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# SOIL EROSION AND THE ADAPTIVE CYCLE METAPHOR

L. K. A. DORREN[1]* AND A. C. IMESON[2]

[1]*CEMAGREF Grenoble, 2 rue de la Papeterie, BP 76, F-38402 Saint Martin d'Hères cedex, France*
[2]*IBED—Physical Geography, University of Amsterdam, Amsterdam, The Netherlands*

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## ABSTRACT

The landscapes that we live in and the changes that they undergo play an important part in the qualities of our lives. They provide natural goods and services of value to us because of the existence of soil, which is a medium between the solid earth and the sphere in which we live our daily life. The medium soil is constantly subject to change and one of the causes is soil erosion. If one tries to understand or to deal with soil erosion it is helpful to consider soil as an integral part of continuously changing landscapes and to be aware of the different functions of a soil in its environmental context at different scales. To clarify this, we present three important concepts. These are: (1) scale/connectivity; (2) change; and (3) resilience. These concepts will be put in an innovative framework called the panarchy theory, which represents a hierarchical structure in which both human and natural systems are linked together in adaptive cycles. Presenting soil erosion in such a framework allows us to link causes and their impacts at different scales. The application of such a framework and the insight obtained could facilitate the assessment of risks and possibilities for sustainable use. Copyright © 2005 John Wiley & Sons, Ltd.

KEY WORDS: soil erosion; panarchy; adaptation; South-Limburg; resilience; geo-ecosystem; The Netherlands

## INTRODUCTION

The landscapes that we live in and the changes that they undergo play an important part in the qualities of our lives as the development of infrastructure and industry, housing and exploitation of the earth's resources are still prerequisites for growth in current Western economies. But landscapes also provide additional natural goods and services of value to us, such as recreation, water and climate regulation, food production, tourism and nature conservation. These goods and services, or so-called functions of nature (de Groot, 1992), are provided because of the existence of soil, which is a medium between the solid earth and the sphere in which we live our daily life. The medium soil is constantly subject to change, the causes of which are dependent on the geographical position of the soil. Examples of such causes are the activity of microorganisms and animals that live in the soil, the weathering of bedrock, which increases the thickness of the soil, the input of organic material by farmers or the accumulation of dead plant material. Another example is soil erosion.

Soil erosion is identified by the European Commission (EC) as one of the major threats to soils in Europe (CEC, 2002). At the time of writing, the European Union (EU) is engaged in the process of developing a policy for soil protection, and erosion will be one of the focal points in it. Since the seventies much research has been done on soil erosion in different parts in Europe. As a result, both the soil-research and soil-protection communities have amassed much data, knowledge and experience that can be applied and used in support of soil-erosion policy development. Unfortunately, this and other information about soils is offered scattered, difficult to read and sometimes seemingly contradictory. The concepts and nomenclature that have enabled soil scientists to build up a world-view of the soil and its dynamics are an enormous achievement, but at the same time they limit access to the

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*Correspondence to: L. K. A. Dorren, CEMAGREF Grenoble, 2 rue de la Papeterie, BP 76, F-38402 Saint Martin d'Hères cedex, France.
E-mail: luuk.dorren@cemagref.fr

initiated. Unfortunately, too, soil science is both highly sophisticated and highly fragmented and policy-makers are consequently presented with often subtly dissimilar, or seemingly contradictory opinions that lead to confusion and withdrawal. Therefore, the aim of this paper is to provide a framework that explains the nature of soil erosion. To do this we will use the adaptive cycle metaphor, which represents change and connectivity and their role in natural systems. We will present soil erosion as a 'big picture' using a framework that allows causes and their impacts to be linked at different scales.

## SOIL EROSION AND LANDSCAPE CHANGE

In order to understand or deal with soil erosion it is helpful to consider soils as integral parts of continuously changing landscapes and to be aware of the different functions of a soil in its environmental context at different scales (Imeson and Lavee, 1998). To clarify this, we will elaborate on three important concepts. These are: (1) scale/connectivity; (2) change; and (3) resilience.

### *Scale and Connectivity*

The concept of scale became widely used in environmental sciences after the introduction of the hierarchical systems theory (Allen and Star, 1982; O'Neill *et al*., 1986). Within a hierarchical system, many subsystems at many spatial and temporal scales can be defined (Bergkamp, 1995). Based on the aim of a stakeholder, such as the writer of a soil-protection policy, the farmer, the scientist, or yourself, a level of interest within a landscape system could be defined. An example could be that you are interested in the soil underlying your favourite spot in a natural landscape. The spatial scale of this level of interest is the area over which you could look easily from this spot, e.g. fifty by fifty metres. The hierarchical systems theory implies that the organization of this level of interest, or actually any level of interest, is generated by at least three levels (Kirkby *et al*., 1996):

1. *A focal level*, which is the area over which we could look in the favourite spot at that moment in time, which is in other words directly concerned with the objectives of a stakeholder.
2. *A higher level*, associated with relatively broader spatial and temporal scales, at which changes occur more slowly. In the example, this means what is happening in the area around the favourite spot and not only at present but also in the past and in the coming years, decades, or sometimes even centuries.
3. *A lower level*, at which changes occur rapidly on fine spatial and temporal scales. This level refers to the spatial scale of a small pit we dug in the ground and the processes that are taking place there, such as the earthworms burrowing in the soil, the growth or decay of plant roots, or the deposition of microscopic matter from the atmosphere.

Connectivity of nature across both adjacent and more distant systems is important as ecological and geomorphological buffering and transmitting takes places across various scales, both in human and natural systems. Therefore, connectivity is a vital element of landscape structure (Taylor *et al*., 1993). To assess connectivity in a landscape, one cannot focus on one scale, the hierarchical structure has to be assessed.

### *Change*

From the concept of scale, it is easy to make a link with change, because understanding what is happening at a certain level of interest implies that we should analyse what is happening at both broader and finer (spatial and temporal) scales than the ones we only tend to observe. In other words we should not restrict our observations to the focal level. If a certain level of interest is studied within the framework of a hierarchical system, it could happen that this certain level, which we considered stable and unchanging, is in fact actually changing or even unstable. This is because change or disturbance (White and Picket, 1985) could take place at another level within the system. This also affects the level that we are interested in. Regarding the concept of change specifically, this means that change in landscape systems can only be understood fully if the concept of scale and connectivity is considered as well. The following example from fluvial geomorphology illustrates this. A change in the base-level of a catchment, e.g. if the land rises relative to the sea, this causes a reaction in the larger rivers in the catchment.

These start to incise into the landscape as the land rises and as a consequence the mean gradient of the river, measured between the upper part of the catchment and the sea-level, increases. Therefore the running water increasingly has more energy to remove soil material or to incise into the bedrock. Smaller rivers, in tributary catchments, where farmers have their agricultural fields, will eventually also react by incising into the underlying terrain. Looking at this moment in time to the agricultural fields in the tributary systems, these are considered not to be changing, apart from some slow but constantly ongoing changes, such as biological, physical and chemical changes in the soil itself, slow weathering that produces more soil from the parent material, the activities of the farmer that change the soil and occasionally running surface water that erodes soil particles. Why is soil erosion such a local problem in both Spain and Norway? This is because both of these regions have undergone dramatic uplift of several hundreds of metres, in the recent geological past and the continuing adjustment of fluvial systems makes erosion almost inevitable.

### *Resilience*

Whether erosion actually occurs depends on the resilience of the ecosystem, which is determined by ecosystem processes at different spatial and temporal scales. Resilience has two meanings in the ecological literature, both related to system state and disturbance. Engineering resilience is the time of return to a global equilibrium following a disturbance. Ecological resilience is the amount of disturbance that a system can absorb before it changes to an alternative stable state. A resilient ecosystem can withstand shocks and rebuild itself when necessary. The alternative meanings of resilience have significant implications for application of the concept to understanding and managing complex systems (Gunderson and Holling, 2002).

## ADAPTIVE CYCLES AND PANARCHY

Many ecosystem dynamics can be represented by an adaptive cycle, in which four distinct stages have been identified: (1) exploitation or growth; (2) conservation; (3) release or collapse; and (4) reorganization (see Figure 1). The adaptive cycle exhibits two major transitions. The first, from exploitation to conservation, is the slow, incremental phase of growth and accumulation. The other, from release to reorganization, is the rapid phase leading to renewal. The first is predictable with higher degrees of certainty. The consequences of the second phase are unpredictable and highly uncertain. The adaptive cycle can be more completely understood as a dynamic loop in multidimensional conceptual space. What this means will be explained in the example case of South Limburg, which is described below.

An important consequence of the adaptive cycle is that the resilience of a system changes throughout the 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.

A panarchy, as defined by Holling (2000) and Gunderson and Holling (2002), represents a hierarchical structure in which both human and natural systems are linked together in adaptive cycles. 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 and 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 soil erosion in Europe. What has happened in the last thirty years to make soil erosion the important issue that it has become? Is soil erosion quantitatively greater today than it was thirty years ago? Most experts would probably claim that erosion is indeed more extensive in certain areas where it was formerly absent. On the other hand the nature of erosion is such that it would be easy to demonstrate many examples of the opposite. To clarify the adaptive cycle metaphor we will describe an example from South-Limburg in The Netherlands, where erosion was, and sometimes still is, considered a problem.

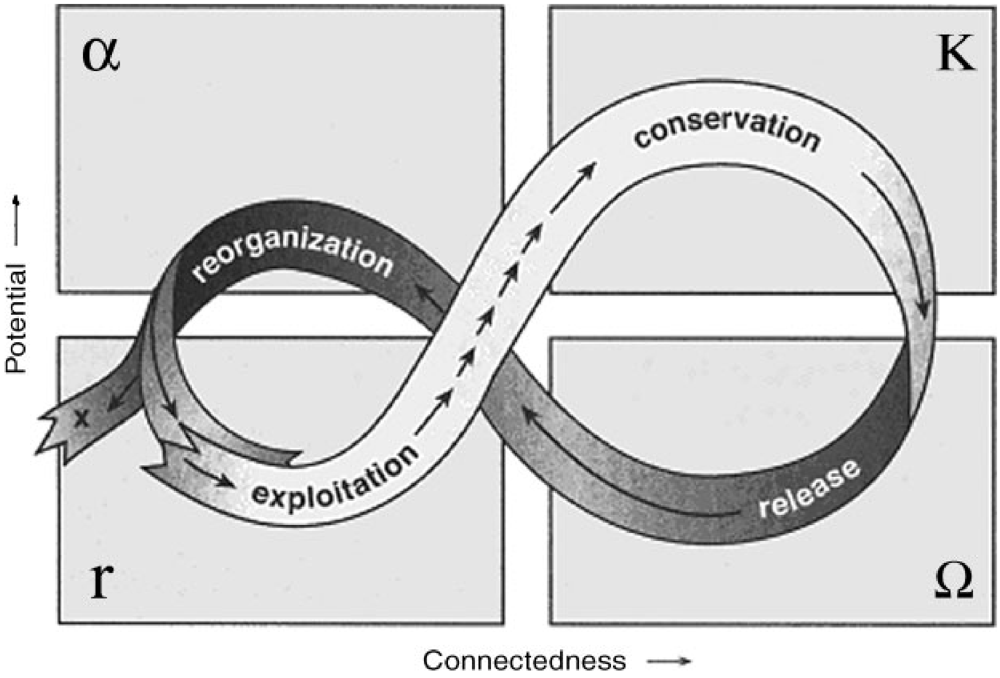

Figure 1. A conceptual representation of the four distinct stages within an adaptive cycle (from Gunderson and Holling, 2002). Reproduced by permission of Island Press.

## EXAMPLE: THE SOUTH-LIMBURG CASE

South-Limburg is the southernmost part of The Netherlands. In this hilly area, soil erosion and surface runoff caused much damage and huge problems, especially during the late 1970s and early 1980s (Schouten *et al.*, 1985). The landscape of South-Limburg could be described as a number of plateaux, which are intersected by river valleys (the highest point is the Vaalserberg, 321 m above sea-level). Many of these valleys today are dry valleys, which are the remnants of a colder and moister glacial past (De Roo, 1993). For a large part, South-Limburg is covered with a layer of loess (loess contains approximately 80 per cent silt, 15 per cent clay and 5 per cent sand), which is mostly two metres but sometimes even twenty metres thick. The loess overlies coarse-grained Quaternary fluviatile sediments, Tertiary sands and Cretaceous limestone. The area is situated in the European loess belt, which extends across SE England, NW France, Belgium, The Netherlands (South-Limburg), Germany and into Poland and Russia and was deposited between 12,000 and 20,000 years BP (Mücher, 1973). During the last 10,000 years temperatures increased and soil formation could take place, which resulted in Luvisols, which are characterized by an A-, Bt- and C-horizon (Mücher, 1986). The climate of the area is temperate oceanic, with rainfall in all seasons and an annual average precipitation of 750 mm. In the summer, rainfall intensity can be quite high ($> 40\,\mathrm{mm\,hr^{-1}}$), which sometimes leads to soil erosion. On the steeper slopes both the A-horizon and the Bt-horizon have been removed and therefore the weathered Cretaceous limestone is exposed. In lower areas considerable amounts of colluvium have been deposited. Before going into details about the current situation regarding land use and erosion in South-Limburg, we will exploit the advantage of the adaptive cycle, which enables the history of erosion in the region to be easily understood.

The main driving forces that have changed the functioning of the landscape in South-Limburg during the last 15,000 years may be generalized as: (a) the deposition of loess; and (b) colonization and use of the landscape by modern man (*Homo sapiens*). The impact of this is summarized in the large first part of the adaptive cycle schematized in Figure 2.

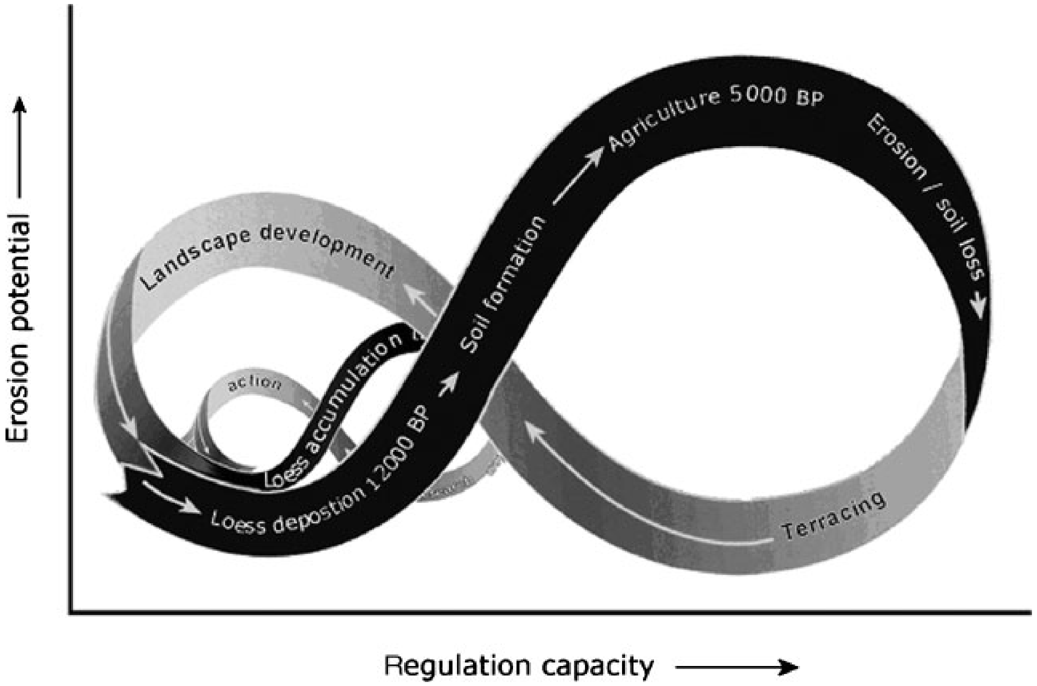

Figure 2. Representation of the adaptive cycle of the South-Limburg case (see the text for explanation). The x-axis represents the regulation capacity of the landscape, the axis of time follows an imaginary point that moves along the depicted cycle in the graph.

The starting point may be thought of as 12,000 years BP at a moment when loess began to be deposited on the pre-existing post-glacial landscape. The history of one place can be schematized along a time-line. The two axes in the figure are described as the potential for erosion and the regulation capacity of the landscape, which is in other words to what degree the landscape is able to perform its regulating function by buffering and transmitting ecosystem processes. Examples of these are transportation of material through the landscape by rivers, intermittent streams or wind at different scales, migration of plant and animal populations, etc.

The gradual deposition and accumulation of loess profoundly influenced the hydrology. A loess layer behaves as a giant sponge that can retain as much as 40 to 60 cm of water for every metre of depth. A ten-metre-thick loess layer could retain 4 to 6 metres of rain, which was possibly also 5- to ten-times the annual rainfall. Although its water retention makes it ideal for agriculture in a humid region, when it was deposited it buried and fossilized the drainage system. Groundwater recharge would have dropped, springs would have dried up, dry valleys would have formed and a new land surface would have been created. In terms of the evolution of the landscape and its functioning, South-Limburg would have gained a highly fertile loess soil but at the cost of losing the drainage system. At the same time, pedogenesis resulted in Luvisols due to the increase in the temperature, as mentioned before.

Human beings settling in South-Limburg enjoyed the benefits of the loess soil (Renes, 1988). These initially increased the fertility of the Luvisols that would have been rather resilient to disturbance because of the positive effect of organic matter and the calcium from the calcium carbonate that the original loess contained on soil structure. Gradually, however, calcium carbonate was leached from the surface soils, which slowly became more erodable (Mücher, 1974).

Agriculture in Neolithic and later Roman periods has been shown by many paleo-ecological investigations to have had some impact on erosion (Van den Broek, 1958; Janssen, 1960; Van de Westeringh *et al*., 1980; Mücher, 1986). In the figure, about 3000 to 1800 years ago we allow the adaptive cycle to experience a downward collapse as soil resources were redistributed by erosion. Sunken lanes were formed and soil accumulated as colluvium in valley bottoms (Mücher, 1974). It is likely that some actions at that time were deliberately targeted at soil protection, such as the construction of hedgerows to encourage the accumulation of sediment. This provoked the formation of terraces, locally called **graften** (Renes, 1988). This may be thought of as a reorganization that led to a restructuring of the landscape. However, it is well known that the introduction of the plough in the early Middle Ages and the Little Ice Age also produced stresses that caused erosion and land degradation (Mücher, 1986). Loss of the productive functions of the soil was then reflected in abandonment and migration, which was a temporal reorganization of the human system.

At the other end of the time line, the second small cycle in Figure 2 which, represents the last century, first shows a net accumulation of loess in the terraced landscape. But after that period it shows the impact of land consolidation and reallocation and modern farming, which led to erosion (the downward loop in the small cycle in Figure 2). This is the impact described by Bork (2003; this volume), which is also represented in Figure 3. In South-Limburg, this meant that small-scale plots, which still existed in the 1950s and 1960s, slowly merged into large agricultural fields. As a consequence, small hedges, trees and shrubs growing on the edges of the **graften** disappeared. Land use changed from a diverse mixed agricultural/natural area to mainly maize, wheat and sugar beet (De Roo *et al*., 1995). The combination of these agricultural practices and heavy rainfall events resulted in huge erosion problems in the 1980s (Kwaad, 1991). Tons of fertile soil were removed from the agricultural fields and were deposited in lower parts of the landscape. These so called off-site effects of soil erosion were even more damaging. Sewerage systems in the villages were clogged, which resulted in large mudflows on the streets. These led to considerable damage to infrastructure, as many of the villages in South-Limburg have been build in the

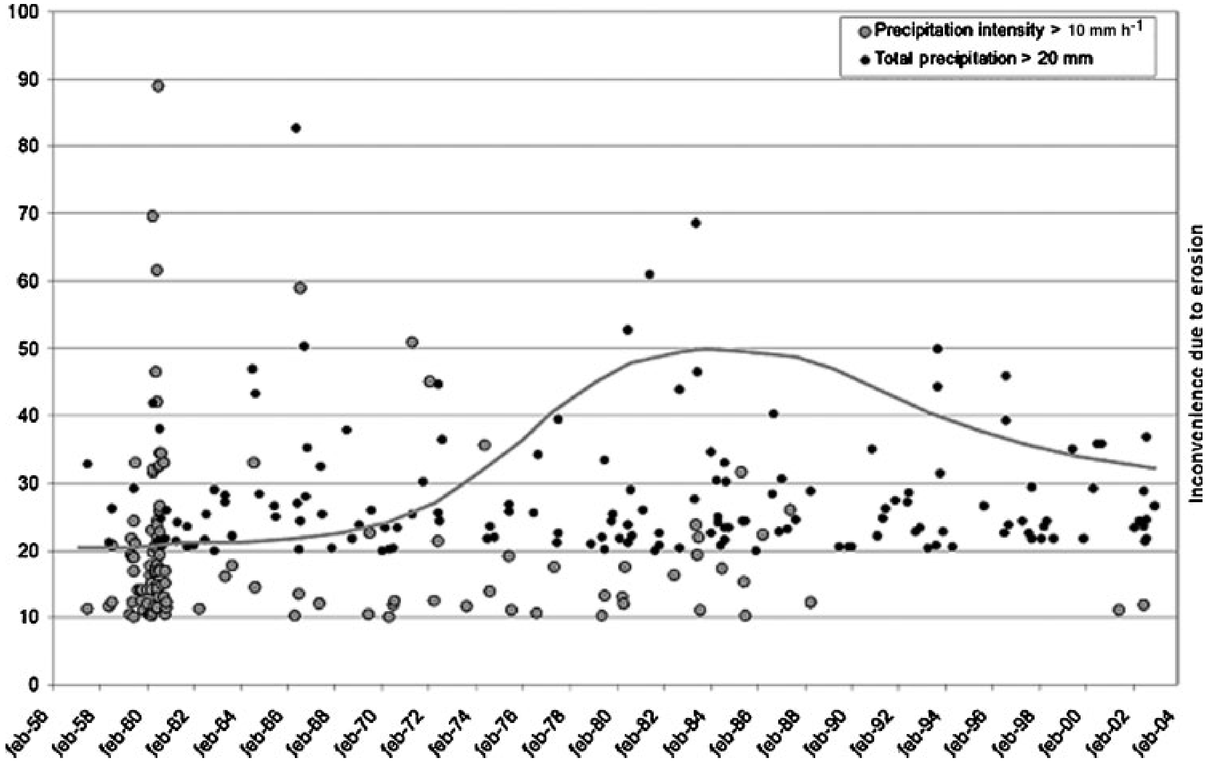

Figure 3. Precipitation measured at the Maastricht station in South-Limburg showing rainfall events with intensities higher than 10 mm per hour and events with a net precipitation amount larger than 20 mm per day (data available at Royal Netherlands Meteorological Institute). The right axis and the dark grey line are relative, and indicate the amount of inconvenience society suffered from the erosion. This is measured from reported erosion events (DLB, 2003, personal communication) and interviews with farmers and residents. Here it is interesting to mention that we investigated the soil aggregate stability at different sites in an agricultural catchment in South-Limburg in 1984 and in 2003. We found no significant difference.

bottom parts of the dry-valleys, which is of course exactly were all the water accumulates in case of extreme events.

One example of adaptation following these events refers to all of the actions that were taken to research and combat this erosion between 1970 and 2000. Examples of action taken following research were: different ploughing and seeding systems applied by farmers; prevention of barren land in the winter by seeding winter rye in the autumn; transforming agricultural plots into meadows; and the construction of large sediment retention ponds in the valley bottoms (Bouten *et al*., 1985; Van Dijk *et al*., 1996; Geelen *et al*., 1995; Kwaad *et al*., 1998). The activities followed the policy cycle now being applied by section Directorate General of EU Environment (DG–Environment) to soil protection. They showed that for all kinds of reasons society adequately dealt with erosion. Erosion itself was stopped, land was assigned other functions by the community and erosion ceased to be an issue. All this could be defined as adaptation in the human system.

In the natural system evidence of adaptation after large-scale erosion can be observed as well. The counterpart of soil erosion is deposition or sedimentation in other parts of the landscape. As described earlier, these so called off-site effects of soil erosion might be damaging. However, these also lead to change in soil properties in the deposition areas. In South-Limburg, we observed an area where loess and the previously underlying gravel were eroded and deposited in the bottom of a dry valley. There, a small so-called alluvial fan developed. This fan slowly migrated upwards into the tributary valley system. As a result the surface slightly rose in height and the infiltration capacity of the soil in the valley bottom increased due to the mixture of loess with coarser material. At the same time, the erosion potential of the tributary valley slopes decreased as more and more loess was removed. Sometimes, the farmer even ploughed into the weathered bedrock. This has all happened during the twenty years since 1980. Despite some heavy rainfall events, the formation of gullies, which normally initiate from the valley bottom in that area, has not been observed since 1990. In the 1980s, gullies frequently formed within this field. The effect of the adaptation of the natural system is currently also reinforced by the fact that a foundation called 'Limburg Landscape', which aims to protect the landscape in South-Limburg, buys land from farmers to reintroduce natural herbs and plants in these fields. This vegetation protects the soil during wintertime as well as increasing the stability of the soil aggregates. The lower part of the field we observed has been transformed into natural land in the spring of 2000. The number of these kind of 'Limburg Landscape' fields is increasing in South-Limburg, in many cases they appear at places where farmers previously had erosion problems.

## CONCLUSION: THE GOLDEN RULES

Holling and Meffe (1996) describe rules for the conservation of natural resources. It is interesting to apply these to erosion. According to these authors, one of the huge mistakes often made is to control ecosystems by responding to erratic or surprising ecosystem behaviour with more command and control. What happens, however, is that unforeseen consequences for both natural ecosystems and human welfare in the form of collapsing resources and losses of ecosystem diversity occur. Holling and Meffe (1996) and Gunderson and Holling (2002) give examples of cases where natural levels of variation in system behaviour have been reduced through command and control. They show that these systems become less resilient to external perturbations, resulting in crises and surprises. The proposed solution is not further command and control (more regulations), but comes from innovative approaches involving incentives leading to more resilient ecosystems, more flexible agencies, more self-reliant industries, and a more knowledgeable citizenry. They eventually propose a Golden Rule of natural-resource management, which is: management should strive to retain critical types and ranges of natural variation in resource systems in order to maintain resilience.

We showed another example of the commonly expressed concern that modern agriculture and the implementation of the common agricultural policy explains many soil erosion problems. If this is the case, and the policy is considered important in Europe, a soil-erosion policy should present opportunities for dealing with erosion. In terms of erosion the Golden Rule would amongst others mean striving towards landscape variability, a healthy mix of agricultural and natural land. It will not be easy to develop and implement a policy aiming at such mixed systems. For this, adaptive management, which will address the complex and inherently unpredictable systems of nature, at regional and local scales has to be introduced. But analysis of ecosystem processes, local knowledge and acknowledging local differences throughout Europe, would provide a sound foundation for both a soil-protection policy and adaptive environmental management. A starting point might be, as Holling and Meffe (1996) describe it: 'Examine bureaucracies to identify underlying reasons for their general inflexibility and fragility, and promote incentives for alternative behaviours. Develop incentives and rewards for innovation that place streamlining, local solutions, and concern for customers and sustainability above adherence to a command structure'.

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