

Soil erosion and the adaptive cycle metaphor

Luuk Dorren and Anton Imeson

IBED - Physical Geography, University of Amsterdam, Amsterdam, The Netherlands.
l.dorren@science.uva.nl / aimeson@science.uva.nl

1 Introduction

The landscapes we live in and the changes they undergo play an important part in the qualities of our lives as development of infrastructure and industry, housing and exploitation of the earth's resources are still prerequisites for growth in the 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), can be provided because of the existence of soil, which is a medium between the solid earth and the sphere we live our daily life in. The medium soil is constantly subject to change, of which the causes are dependent on the geographical position of the soil. Examples of causes are activity of microorganisms and animals that live in the soil, weathering of bedrock, which increases the thickness of the soil, input of organic material by farmers or dead plant material. Another example is soil erosion.

Soil erosion is identified by the European Commission as one of the major threats to soils in Europe (CEC, 2002). At the time of writing, the European Union is engaged in the process of developing a policy for soil protection and erosion will be one of the focal points in it. During the previous decades 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 worldview of the soil and its dynamics are an enormous achievement that at the same time limits access to the 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. Soil erosion will be presented in a bigger picture or framework, allowing causes and their impacts to be linked at different scales.

2 Soil erosion and landscape change

If one tries 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, let's elaborate on two important concepts, which are (1) scale/connectivity, (2) change and (3) resilience.

2.1 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 maker of the 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 underneath your favourite spot in a garden or a park. The spatial scale of this level of interest is the area that you at could overlook easily from this spot, e.g. fifty by fifty meters. The hierarchical systems theory implies that the organisation 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 we could overlook in the garden or park, the area we are directly interested in, 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 park as a whole or on the area around the garden 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, the deposition of microscopic parts from the atmosphere.

Connectivity of nature across both adjacent and more distant systems is important as ecological 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.

2.2 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 we are interested in. Regarding specifically the concept of change, this means that change in landscape systems could only be understood fully if the concept of scale and connectivity is considered as well. An example from fluvial geomorphology illustrates this. When there is a change in base-level, that is if the land rises relative to the sea, the larger rivers in the area react to this. They start to incise in the landscape as the land rises and 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 in bedrock. Small rivers, in tributary

catchments, where farmers have their agricultural fields, also react by incising the underlying terrain. If only looking at the agricultural fields in the tributary systems, these are considered not to change, 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, activities of the farmer that change the soil and some water that erodes particles from the surface of the soil. 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.

2.3 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).

3 Adaptive cycles and Panarchy

Many ecosystem dynamics can be represented by an adaptive cycle, in which four distinct stages have been identified: (i) exploitation or growth, (ii) conservation, (iii) release or collapse and (iv) 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 reorganisation, is the rapid phase of reorganization 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 become clear when it is explained in the example case of South Limburg, which will be described below.

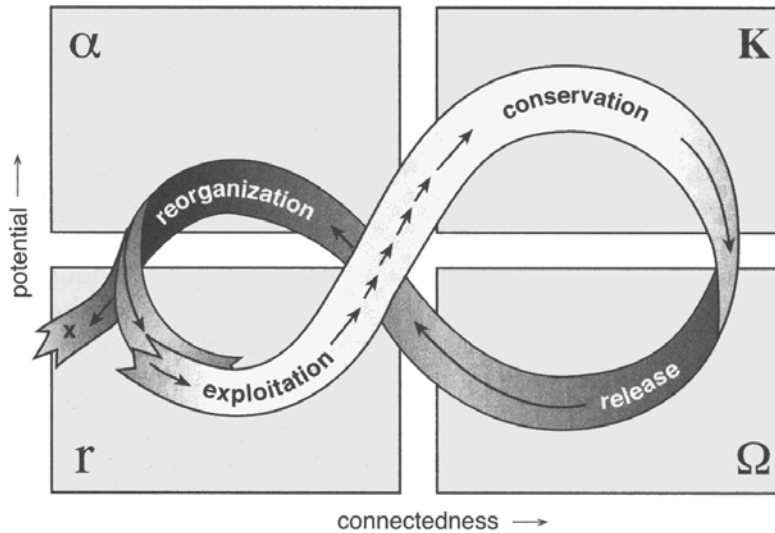


Figure 1. A conceptual representation of the four distinct stages within an adaptive cycle (after Gunderson and Holling, 2002)

An important consequence of the adaptive cycle is that the resilience of a system changes throughout an adaptive cycle. 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). 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 that makes soil erosion the important issue 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 the South-eastern part of the Netherlands, where erosion was and sometimes still is considered a problem.

4 Example: The South-Limburg case

South-Limburg is the southeasternmost region in the Netherlands. Especially during the late seventies and early eighties, soil erosion and surface runoff caused damages and problems in this hilly area (Schouten et al., 1993). The landscape of South-Limburg could be described as a number of plateau's, which are incised by river valleys (the highest point is the 'Vaalseberg', 321 m above sea level). Many of these valleys today are so-called 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% silt, 15% clay and 5 % sand), which is mostly 2 metres but sometimes even 20 metres thick. The loess overlies coarse-grained Quaternary fluvial sediments, Tertiary sands and Cretaceous limestone. The loess is part of the European loess belt, which extends across SE England, NW France, Belgium, The Netherlands (South-Limburg) Germany and into Poland and Russia and has been deposited between 12.000 – 20.000 years Before Present (BP) (Mücher, 1973). During the last 10.000 years (The Holocene), when temperatures increased, the process of soil formation (pedogenesis) could take place, which resulted in so-called Luvisols that are characterized by an A, Bt and a 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 could be quite high, which sometimes leads to soil erosion. On the steeper slopes both the A horizon and the Bt horizon have been removed and therefore the C-horizon 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 15000 years may be generalised as a) the deposition of loess and b) colonisation and use of the landscape by modern man (*homo sapiens*). The impact of this is summarised in the large first part of the adaptive cycle schematised in figure 1. In this figure, the axis of time follows an imaginary point that moves along the depicted cycle in the graph.

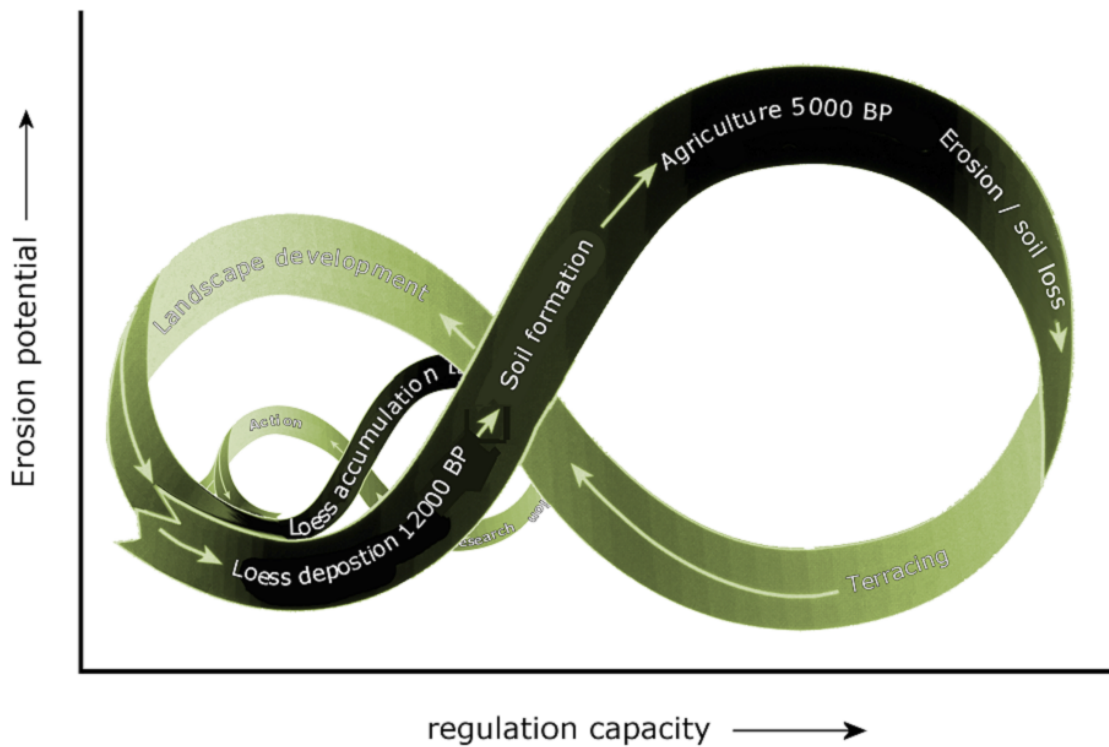


Figure 2. Representation of the adaptive cycle of the South-Limburg case (see the text for explanation). The x-axis represents the regulation capacity of the landscape, the axis of time follows an imaginary point that moves along the depicted cycle in the graph

The starting point may be thought of as 12000 years BP at a moment when loess began to be deposited on the pre-existing postglacial landscape. The history of one place can be schematised 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 which 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 fossilised the drainage system. Groundwater recharge would have dropped, springs would dry up, dry valleys would have formed and a new land surface created. In terms of the evolution of the landscape and its functioning, South-Limburg would gain a highly fertile loess soil but this was at the cost of losing the drainage system. At the same time, pedogenesis resulted in Luvisols due to increase of 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 surface soils, which would slowly become more erodible (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 accumulate sediment behind them. This formed terraces known as 'graftern' (Renes, 1988). This may be thought of as a reorganisation 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 provided 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 reorganisation of the human system.

At the other end of the time line, the second small cycle in Figure 2 that 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) in this volume, which is also represented in Figure 3. In South-Limburg, this meant that small-scale plots, which still existed in the fifties and sixties, slowly merged into large agricultural fields. As a consequence, small hedges, trees and shrubs growing on the edges of the 'graftern' 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 eighties (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. Sewage 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 built in the bottom parts of the dry-valleys, which is of course exactly where 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 to 2000. Examples of combat action following research are 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 valleys 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 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.

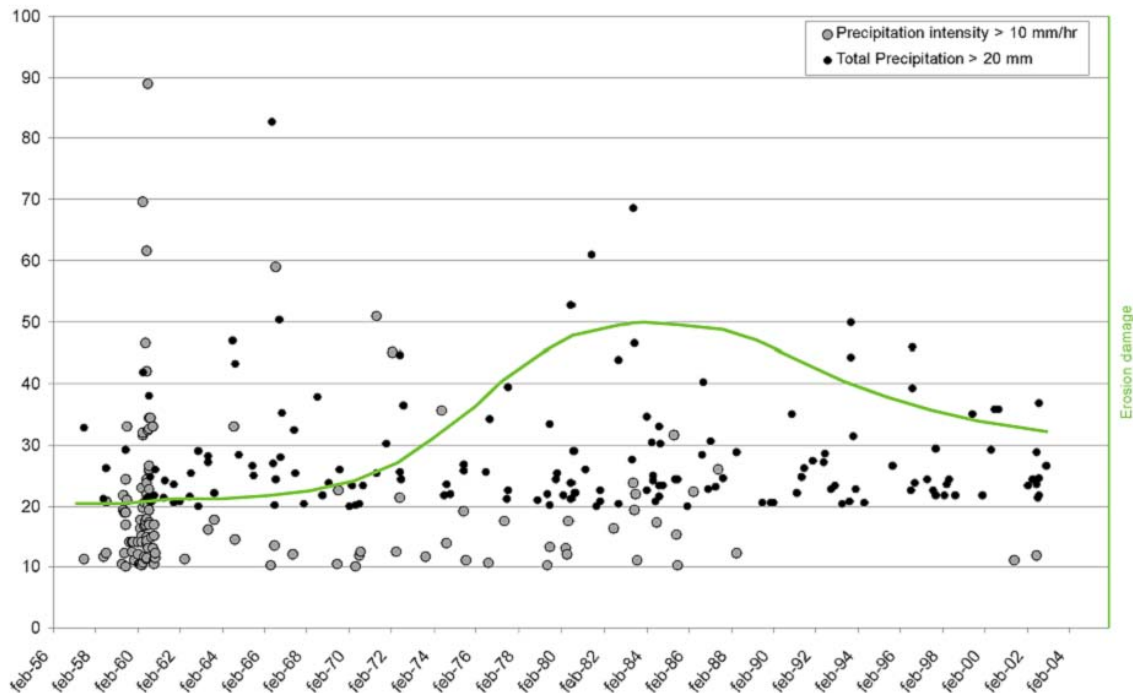


Figure 3. Precipitation measured at the Maastricht station in South-Limburg showing rainfall events with intensities higher than 10 mm per hour and events with a net precipitation amount larger than 20 mm per day. The erosion damage on the right axis is a relative axis, which indicates the amount of inconvenience society had from 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.

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 the 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 decreases as more and more loess was removed. Sometimes, the farmer even ploughed into the weathered bedrock. This all happened the last twenty years. Despite some heavy rainfall events, the formation of gullies, which normally initiate from the valley bottom in that area, has not been observed during the last 10 years. In the eighties, 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', who aims to protect the landscape in South-Limburg, buys land from farmers to reintroduce natural herbs and plants on

these fields. This vegetation protects the soil during wintertime as well and increases the stability of the soil aggregates. The lower part of the field we observed has been transformed into natural land three years ago. The number of these kind of 'Limburg Landscape' fields is increasing in the landscape in South-Limburg, in many cases they appear at places where farmers previously had erosion problems.

5 Concluding: the golden rules

Holling and Meffe (1996) describe rules for the conservation of natural resources. It is interesting to apply these to erosion. One of the huge mistakes often made according to them 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 behavior 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 to strive towards landscape variability, a healthy mix between 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 scale 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."

References

- Allen, T.F.H. and Starr, T.B., 1982. Hierarchy: perspectives for ecological complexity. University of Chicago Press, Chicago, 310 pp.
- Bergkamp, G., 1995. A hierarchical approach for desertification assessment. *Environmental Monitoring and Assessment* 37(1), 59-78.
- Bork, H.-R., 2003. State-of-the-art of erosion research - soil erosion and its consequences since 1800 AD. Briefing Papers of the first SCAPE Workshop, C. Boix-Fayos, L.Dorren and A.C. Imeson, pp. 11-14.

- Bouten, W., Van Eijsden, G., Imeson, A.C., Kwaad, F.J.P.M., Múcher, H.J. and Tiktak, A., 1985. Ontstaan en erosie van de lössleemgronden in Zuid-Limburg. *Geografisch Tijdschrift* 19, 192-208 (in Dutch).
- CEC, 2002. Communication from the commission to the Council, the European Parliament, the Economic and Social Committee and the Committee of the Regions: Towards a thematic strategy for soil protection. Brussels, 16.4.2002, COM (2002) 179, 35 pp.
- De Groot, R.S., 1992. Functions of Nature: evaluation of nature in environmental planning, management and decision-making. Wolters Noordhoff BV, Groningen, the Netherlands, 345 pp.
- De Roo, A.P.J., 1993. Modelling surface runoff and soil erosion in catchments using Geographical Information Systems. *Netherlands Geographical Studies*, vol. 157, Universiteit Utrecht, Utrecht, The Netherlands, 295 pp.
- De Roo, A.P.J. van Dijk, P.M., Ritsema, C.J., Cremers, N.H.D.T., Stolte, J., Oostindie, K., Offermans, R.J.E., Kwaad, F.J.P.M. en Verzandvoort, M.A., 1995. Erosienormeringsonderzoek Zuid-Limburg. Veld- en simulatiestudie. Rapport 364.1, DLO Staring Centrum, Wageningen, 234 pp (in Dutch).
- Geelen, P.M.T.M., Kwaad, F.J.P.M., Mulligen, E. van, Wansink, A, en Zijp, M. van der, 1995. Optimalisatie van erosieremmende teeltsystemen. Onderzoeksresultaten over 1995 van de Proefboerderij Wijandsrade, Stichting Proefboerderij Wijandsrade, pp. 93-99 (in Dutch).
- Gunderson, L.H. and Holling, C.S., 2002. *Panarchy: understanding transformations in human and natural systems*. Island Press, Washington, DC, 507 pp.
- Holling, C.S. and Meffe, G.K., 1996. Command and control and the pathology of natural resource management. *Conservation Biology* 10(2), 328-337.
- Holling, C.S., 2000. Theories for sustainable futures. *Conservation Ecology* 4(2), 7. [online] URL: <http://www.consecol.org/vol4/iss2/art7>
- Imeson, A.C. and Kwaad, F.J.P.M., 1980. Gully types and gully prediction. *Geografisch Tijdschrift* 14, 430-441.
- Imeson, A.C. and Lavee, H., 1998. Investigating the impact of climate change on geomorphological processes: the transect approach and the influence of scale. *Geomorphology* 23, 219-227.
- Janssen, C.R., 1960. On the Late-glacial and Post-glacial vegetation of South-Limburg (The Netherlands). North-Holland Publ. Company, Amsterdam, 112 pp.
- Kirkby, M.J., Imeson, A.C., Bergkamp, G. and Cammeraat, L.H., 1996. Scaling up processes and models from the field plot to the watershed and regional areas. *Journal of Soil and Water Conservation* 51(5), 391-396.
- Kwaad, F.J.P.M., 1991. Summer and winter regimes of runoff generation and soil erosion on cultivated loess soils (The Netherlands). *Earth Surface Processes and Landforms* 16, 653-662.
- Kwaad, F.J.P.M., Van der Zijp, M. and Van Dijk, P.M., 1998. Soil conservation and maize cropping systems on sloping loess soils in The Netherlands. *Soil and Tillage Research* 46, 13-21.
- Múcher, H.J., 1973. Enkele aspecten van de loess en zijn noordelijke begrenzing, in het bijzonder in Belgisch en Nederlands Limburg en in het aangrenzende gebied in Duitsland. *KNAG Geografisch Tijdschrift* 7(4), 259-276 (in Dutch).
- Múcher, H.J., 1974. Micromorphology and slope deposits: the necessity of a classification. In: Rutherford, G.K. (Ed.), *Soil microscopy*, The Limestone Press, Kingston, Ontario, Canada, pp. 553-566.
- Múcher, H.J., 1986. Aspects of loess and loess-derived slope deposits: an experimental and micromorphological approach. PhD Thesis, Universiteit van Amsterdam, 270 pp.
- O'Neill, R.V., DeAngelis, D.L., Waide, J.B. and Allen, T.F.H., 1986. *A hierarchical concept of ecosystems*. Princeton University Press, Princeton, New Jersey.
- Renes, J., 1988. De geschiedenis van het Zuidlimburgse cultuurlandschap. Van Gorcum, Assen, 265 pp. (in Dutch).
- Schouten, C.J., Rang, M.C., Huigen, P.M.J., 1985. Erosie en wateroverlast in Zuid-Limburg. *Landschap* 2, 118-132 (in Dutch).
- Taylor, P. D., L. Fahrig, K. Henein, and G. Merriam. 1993. Connectivity is a vital element of landscape structure. *Oikos* 68, 571-573.
- Van den Broek, J.M.M., 1958. *Bodenkunde und Archäologie mit besonderer Bezugnahme auf die Ausgrabungen im Neolithikum von Sittard und Geleen*. *Palaeohistoria* 7, 7-18 (in German).
- Van de Westeringh, W., Miedema, R., Havinga, A.J., Van den Berg van Saparoea, R.M., 1980. Soil conditions, soil carbonates and former vegetation in the Geul valley from Gulpen to Meerssen (South-Limburg, The Netherlands). *Mededelingen Landbouwhogeschool Wageningen* 80(8), pp. 1-60.
- Van Dijk, P.M., Kwaad, F.J.P.M. and Klapwijk, M., 1996. Retention of water and sediment by grass strips. *Hydrological Processes* 10, 1069-1080.
- White, P.S. and Picket, S.T.A., 1985. Natural disturbance and patch dynamics: an introduction. In: S.T.A. Picket and P.S. White (Eds.), *The ecology of natural disturbance and patch dynamics*. Academic Press, New York, pp 3-13.