaptive nature of such systems, organized by periodic and transient phases of growth, conservation, collapse and reorganisation and the interaction with human systems has tended to be lost. Therefore, Panarchy, a term devised to describe evolving hierarchical systems with multiple interrelated elements, offers an important new framework for understanding and resolving this dilemma. By examining complex natural systems within this structure it should be possible to identify moments or periods within a single cycle where the system is most receptive to actions that create positive change and enhance sustainability (after Gunderson & Holling 2002). In other words this framework should help identify which actions are necessary and which are redundant.

Back from the theory on adaptive cycles to the reality of protection forest and natural risk management. To clarify the adaptive cycle metaphor and Panarchy we will describe an example from a forest that protects against rockfall in the European Alps, in which forest management or silvicultural interventions are required to sustain its protective function. Here, the protection forest, the organisation responsible for managing the forest and the rockfall risk, as well as the occurrence of rockfall throughout a year follow cycles that could be described by the adaptive cycle metaphor. The following paragraphs will provide some background information on the rockfall and protection forests and their link with the Panarchy case explained here.

3 FORESTS AND ROCKFALL

3.1 *Protection forest*

Generally, a protection forest has mainly an object-protection or direct protective function (Schönenberger 2000). At the same time a forest provides a site-protection or indirect protective function, which is actually a prerequisite for the direct protective function. In addition, like all mountain forests, protection forests provide multiple functions, such as recreation, sequestration of carbon dioxide and conservation of biodiversity.

The direct-protective function of a forest implies that the forest directly protects people, buildings and infrastructure against the impact of natural hazards such as snow avalanches and rockfall. The indirect-protective function is important, as a forest stand needs to protect its site against processes such as excessive soil erosion. If the site-protection function is impaired, the forest site erodes, which results in a loss of the forest ecosystem as a whole (Dorren et al. 2004a).

Mountain forests are self-organising ecosystems if regarded at a landscape scale, which normally do not need any silvicultural intervention for their continued existence. But people want to exploit the multiple services provided by forests continuously. Therefore, some forests have become degraded as a result of over-harvesting, heavy ungulate browsing or livestock grazing and need to be managed in order to fulfil the protective function. This means that some forests can be left untouched, others can be managed and some need to be managed.

Mountain forest stands constantly evolve from a regeneration phase to an optimal phase and back again, as illustrated in Figure 2. During the transition phases in between the forest structure develops or breaks down. As a consequence the protective function decreases during those phases (Motta & Haudemand 2000), which is also indicated in Figure 2. The rate of transition into a next phase is not only determined by growth or ageing of individual trees, but also by the effect of disturbances on the forest ecosystem (Picket & White 1985). Rockfall and snow avalanches are natural disturbances in mountain forests that drive development and change. By doing so, they also affect a forest stand in a positive way, if their magnitudes are limited, that is to say, if they do not destroy the entire forest stand.

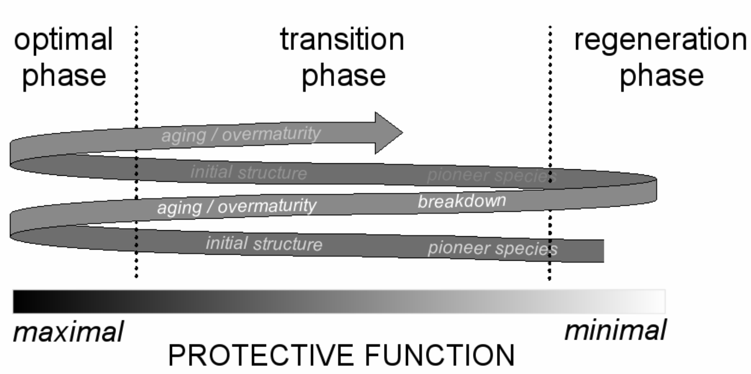

Figure 2. Developmental phases in mountain forests in relation to the level of protection they provide.

Due to the constant evolution of a forest following century or centuries long cycles shown in Figure 2, forests exhibit great examples of adaptive cycles. The stage r in Figure 1 represents succession and growth from pioneer species to "climax" species, which is the optimal phase K. This is followed by an aging/overmaturity phase where the forest is vulnerable for major disturbances like storms or bark beetle invasions (phase Ω). As a consequence, the forest ecosystem "breaks down" and reorganizes itself in a new cycle, phase α (after Holling 2004). For a protection forest in the European, such a cycle could take 250 years.

3.2 *Rockfall*

Rockfall starts with the detachment of rocks from bedrock slopes, which is mostly a cliff face in case of a rockfall source area. All bedrock slopes are subject to various degrees of weathering, which may lead to fracturing, opening of joints and therefore to promotion of rockfall. Apart from the weathering rates, trigger mechanisms also determine whether rockfall occurs or not. The most well known promoter and cause of rockfall is the frost-thaw cycle (cf. Dorren 2003). This is also being confirmed by research findings on rockfall and global warming. In the European Alps, an increase of rockfall events can be expected due to the melting of permafrost on steep slopes and cliffs (Harris et al. 2000, Gruber et al. 2004, Gude & Barsch 2005). Stoffel et al. (in press) showed on a site in the Swiss Alps that rockfall is most active in spring. Another promoter of rockfall events is heavy rainfall. In the European Alps, this generally occurs in the summer and autumn. Looking at the graph of the adaptive cycle (Fig. 1), two high potential phases can be recognized. The highest potential is during phase K. Between this phase and the next phase Ω, connectedness reaches its maximum value and consequently decreases. Literally, this could represent the weathering rate in the bedrock, i.e. how 'loosened up' the rock wall is. Then, this phase would represent the winter going into spring when the ice that holds the bedrock together melts. This leads to frequent rockfall events. The other phase where rockfall frequently occurs is between phase α and r (Fig. 1). This would then represent the late summer and autumn. As such, the adaptive cycle metaphor can be used to describe a one-year cycle of potential rockfall events. This cycle is, however, not very adaptive, but rather similar through time.

After the rock has been detached and starts to move, it descends the slope in various modes of motion, which can be: freefall through the air, bouncing on the slope surface, rolling and sliding. The effect of a forest cover on these modes of motion is significant. Our real size field experiments on forested and non forested slopes show that the mean bounce height decreases at least with 33% and the velocity decreases with at least 26% if a forest cover consisting of 290 trees per ha is present (Dorren et al. in press). This confirms the findings of previous research on rockfall in forests (Jahn 1988, Zinggeler 1990, Gsteiger 1993, Doche 1997, Dorren et al. 2004b, Perret et al. 2004). Also the residual rockfall hazard on a 38° slope, expressed in the number of rocks that surpass a zone with a length of 223 meters, decreases from 95% to 34% when going from the non-forested to the forested site. The paradox is that a big rock has a bigger chance to impact a tree, but also bigger trees are required to stop the rock. For smaller rocks, smaller trees are effective, but many more trees are required to increase the probability of an impact. In general, we believe that for effective protection, a large number of trees is more important than having thick trees only. This fact offers good possibilities for promoting protection forests as sustainable protective measures. It allows the application of selective thinning of forest stands or other minimal tending techniques that promote regeneration and ensure the forest to stay in an optimal condition regarding its protective function (Motta & Haudemand 2000, Dorren et al. 2004a).

4 PANARCHY SIMULATION

4.1 *Main actors*

The main actors in the Panarchy of a rockfall protection forest are the frequency and magnitude of rockfall, growth of individual trees, regeneration and breakdown of the forest as well as silvicultural or technical interventions. These variables are all interacting. At the same time, some of them are the result of an adaptive cycle within themselves. For example, whether or not silvicultural interventions will be carried out in protection forests depends on factors acting in social, economical and to a lesser extent forest ecological systems. During our Panarchy simulation study we defined three adaptive cycles: 1) the cycle of the protection forest, 2) the rockfall cycle and 3) the cycle of the forestry organisation. The latter is, in the European Alps, partly responsible for the reduction of the risk posed by natural hazards such as rockfall, snow avalanches, soil erosion, debris flows and torrential floods.

As shown by Bunnell (2005), human organisations can perfectly be described by an adaptive cycle. A starting organisation has generally a pioneer spirit, a lot of energy to work and creates many opportunities. This starts a progression from r to K as they grow and accumulate potential from resources acquired. Connectedness in the organisation and its network begins to increase. In phase K, increasing efficiency and minimizing costs achieve more return. At the same time the organisation becomes more vulnerable to surprise. And slowly, it could become bureaucratised, rigid and internally focused, of course depending on management and design. In the cases of extreme and growing rigidity, all systems become accidents waiting to happen. The trigger might be entirely random and external - a new critic appointed to the Board of Directors of the company, an election of new Minister of Government responsible for the agency. As a consequence a gale of creative destruction can be released in the resulting Ω phase. People are fired and the organisation will be reorganized (phase α). Some of the skills, experience and expertise lost by the disintegrating organisation remain in the individuals and hence exist as a potential for future use (after Bunnell 2005).

4.2 *Model settings and rules*

Our study case deals with a 100 × 100 m sloping area, covered by forest, which protects a down slope road and a settlement against rockfall. Time periods of 50 - 100 years are simulated, during which the forestry organisation has to decide what rockfall risk reduction techniques (silvicultural or technical) will be used. The goals of the simulation are firstly to estimate the amount of money required over time to keep the rockfall risk under the forested slope as low as possible. Secondly, the simulation model calculates the actual risk for each time-step, which allows analysing the efficacy of the investments in terms of risk reduction.

Three cycles are simulated, which cover different time scales: the protection forest cycle, which covers 250 years, the rockfall cycle, which covers 1 year, and the forestry organisation cycle, which covers 20 years. The decisions taken by the forestry organisation depend on the rockfall risk, on the available amount of money and on the cycle phase the forestry organisation is in. The rockfall risk is determined by the rockfall hazard potential (the rockfall cycle), by the state of the protection forest (the protection forest cycle) and, of course, by chance (probabilistic simulation). Three probabilistic algorithms are very important in the model:

1. a randomiser that determines whether a rock will actually fall; the rockfall cycle determines the probability of a potential rockfall
2. a power law, described by Hergarten (2004), that determines the volume of the falling rock (all rocks are assumed to fall from a cliff with a height of 20,4 m, which results in

a velocity on the slope surface of 20 m/s). The following power-law size distribution is used to calculate the volume (V) of the falling rock during each time step:

$V = (500 * \text{rand})^{-0.5}$ (1)

where *rand* is a random number chosen from a uniform distribution on the interval (0, 1.0). Each simulation time step, which equals 1 month, we use the maximum event size of 30 simulated rockfall events. Therefore, we chose the parameters of the power law as such that small rockfall events (< 0.04 m^3) would not occur. By doing so, we assumed that these small events occur throughout each month, but they do not affect protection forests.

3. a randomiser that determines whether the rock is stopped by the forest. This depends on the protective potential of the forest, which is determined by the forest cycle and is expressed in the percentage of rocks that surpasses the forested zone (Fig. 3).

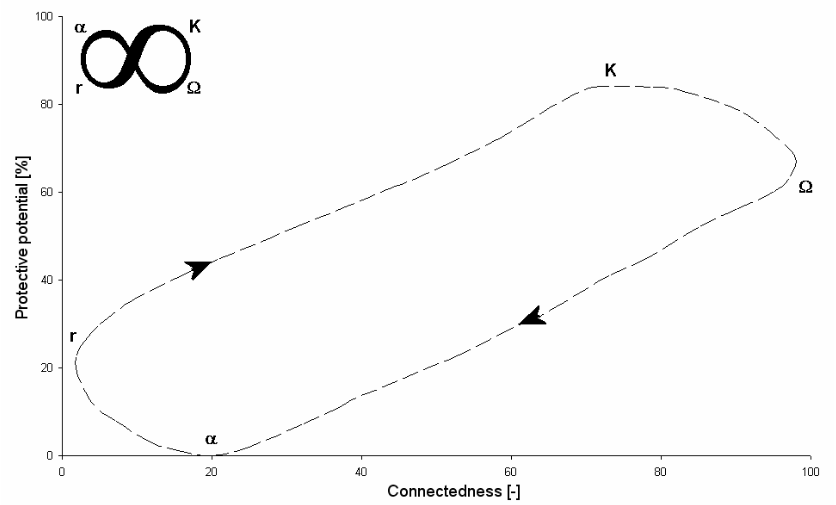

Figure 3. The protective potential of a forest, expressed in the percentage of rocks that surpasses the forested zone, for each phase in the adaptive cycle.

The protective potential of the forest changes each time step, because it depends on the protection forest cycle phase (Fig. 3), and it decreases due to rockfall damages on trees, depending on the volume of the rockfall event (cf. Table 1). There are no existing data to confirm the latter rule, but simulation tests showed it provides realistic results.

Silvicultural interventions, carried out by the forestry organisation , result in forward or backward phase shifts in the cycle, which have a direct link with the level of protection provided by the forest. The forestry organisation does not intervene in the forest before a rock reached the area under the forested slope with a kinetic energy of 50 kJ (we define this as risk level 5, a rock surpassing the forested slope with 1000 kJ means a risk level 100). The risk level 5 is sufficient to damage a car or even kill someone. To reduce the rockfall risk, the forestry organisation can decide to use silvicultural/eco-engineering or civil engineering techniques, depending on the forest cycle phase and the available capital. Eco-engineering techniques refer to selectively cutting trees and leaving the stems in the forest, which will then act as barriers against rockfall. We assumed that if such stems were present on the whole slope, the protective effect would be 95%, i.e. only 5% if the rocks would pass the forested zone, under the condition that falling rocks would not reach an energy of more than 1000 kJ. If the forest cycle is in phase K or Ω, the above mentioned techniques are very effective, because many mature trees are present. The protective effect provided by eco-engineering (EcoProt) is thereby assumed to be effective for 10 years, i.e. the tree stem barriers are assumed to provide effective protection for 10 years (EcoProt = 10 years, cf. Table 1).

Table 1. Rules and conditions used in the simulation model.

Variable	Phase	Implication	Condition / Rule 1	Condition / Rule 2
Forest	r	Protective potential 12-55%	If rockfall event > 1000 kJ then protection = 0%	Protective potential of forest decreases with 0.25 (%/kJ) * energy of rockfall event (kJ)
	K	Protective potential 55-85%		
	Ω	Protective potential 25-67%		
	α	Protective potential 0-25%		
Rockfall	r	Rockfall potential 2-31%	Rock mass = 2800 kg	Initial rock velocity = 20 m/s
	K	Rockfall potential 37-97%		
	Ω	Rockfall potential 60-98%		
	α	Rockfall potential 7-53%		
Forestry organisation	r	EcoProt = 2 years, FC + 1*	Forest in phase r	Capital > = 10.000 €
		EcoProt = 10 years, FC→K(1)**	Forest in phase K	Idem.
		EcoProt = 10 years, FC→r(1)***	Forest in phase Ω	Idem.
		EcoProt = 5 years, FC→r(1)	Forest in phase α	Idem.
	K	CEProt = 20 years, FC + 1	Forest in phase r	Capital > = 100.000 €
		EcoProt = 10 years, FC→K(1)	Forest in phase K	Capital > = 10.000 €
		EcoProt = 10 years, FC→r(1)	Forest in phase Ω	Capital > = 20.000 €
		CEProt = 20 years, FC→r(1)	Forest in phase α	Capital > = 75.000 €
	Ω	CEProt = 20 years, FC + 1	Forest in phase r	Capital > = 120.000 €
		EcoProt = 10 years, FC→K(1)	Forest in phase K	Capital > = 20.000 €
		EcoProt = 10 years, FC→r(1)	Forest in phase Ω	Capital > = 40.000 €
		CEProt = 20 years, FC→r(1)	Forest in phase α	Capital > = 100.000 €
	α	No actions can be taken		

* FC +1: The forest ecosystem advances 1 step in the current forest cycle phase
** FC→K(1): the forest cycle shifts to the beginning of phase K
*** FC→r(1): the forest cycle shifts to the beginning of phase r

In the forest cycle phase α and r, additional civil engineering techniques, such as the installation of rockfall nets, will have to be used. Thereby, the protective effect provided by civil engineering (CEProt) is assigned a lifetime of 20 years (CEProt = 20 years, cf. Table 1). In these forest cycle phases eco-engineering protection is only effective for 2 - 5 years. However, this can only be done if the forestry organisation has enough capital available. The installation of rockfall nets all along the slope would cost 100.000 €, which corresponds exactly to the available capital of the forestry organisation at the beginning of the simulation. Eco-engineering interventions cost about 10.000 €, but the costs are depending on the cycle phase of the forestry organisation and on forest the cycle phase, because trees provide additional protection and less rockfall nets are needed. In phase Ω, everything is more expensive. The simulation model has an option to include state subsidies for emergency projects. Additional model rules that are too specific to describe in the text are given in Table 1.

5 FIRST RESULTS OF SIMULATION EXPERIMENTS

Out of the wide range of our first simulation results, we will present some key outcomes. The two most important factors for analysing during the simulations were the forest cycle phase at the beginning of the simulation and the availability of subsidies for risk preventive/reductive measures. Figure 4 shows an example of a simulation result with a forest in an optimal phase (forest cycle phase K) and the availability of a subsidy of 10.000 € each year. The initial capital of the forestry organisation was 100.000 €. The upper graph shows the kinetic energy of the rockfall events that were simulated for each month during the simulation period of 50 years. The graph below shows the evolution of the protective capacity of the forest during the simulation period. This shows that by taking silvicultural interventions the protective capacity can be maintained at 85%. This has, however, an effect on the costs of managing the protection forest, which are shown in the graph below. After 50 years the forestry organisation spent 79.000 € for reducing the rockfall risk in the case study forest. The efficacy of the investments is shown in the bottom graph. Without the forest cover, the rockfall event of almost 500 kJ that took place in year 23, would pose a serious risk. With the protection forest and an investment of 20.000 €, however, the simulation model produced a risk of 0. The results show that there are many examples such as this one.

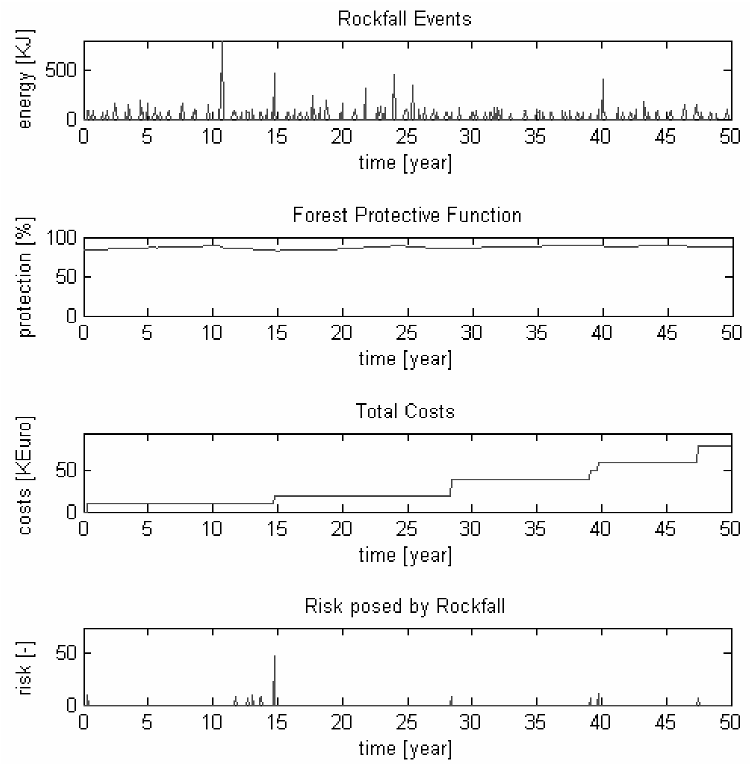

Figure 4. The results of a Panarchy simulation with a forest in an optimal phase (K) and the availability of a subsidy of 10.000 € each year.

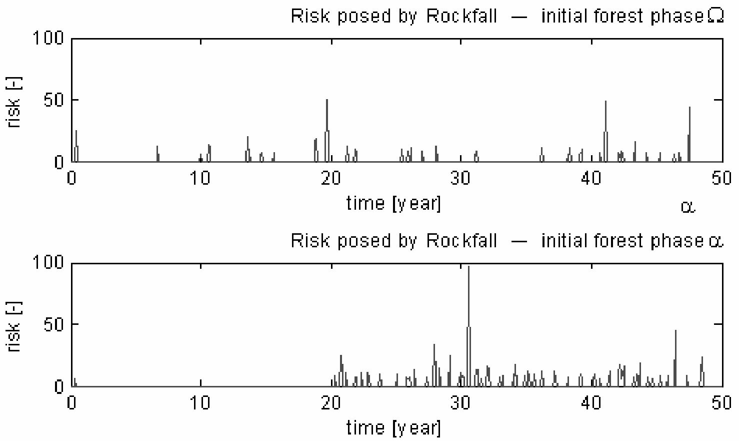

Figure 5. The risk posed by rockfall resulting from a Panarchy simulation with a forest in an aging/overmaturity phase (Ω) and in a breakdown/reorganisation phase (α) without a yearly subsidy.

Two different cases are shown in Figure 5. The upper graph shows the risk posed by rockfall resulting from a Panarchy simulation with a forest in an aging phase (forest cycle phase Ω) and the lower graph with a forest in a breakdown phase (forest cycle phase α). In both simulations, subsidies were not available. The initial capital of the forestry organisation was 100.000 €. The results show that the risk can be maintained below a level of 50 in the case of a forest in an aging phase; only silvicultural interventions have to be used, resulting in a total cost of 90.000 € after 50 years. In the second case, where the forest is in transition between the breakdown and the reorganisation phase, civil engineering techniques are required, resulting in a total cost of 100.000 € in the beginning of the simulation. As subsidies are not available, no further investments can be done in reducing the risk on the case study slope. The resulting increase in the posed risk from year 20 onwards is clearly shown in the bottom graph in Figure 5.

6 DISCUSSION

The Panarchy theory, which links different adaptive cycles, provides a wide range of possibilities to design simulation models to understand the interactions between protection forests, rockfall and human organisations that have to take decisions on managing rockfall risks. By developing a simulation model based on the Panarchy theory, we demonstrated different cases of investments in protection forest management and civil engineering solutions and the effects on the rockfall risk over time. Here, we presented results that could be easily explained, but they show that a Panarchy simulation, where completely different actors are linked, provides insight on the effects of different management strategies and their costs on the long term. As losses due to natural disasters are steadily increasing, despite many investments in technical protective measures in the past, we believe that traditional protective measures should be re-evaluated. Present economic restrictions justly require more and more the development of models for 1) quantifying the efficacy of different protective measures and 2) for the optimal allocation of finances. A Panarchy simulation as demonstrated here could provide a good basis for that.

One of the positive aspects of the Panarchy simulation is that rather basic rules can simulate complex problems that exist in reality and provide a basic insight. In addition, the open structure of the developed Panarchy model easily allows increasing the complexity of the used model. Using process-based models for rockfall simulation and forest stand development in combination with socio-economic decision models for the forestry organisation could do this. Finally, an advantage is that the process of developing simulation models forces to structure available knowledge and data. This automatically identifies current gaps and research needs to answer important questions raised by foresters, risk managers and policy-makers.

7 CONCLUSIONS

The adaptive cycle provides a good metaphor for the evolution of a protection forest ecosystem, as it describes how forest stands constantly evolve from a regeneration phase to an optimal phase and back again. A simulation model based on the Panarchy theory, which links different adaptive cycles, helps understanding the interactions between protection forests, rockfall and human organisations that have to take decisions on managing rockfall risks. It provides insight on the effects of different management strategies and their costs on the long term. Current models and knowledge show that, in many cases, innovative forest management could be sufficient to reduce the rockfall to a level that could be accepted by local authorities, depending on the location. In the remaining cases, where technical protective measures are needed, an existing forest cover, enhanced with eco-engineering techniques, has a additional mitigating effect, which should be taken into account when planning and designing technical protective measures. Finally, we believe that the Panarchy theory and research on combined natural and human systems can help to develop models for quantification of the efficacy of different protective measures to optimise the allocation of investments for risk reduction.

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