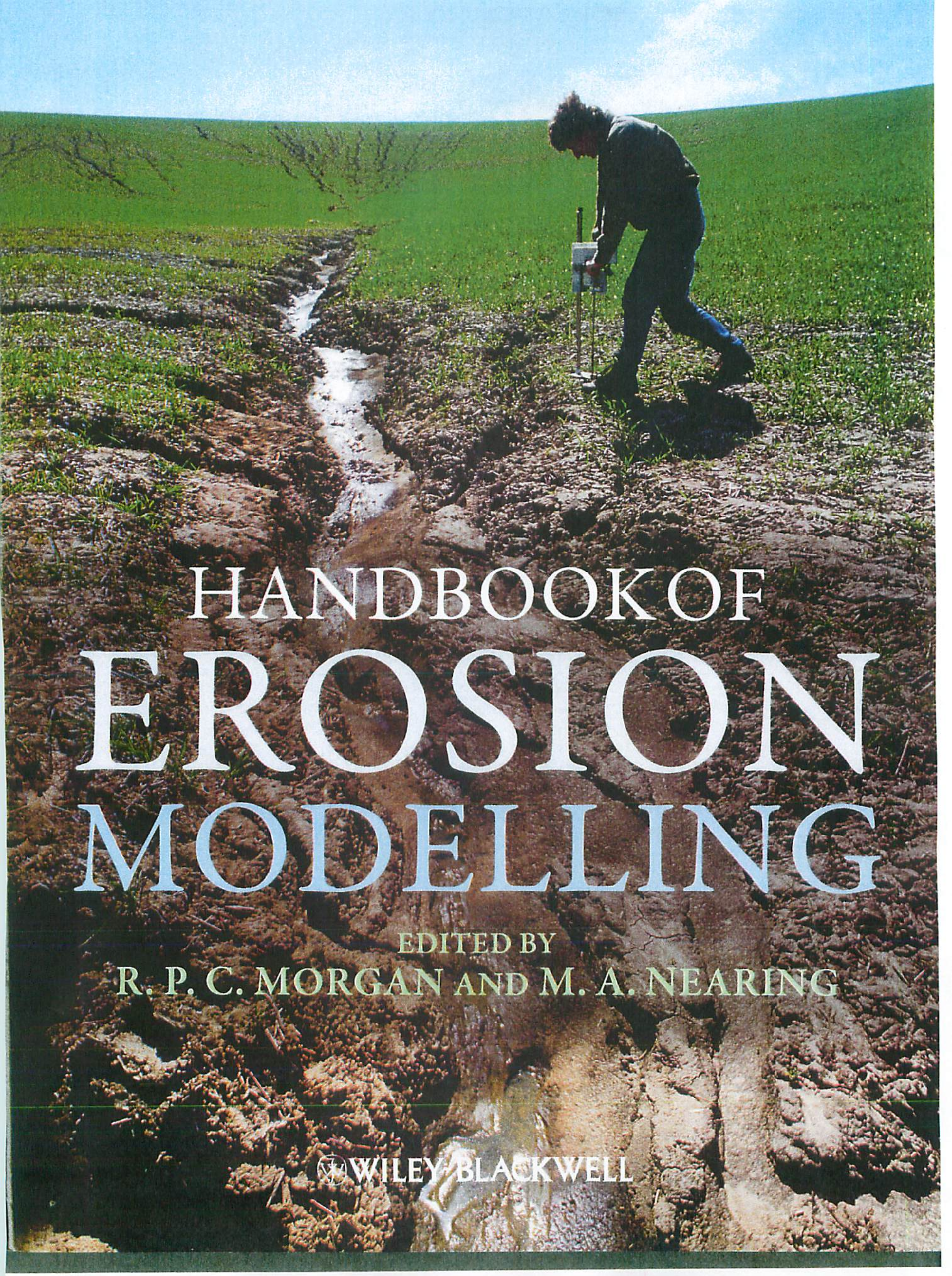

HANDBOOK OF EROSION MODELLING

EDITED BY
R. P. C. MORGAN AND M. A. NEARING

WILEY-BLACKWELL

Handbook of Erosion Modelling

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15 Modelling Impacts of Climatic Change: Case Studies using the New Generation of Erosion Models

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15.1 Introduction

There is a growing consensus in Earth systems sciences that global temperatures are increasing and will continue to do so during the next century, leading to changes in global climate patterns (IPCC, 2007). Although different regions of the globe could respond differently to global warming, most are expected to suffer significant changes to the amount and variability of rainfall and temperature (Giorgi, 2006), associated with an increase in the frequency of extreme episodes such as heat waves and high-intensity storms (Tebaldi *et al*., 2006).

These changes have the potential to alter significantly the driving forces and parameters behind soil erosion; examples include changes to rainfall intensity, vegetation cover and surface runoff generation (Kundzewicz *et al*., 2007). There is therefore a need to quantify the impacts of climate change on soil erosion and on the most important erosion drivers, to estimate on- and off-site consequences, and support the development of adequate adaptation measures. This can be a challenging problem due to the nonlinear relationships between soil erosion drivers and processes and the complex interactions between climate change impacts. Erosion models can be useful assessment tools to support climate change studies, since they codify the existing knowledge on soil erosion processes and their response to climate forcing, allowing the quantification of the impacts of changed climate patterns in a feasible and, hopefully, robust way.

The purpose of this chapter is to explore these challenges. It begins by discussing potential impacts of climate change on soil erosion drivers and processes, and potential interactions between them. It then proceeds with a systematization of soil erosion modelling applied to climate change studies, discussing issues such as climate change scenario and model selection, or calibration and validation issues. This is followed by a number of case studies from around the globe which exemplify climate change impact assessment supported by a modelling framework. The chapter concludes with a discussion of research results in this area, current limitations and potential avenues of future research.

15.2 Potential Impacts of Climatic Change on Erosion Processes

Climate change is expected to impact upon a number of soil erosion drivers and processes, which should be taken into account when

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designing a modelling strategy. The fourth assessment report of the Intergovernmental Panel for Climate Change (IPCC) (Parry *et al.*, 2007; Solomon *et al.*, 2007) reviews a number of potential changes to soil erosion drivers and processes. This chapter summarizes these impacts as changes to rainfall erosivity, water runoff, vegetation cover and soil erodibility, with a focus on the combined changes caused by desertification.

15.2.1 Rainfall erosivity

One of the most direct impacts of climate change could be an increase in the erosive power of rainfall. In the IPCC's fourth assessment report, Meehl *et al.* (2007) reported that global general circulation models (GCMs) point to an average increase in rainfall of 5% over land masses by 2100, but unevenly distributed, with the high latitudes, the tropics and the monsoon region of southeast Asia experiencing the highest increases (up to +20%) and with the largest decreases over the Caribbean and Mediterranean seas and in the western subtropical coasts of each continent (down to –20%). Rainfall increases are expected to reflect disproportionately in heavy precipitation events, with average rainfall intensity increasing, which is also a trend that has been observed in the global climate record (Groisman *et al.*, 2005; Trenberth *et al.*, 2007). Even in regions where rainfall decreases, this is expected to lead to an increase in the length of dry periods, with rainfall intensity in wet periods increasing; in some of these regions this fact could be particularly significant due to the contribution of rare extreme events for overall soil erosion (e.g. González-Hidalgo *et al.*, 2007). Finally, rainfall increases could accumulate with a shift from snowfall to rainfall due to the warmer climate (Kundzewicz *et al.*, 2007).

As an example of current climate change scenarios for extreme events, Tebaldi *et al.* (2006) analysed historical and future simulations of precipitation extremes indicators by nine GCMs, under a range of emission scenarios. The authors reported a significant global trend of greater precipitation intensity emerging from model results, although with a high regional, interannual and inter-model variability. The largest and most significant changes were found in days with rainfall over 10 mm, and 5-day maximum rainfall, which indicate more precipitation for a given event, resulting from the greater moisture-holding capacity of a warmer atmosphere and a polewards shift of storm tracks. Precipitation intensity is expected to increase over all land masses, with significant increases in the mid to high latitudes of the northern hemisphere and the tropical regions of Africa and South America. In the subtropical regions, an increase in the number of dry days is coupled with no significant changes to rainfall intensity.

Climate change projections from GCMs should be treated with care, since the non-linear nature of the climate system and natural forcings, compounded with differences in the formulation of different GCMs, causes an intrinsic level of uncertainty in GCM-based climate change predictions (Stott & Kettleborough, 2002; Giorgi, 2005). Nevertheless, the consistency of the predictions among the GCMs as well as with the historical climate record indicates that rainfall erosivity will increase in many regions throughout the globe. Ongoing research focusing on regional climate change predictions and climate extremes (e.g. Hanson *et al.*, 2007) should provide better estimates of the impacts of climate change on rainfall erosivity in the near future.

15.2.2 Water runoff

The estimated impacts of climate change on runoff are more complex than on rainfall. The IPCC's fourth assessment report (Kundzewicz *et al.*, 2007) points to significant changes in river runoff, due to changes in rainfall coupled with an increase in potential evapotranspiration, as higher temperatures increase the atmospheric vapour pressure deficit. Changes to runoff are generally expected to follow changes in rainfall, increasing in high latitudes, southeast Asia and the tropics (where rainfall is expected to increase more than evapotranspiration), and decreasing in the Mediterranean coastline and in the western subtropical regions of each continent. However, the IPCC report and other global studies on climate change impacts (e.g. Wetherald & Manabe, 2002; Nohara *et al*., 2006) do not separate surface runoff from total runoff; changes to surface runoff have consequences for soil erosion processes at the field and hillslope scales, including gully erosion, while changes to total runoff can impact upon channel erosion and deposition processes and watershed sediment yield.

One of the expected impacts of an increase in rainfall intensity is greater surface runoff generation through infiltration-excess processes, especially when coupled with soil surface crusting (Bronstert *et al*., 2002). However, soil moisture rates are also an important factor for runoff generation in humid and semi-arid catchments, particularly for low- and medium-intensity storms (e.g. Cammeraat, 2002; Boix-Fayos *et al*., 2006). The IPCC report (Meehl *et al*., 2007) points to a global decrease in soil moisture; this is more marked in regions where rainfall decreases, but also predicted to occur in high latitudes despite an increase in rainfall due to the earlier start of snowmelt. Global modelling results obtained by Wetherald and Manabe (2002) and Manabe *et al*. (2004) point to a high seasonal variability of soil moisture changes, which are expected to occur mostly in the spring-to-autumn period. For example, soil moisture in the Mediterranean is not expected to decrease significantly in the winter despite a large annual decrease, while in the mid latitudes, soil moisture is expected to increase in winter and decrease in summer leading to small changes in annual averages.

These changes are likely to have an impact on surface runoff generation and therefore on soil erosion, especially during low- to medium-intensity storms; in general terms, surface runoff generation can be expected to follow overall runoff trends. However, changes to runoff generation processes are expected to have a high degree of spatial variability, with the spatial distribution of soil hydrological properties playing a significant role (e.g. Bronstert *et al*., 2002; van den Hurk *et al*., 2005; Nunes *et al*., 2008). Another important difference could be a shift in the most important runoff generation processes for regions where climatic aridity surpasses desertification thresholds (Cammeraat, 2002); this issue is discussed further below. In summary, the processes linking rainfall, soil moisture and surface runoff generation are non-linear and often particular to a small catchment or region, and therefore it is difficult to generalize impacts at the continental or global scale (Kleinen & Petschel-Held, 2007). It should be noted that most soil erosion modelling studies presented in this chapter also focus on surface runoff generation.

Furthermore, Kundzewicz *et al*. (2007) pointed to a greater irregularity of streamflow throughout the globe, both in seasonal and daily terms, coupled with an increase in flash flood frequency, especially in mid to high latitudes. Higher flow seasonality is expected due to changes in evapotranspiration and seasonal soil moisture patterns, coupled with shifts in rainfall seasonality and, in the mid to high latitudes, by a shorter snow accumulation season and earlier onset of snowmelt (Meehl *et al*., 2007). These changes, compounded with the increases in rainfall intensity described earlier, can combine to increase significantly the probability of occurrence of large floods (Kundzewicz *et al*., 2007); in a global study, Kleinen and Petschel-Held (2007) found that up to 20% of the world population could be affected by a significant increase in the occurrence of large-scale inundations of flood plains. Meehl *et al*. (2007) also pointed out the impact of an increase in snowfall extremes on the occurrence of large spring floods. In short, climate change could lead to an increase of high peak flow events in many river basins, with potential impacts on channel erosion processes.

15.2.3 Vegetation cover

Climate change is also expected to have complex impacts on both natural and agricultural vegetation, affecting the protection given by canopy cover from the erosive power of rainfall. A review in the IPCC's fourth assessment report (Fischlin *et al.*, 2007) points to changes in vegetation productivity patterns, resulting from the interaction between increased atmospheric CO_2 concentrations, generally leading to increased vegetation productivity, and rising temperatures, whose effect on productivity depends on vegetation species and current adaptability to the local climate. Rainfall decreases and changed soil moisture patterns could also lead to a decrease in vegetation productivity in water-stressed regions. At the global scale, the report points to a global increase in productivity for mild climate change conditions, with vegetation benefiting from CO_2 fertilization and longer growing seasons, followed by negative impacts of more severe climate change scenarios where these benefits are counterbalanced by higher evapotranspirative demands and temperature inhibition to growth.

Ecosystems are expected to dampen the impacts of modest amounts of climate change, but changes above a certain threshold can lead to major transitions or productivity collapses. While shifts in biogeographical regions could be expected, landscape fragmentation associated with evolving human land uses is likely to impede migrations and therefore reduce the potential for natural adaptation to climate change. Furthermore, the increase in climate instability, especially drought frequency and intensity (Meehl *et al.*, 2007), could lead to a greater frequency of vegetation disturbances such as droughts, wildfires or pest outbreaks (Martínez-Vilalta *et al.*, 2002; Mouillot *et al.*, 2002), leading to vegetation mortality and exposing the soil to erosive forces. The IPCC report (Fischlin *et al.*, 2007) points to a potential for extensive forest and woodland decline in mid to high latitudes and the tropics associated with an increase in disturbance regimes.

These changes will also have impacts on agricultural systems, which are particularly vulnerable to soil erosion and land degradation. The IPCC review by Easterling *et al.* (2007) pointed to a negative impact of even a moderate increase in temperature upon crop yields in low latitudes. In the mid to high latitudes, an increase in crop yields can be expected with moderate warming, but more severe climate change can have increasingly negative effects. An increase in the frequency of disturbances can also lead to lower overall agricultural productivity. However, it is likely that cropping systems can be adapted to some climate changes as long as new options for cultivation are available, although smallholders and poor farmers in low-latitude regions have significantly less adaptive capacity than farmers in developed countries (Berry *et al.*, 2006; Easterling *et al.*, 2007). Potential adaptations include changes to cropping practices, such as different planting and harvesting dates to adapt to the new growing season, or irrigation rescheduling to adapt to new rainfall patterns; these changes could alter the seasonal patterns of vegetation cover.

Geographical changes in cropping systems could also follow climate shifts. It is difficult to predict the extent of these changes due to the complexity of the processes involved, crossing between biophysical and socio-economic systems; however, combined models exploring interactions between these systems are currently being developed and applied to climate change impact assessment. For example, the modelling approach developed by Wu *et al.* (2007), combining climate impacts with crop prices, points to an increase in the cropping areas of rice (in Asia and South America) and wheat (in all regions except Oceania) by 2035, while maize shows an uneven trend. This would lead to a combined spatial and temporal shift in vegetation cover patterns, with complex consequences for soil erosion. These changes would be superimposed over other processes with socio-economic motivations, for example the increase in cereal demand for food and biofuel production, leading to the cultivation of more marginal lands (Garbrecht *et al.*, 2007).

15.2.4 Soil erodibility

Climate change can have multiple impacts on the ability of soils to resist erosion. One impact that can be predicted with some certainty is the deeper permafrost thawing in the high latitudes (Meehl *et al.*, 2007), which will expose soil that was previously protected from erosion processes. The changes in vegetation productivity, described in the previous paragraphs, would also lead to changes in ground cover by vegetation residue, with additional impacts from changes in microbial activity driven by temperature and soil moisture availability (Kundzewicz *et al*., 2007).

The impacts of climate change upon soil organic matter and structural properties are more difficult to estimate, since the processes involved are complex and not completely understood (e.g. Dawson & Smith, 2007). A number of studies along climatic gradients (e.g. Lavee *et al*., 1998; Boix-Fayos *et al*., 2001; Sarah, 2006) have demonstrated how soil structural stability is related to soil organic matter content, which varies with temperature and soil moisture in a non-linear way, although with high spatial heterogeneity due to relationships with vegetation cover patterns. The IPCC report points to climate change impacts on soil carbon dynamics, however, due to a combination of changes to vegetation productivity and an increase in soil respiration; this could lead to a global decrease in soil organic carbon content, with soil becoming a net source of CO_2 during the early stages of climate change until a carbon equilibrium is eventually re-established (Fischlin *et al*., 2007). While there is significant uncertainty in the magnitude of this process, it could lead to a decrease in soil structural stability in many regions.

15.2.5 Crossing desertification thresholds

The potential of climate change to aggravate desertification processes in drylands illustrates how the different impacts of climate change on soil erosion drivers can combine and reinforce each other and lead to severe problems of land degradation. Desertification can be defined as the degradation of biophysical and socio-economic conditions in dry regions, leading to land degradation, reduced vegetation productivity and human abandonment (Thornes, 1998; Fernández, 2002). This process usually occurs when biophysical conditions (e.g. soil and climate) are insufficient to support existing natural and socio-economic systems, due to either overexploitation or a reduction in the carrying capacity for these systems (Puigdefábregas, 1998; Fernández, 2002; Herrmann & Hutchinson, 2005).

As described above, climate change could lead to decreased water availability and increased physical constraints on ecosystem productivity in drylands, especially in subtropical regions and Mediterranean-type ecosystems in the mid latitudes, increasing their vulnerability to desertification (Fischlin *et al*., 2007). An increase in climatic aridity can surpass a threshold where available water cannot support full vegetation canopy cover; ecosystems adopt strategies to harvest water and nutrients by adopting a pattern of vegetated and bare patches, with the latter acting as runoff and sediment sources for the former, leading to an increase in runoff generation and soil erosion when compared with drylands above the threshold (Bergkamp *et al*., 1999; Imeson & Prinsen, 2004; Ludwig *et al*., 2005). This process can be self-reinforcing, as reduced biological activity in the bare patches promotes an increase in runoff generation and a decrease in soil structural stability, resulting in greater erosion and poorer conditions for vegetation support in these patches (Imeson & Lavee, 1998; Yair & Kossovsky, 2002).

This process can be exacerbated by soil erosion, due to a reduction in the soil's capacity to support vegetation when compared with non-eroded soils in a similar climate as a result of nutrient losses and, in severely eroded soils, to a decrease in the soil water-holding capacity (Arora, 2002; Bakker *et al*., 2004; Boer & Puigdefábregas, 2005). Intensive agricultural, forestry and grazing practices are common in many dryland regions, usually leading to increased soil erosion and land degradation; high market prices, government subsidies and other socio-economic factors can extend these practices to unsuitable regions, such as marginal areas with steep slopes and low water availability, and maintain them even after the onset of land degradation and consequential decreases in crop yield (Martínez-Fernández & Esteve, 2005; Audsley *et al*., 2006; Vogiatzakis *et al*., 2006). Furthermore, disturbances common in drylands such as severe droughts and wildfires can increase soil erosion during the subsequent window of vulnerability, while vegetation recovers (e.g. Imeson & Lavee, 1998; Shakesby & Doerr, 2006).

Eventually, degraded regions subjected to these pressures can be pushed beyond their resilience threshold by extreme disturbances, leading to land abandonment (Puigdefábregas, 1998; Martínez-Fernández & Esteve, 2005). This can result in the recovery of natural vegetation and gradual increase in soil quality (e.g. Vicente-Serrano *et al.*, 2004; Martínez-Fernández & Esteve, 2005), but severe land degradation and continuing climatic instability can reinforce desertification processes in abandoned lands, and as described above, the process itself is self-reinforcing (Puigdefábregas, 1998; Bakker *et al.*, 2005). This conclusion is sustained by several observations of increased soil erosion processes, particularly gully erosion and vegetation patchiness in degraded landscapes (e.g. Cammeraat & Imeson, 1999; Oostwoud Wijdenes *et al.*, 1999; Seixas, 2000; Ries & Hirt, 2008). In these cases, land degradation and desertification can be irreversible without extensive human intervention, and misapplied intervention practices (e.g. intensive irrigation, afforestation) can even increase the problem (Thornes, 1998; Puigdefábregas & Mendizabal, 1998; Martínez-Fernández & Esteve, 2005).

In the past, drylands have experienced periods of alternating human expansion and contraction due to changes in climate; humid periods, leading to increased pressure on natural resources, alternated with dry periods, leading to irreversible degradation if pressure is not released before resilience thresholds are exceeded (Puigdefábregas, 1998). As described above, climate change can be expected to bring about a transition into a drier period for these regions, leading to lower support for vegetation productivity and soil structure stability, combined with constant or increasing rainfall intensity and increased frequency of disturbances. The interaction between these three factors is likely to determine the impacts of climate change on soil erosion in drylands (Imeson & Lavee, 1998).

Desertification is an example of how the combined impacts of climate change on vegetation cover and soil properties can interact and reinforce each other, increasing soil erosion in a region where lower rainfall rates might indicate otherwise. This complexity should be taken into account in modelling studies where the aim is to assess accurately the multiple impacts of climate change on soil erosion processes.

15.3 Erosion Modelling Approaches and Climatic Change

The previous section described a number of potential impacts of climate change on soil erosion drivers; this section presents modelling strategies used to assess these impacts for particular problems or locations. Model-based impact assessment studies can evaluate the potential and magnitude of these impacts. In the context of climate change vulnerability assessment frameworks, such as the one proposed by Adger (2006), modelling studies can be useful to:

- assess the sensitivity of soil erosion processes to climate shifts;
- evaluate whether climate change will move soil erosion beyond existing thresholds for desertification, land degradation, or loss of ecosystem services;
- test eventual adaptation measures that can mitigate the impacts of climate change.

Most modelling studies so far have focused on sensitivity assessment, with a small number (e.g. O'Neal *et al.*, 2005) testing adaptation measures. Threshold evaluation studies have been hampered by the difficulty in their delineation, due to the current lack of knowledge on the interactions between soil erosion, soil quality and vegetation support (Herrmann & Hutchinson, 2005; Boardman, 2006). Sensitivity assessment has usually focused on coupled hydrological and erosion prediction, attesting to the fact that an accurate estimate of runoff depth and velocity is at least as important as the correct estimation of other soil erosion parameters (Aksoy & Kavvas, 2005). Modelling exercises have differed in terms of objectives, model used, spatial and temporal extent of the study, and climate change scenario strategy. The processes used to represent

Table 15.1 Example of modelling studies on the impacts of climate change on soil erosion.

Temporal scale	Spatial scale	Climate change scenario	Geographical region	Reference
Continuous	Slope	Downscaling	South America (Amazon river basin)	Favis-Mortlock & Guerra (1999)
			Europe	Mantel *et al.* (2003)
			US	Pruski & Nearing (2002b)
			US (Midwest)	O'Neal *et al.* (2005)
			US (Oklahoma)	Zhang & Nearing (2005)
			China (Yellow river basin)	Zhang & Liu (2005)
		Hypothetical	US	Pruski & Nearing (2002a)
	Catchment	Downscaling	Europe (Finland)	Bouraoui *et al.* (2004)*
			Europe (Britain)	Lane *et al.* (2007)
			Europe (Denmark)	Thodsen *et al.* (2008)
		Hypothetical	US	Istanbulluoglu & Bras (2006)
			US (Iowa and Texas)	Chaplot (2007)
			Europe (Portugal)	Nunes *et al.* (2008)
			China (Yangtze river basin)	Zhu *et al.* (2008)**
Event-based	Slope	Downscaling	Europe (Germany)	Michael *et al.* (2005)
	Catchment	Downscaling	Europe (Portugal)	Nunes (2007)
		Hypothetical	US (Arizona) and Europe (Belgium)	Nearing *et al.* (2005)
			Europe (Portugal)	Nunes (2007)

*Climate in the late 20th century, with variability removed.
**Empirical model using Artificial Neural Networks (ANN).

hydrology and soil erosion in most models (Favis-Mortlock *et al.*, 2001) are similar enough to allow for a comparative analysis, grouping similar models into more general categories. These categories can be matched to a particular approach to climate change impact assessment, and can be a useful guide when devising modelling strategies for other studies.

Table 15.1 summarizes a number of soil erosion studies reviewed in this chapter, grouped according to temporal scale, spatial scale, and climate change scenarios. Almost all studies used models based on a conceptual description of water and sediment sources and sinks, also called process-based models. The terms used for each group follow the model reviews by Aksoy and Kavvas (2005) for the first two categories, and Xu and Singh (2004) for the third. Temporal and spatial scales in the Table refer to the model extent (the period or area of simulation encompassed by the model) rather than the model resolution (the level of discretization with which time or space are represented). The categories used in the table can be described as follows:

• *Temporal scale*: Modelling studies can be divided into (i) continuous, if the model is applied to consecutive rainfall events occurring during a season or longer period; and (ii) event-based, if the model is applied to a single rainfall event. The processes governing the long-term temporal variability of hydrological and erosion processes are quite different from those operating within an extreme event (Imeson & Lavee, 1998; Favis-Mortlock *et al.*, 2001), which has led to a structural distinction in soil erosion models. Models which operate continuously usually incorporate some sort of vegetation modelling component as well as long-term hydrological processes such as evapotranspiration and subsurface runoff, while in models operating for single events, these parameters are considered to be constant or negligible (Morgan & Quinton, 2001) This scale difference means that continuous models usually do not simulate at the within-event scale, as the inclusion of these processes would make a model too cumbersome.

• *Spatial scale*: Modelling approaches exist at the (i) slope-scale, representing processes occurring mostly at the field and hillslope scale, such as splash and rill erosion; and (ii) catchment-scale, also representing processes operating in regions of accumulated runoff, such as gully erosion and channel sediment processes (e.g. Lane *et al*., 1997; de Vente & Poesen, 2005); there is often some juxtaposition between scales. It should be noted that this distinction is between the simulated processes rather than the extent of the area of application; slope-scale models can be applied to catchments without representing other processes. As an example, Mantel *et al*. (2003) applied the PESERA model to large areas in northern France and Belgium and southern Iberia, but the model did not represent gully erosion and channel processes within these regions and therefore the study was classified as slope-scale.

• *Climate change scenario*: A common problem in climate change studies is the mismatch between GCM results, with higher quality at coarse spatial scales and for annual and seasonal values, and those required for model application, at fine spatial scales and for daily averages (Xu & Singh, 2004). Therefore, GCM results are usually taken as a starting point to generate climate change scenarios using two processes: (i) downscaling of GCM results to the desired spatial and temporal scale; and (ii) hypothetical, where GCM results are used to provide a range of possible changes to climate variables and scenarios are artificially built within these ranges. The most common downscaling methods referred to by Xu and Singh (2004) are (a) dynamic downscaling, where GCM results are used to force regional simulations of climate change at finer spatial and temporal scales using regional climate models (RCM); and (b) statistical downscaling, which uses a statistical relationship between GCM 'control' runs (for current conditions) and the observed climate patterns in a given location to provide future climate scenarios at the desired spatial and temporal scale. The choice of downscaling method can have significant impacts on the results given by erosion models (Zhang, 2007). In contrast, hypothetical scenarios are usually perturbations of current climate conditions with several degrees of change, aiming to obtain a response function of soil erosion to changes in climate parameters, in effect studying the sensitivity of soil erosion to changes in climate given a reasonable interval (Xu & Singh, 2004).

Selecting between the modelling approaches summarized in Table 15.1 depends upon the overall objectives of the study. It should be taken into account that increasing the complexity of a modelling study – in terms of both process description and spatial and temporal discretization – does not lead to improved results, due, to a great extent, to the uncertainty associated with the input parameters required by complex models which often lead to a greater uncertainty in the results without providing additional predictive power (Jetten *et al*., 1999, 2003; see also Section 6.4). Therefore, the complexity of the selected approach should match the questions which the modelling study wishes to answer. Two examples of this selection process can be taken from the studies in Table 15.1:

• studies with a continuous modelling approach focus on interactions between climate, vegetation growth and soil erosion at longer temporal scales, while those with an event-based approach focus on non-linear processes such as gully erosion and peak discharge/sediment yield relationships;

• studies at the catchment scale usually focus on within-watershed erosion patterns (e.g. gully erosion and sediment deposition) and channel processes, while studies focusing on soil erosion in agricultural fields constrained simulations to the slope scale.

Other factors should also influence the selection of a modelling approach, such as the dominant erosion processes in the study area or the availability of data for model parameterization and validation (Jetten *et al*., 1999, 2003; Section 6.4). In some cases, a multiscale modelling framework could be selected, using different models to study different problems with the required degree of complexity; this approach can be exemplified by the work of Nunes (2007), who studied the interaction between vegetation growth (using a continuous model) and soil erosion processes at different spatial scales (using an event-scale model).

As for the selection of a specific model to implement the study, some recommendations by Jetten *et al*. (1999) can be taken into account:

- input data quality (both quantitative measurements and qualitative knowledge of the study area), calibration procedures, and the knowledge of modellers can be more important than model structure for successful erosion simulations (see Chapter 3 for further discussion);
- models usually perform better for the processes and at the spatial and temporal scale they were designed to operate in, so evaluating different model structures and applications can provide an insight on the most appropriate model for a given case study;
- when modelling for changing conditions, process-based models can accommodate processes that do not currently occur, while empirical approaches are constrained by currently operating processes.

Finally, when designing a modelling study, some attention should also be given to calibration and validation strategies for climate change scenarios. Calibration and validation is a complex process, especially for models requiring large amounts of input data. Typical problems include the lack of measured data at the appropriate scale used by the model; parameter equifinality, where different sets of calibrated parameters provide equally good results; and over-calibration, where model parameterization is optimized using an excessively small sample of observations (e.g. Quinton, 1997; Beven, 2000; Boardman, 2006). Since models usually perform best for the range of conditions for which they were calibrated (Favis-Mortlock *et al*., 2001), calibrating and validating a model for future conditions presents a number of additional problems. For example, calibrated model parameters can have limited transferability in time, particularly in the face of significant changes to climate parameters or watershed conditions (Apaydin *et al*., 2006). Parameter equifinality can present a similar challenge, since parameter sets performing equally well for current conditions can lead to significant differences in climate change predictions (Wilby 2005). Toy *et al*. (2002) defined a robust model as one able to perform reasonably well with similar parameter values, including highly dynamic ones, for the widest possible range of conditions; calibration and validation problems for uncertain future conditions call into question the robustness of runoff and erosion models for climate change analysis (Beven, 2000; Morgan & Quinton, 2001).

To address this problem, models used for climate change studies should demonstrate an increased degree of robustness considering both current conditions and those as close to possible changes as achievable. One important strategy to increase robustness is to demonstrate that the model can simulate alterations to hydrological and erosion processes caused by changes in climate; this can be achieved using a 'space-for-time' approach, where the consequences of future climate change are studied using a comparative analysis between one study area and another with climatic characteristics resembling GCM predictions (Imeson & Lavee, 1998). In practice, this strategy can be implemented by calibrating and validating a model for different study areas with different climates and hydrological and erosion processes operating, or by using periods with different climate conditions in the calibration and validation process, especially if these conditions represent in some way the expected climate change scenarios (e.g. Bronstert, 2004; Xu & Singh, 2004). This approach can be further detailed by reproducing climate change in the calibration and validation process; for example, Xu and Singh (2004) proposed that, if the goal is to simulate a drier climate scenario, a model should be calibrated for a wet year and validated for a dry year, thus demonstrating its ability to simulate a wet/dry transition.

Another approach to increase model robustness is multi-process validation, i.e. to calibrate and validate a model for the highest possible number of variables representing different processes occurring at different scales, such as splash, rill and gully erosion, sediment yield, soil moisture and runoff at different spatial and temporal scales; this strategy can also address the problem of parameter equifinality (Ebel & Loague, 2006). However, this approach requires an increase in the data used for the calibration and validation process, which contrasts with the generally poor availability of data; hydrological data are often only available for catchment outlets, while erosion data are often not available at all, preventing a calibration and validation study of this kind in most catchments (Beven, 2000; Morgan & Quinton, 2001). To overcome this problem a qualitative evaluation of model performance can be used when quantitative data are not available; this approach consists of comparing model outputs with expected results in terms of process knowledge to assert the rationality of model behaviour, and therefore the model's capacity to simulate responses to changes in environmental conditions (Favis-Mortlock *et al.*, 2001; Ebel & Loague, 2006). In this approach, soft knowledge of the impacts of climate change – from observations in different sites, laboratory experimentation or extrapolation from observations in different climatic regions – can be useful to judge model performance under changed climates.

15.4 Case Studies

This section presents a number of case studies to demonstrate the application of different modelling strategies to different problems. Each case study includes a number of different studies and publications (listed in Table 15.1) grouped thematically, in order to illustrate how different modelling approaches were used to answer different questions.

15.4.1 Continuous modelling at the slope scale

This case study reviews work using the WEPP model – Water Erosion Prediction Project (Flanagan & Nearing, 1995). WEPP simulates hillslope processes such as inter-rill and rill erosion, sediment transport and deposition, as well long-term processes such as vegetation growth, plant residue generation and decomposition, or soil consolidation. An additional model feature is the capacity to simulate agricultural operations and their impact on soil properties, making this a good tool to simulate agricultural hillslopes (although the model also simulates catchment-scale processes operating in small watersheds driven by infiltration-excess surface runoff). The following applications of WEPP focused on the model's strengths, namely the continuous simulation of cultivated hillslopes.

Several publications have reported on climate change impact assessment in the US using WEPP (Table 15.1; for a partial review see Nearing *et al.*, 2004). A first approach was reported by Pruski and Nearing (2002a); this comprised applying hypothetical changes to annual rainfall (from –20% to +20%) for three soils, three slopes, and four crops in three locations in the US with different climate characteristics. The results include a ratio of sensitivity to climate change; WEPP indicates a 2.0 ratio of surface runoff increase to rainfall increase, and a 1.7 ratio of erosion increase to rainfall increase, showing the enhanced sensitivity of these parameters to changes in climate. Furthermore, this ratio also depends on the mode in which rainfall changes; the ratios reported above assume that half of rainfall changes are due to changes in intensity, with the remainder due to changes in the number of rain days. However, when the model is applied with rainfall intensity changes only, the sensitivity ratios increase to 2.5 and 2.4 for runoff and erosion respectively. This points to the importance of knowing how climate change may impact upon individual rainfall events before estimating impacts on soil erosion.

Pruski and Nearing (2002b) also applied the WEPP model with a climate change scenario downscaled from the HadCM3 GCM. WEPP was modified to take into account plant fertilization by CO_2, and applied to eight locations in the US with the climate change scenario. The results point to the complex interactions between different erosion drivers, particularly rainfall and vegetation biomass production; rainfall changes were often not the dominant impact on soil erosion. The importance of different drivers changed with location and was complicated by changes to seasonal climate patterns. However, one trend emerged from this work: in the US, erosion can be expected to increase where rainfall increases significantly, but where rainfall decreases the impacts are more complex and erosion can either increase or decrease, depending upon the interactions between the impacts of plant biomass and rainfall on erosion.

Finally, this work also focused on the impacts of adaptations to climate change on soil erosion. O'Neal *et al.* (2005) studied the combined impact of changes to climate and crop management on soil erosion in the Midwestern US using WEPP, with a similar climate change scenario to the one described above, and downscaling results using a stochastic weather generator, CLIGEN (using a method similar to the one described by Zhang *et al.*, 2004). Management practices were adapted to fit the climate scenarios by adjusting planting, tillage and harvesting dates, and changing crop rotations; the scenario used a future shift from maize and wheat to soybeans. Model results point to an increase in soil erosion between 33% and 274% by the 2050s in most of the study areas; the increase in erosion can be attributed to higher rainfall, later planting dates leaving the soil exposed for longer, and shifts towards greater cultivation of soybeans. Vegetation changes led to more erosion even in regions with lower rainfall. Zhang and Nearing (2005) used WEPP to study the impacts of three climate change scenarios (A2a, B2a and GGa1) on soil erosion in central Oklahoma. The climate scenarios were downscaled from HadCM3 predictions for the 2070s, also with CLIGEN, and predicted less rainfall and higher temperatures. However, WEPP predicted an increase in soil erosion of between 18% and 82% due to the combined impacts of higher rainfall variability (resulting in increased frequency of large storms) and, in some scenarios, a decrease in wheat yield. The authors also studied the impacts of adopting conservation tillage and no tillage to counteract soil erosion increase, with model results indicating their effectiveness as adaptation measures.

A similar approach was subsequently applied to the Yellow River basin in China, focusing on the Loess plateau drylands, a region which already experiences high levels of soil erosion (Zhang & Liu, 2005) and where climate change is expected to increase rainfall and, in particular, rainfall erosivity (Zhang *et al.*, 2005). High soil erodibility and different climate and cropping systems presented different challenges to this work. Zhang and Liu (2005) applied the WEPP model to two slopes in this region, using a stochastic weather generator (CLIGEN) to downscale three climate change scenarios (A2a, B2a, and GGa1) from the HadCM3 GCM for the 2080s. The results point to an increase in soil erosion of between 2% and 81% despite a significant increase in crop yield; in this region the rise in rainfall was the dominant driving force for soil erosion changes. The authors also concluded that the adoption of conservation tillage could be sufficient to adapt to climate change and reduce the negative impacts on soil erosion. In a subsequent work, Zhang (2007) tested the impacts of different downscaling methods on WEPP predictions. The downscaling approach described above was refined by introducing an intermediate step, where GCM results were first downscaled spatially using current climate data for local stations, using a transfer function; the spatially downscaled results were then used to drive the stochastic weather generator. Using this approach, the author reached soil erosion predictions of 4 to 10 times higher than previously. These results point to the importance of correctly downscaling GCM predictions when studying the impacts of climate change on soil erosion.

Finally, the WEPP model was applied to hillslopes cultivated with soya on a tropical hillslope in Brazil (Favis-Mortlock and Guerra, 1999). Future climate scenarios were taken from three GCMs (HADCM2, CSIRO9 Mk2 and ECHAM3TR) for 2050; two of the models predict a large increase in summer rainfall, while the third points to a slight decrease. These scenarios were also downscaled using a statistical approach based on CLIGEN. WEPP predicted changes to soil erosion from –9% to +55%, following relatively modest changes in rainfall (–2 to +10%), a result also of increased water stress during the growing period for soya leading to less vegetation cover. This was accompanied by an increase in the spatial and temporal variability of erosion.

Overall, these studies provide a good example of a comprehensive modelling approach to evaluate the impacts of climate change on soil erosion. They are also representative of a type of early modelling study (e.g. Favis-Mortlock & Boardman, 1995) not discussed in this section. The results for the US cover the range of possible impacts using hypothetical climate change scenarios (Pruski & Nearing, 2002a) and evaluate interactions between changes in rainfall, runoff and vegetation productivity for different climatic conditions (Pruski & Nearing, 2002b), as well as the impacts of agricultural land use changes (O'Neal *et al.*, 2005) and the potential to implement adaptation measures (Zhang & Nearing, 2005). In China, the uncertainty inherent in climate change predictions was also explored (Zhang, 2007). The main results point to the complex interactions between different impacts of climate change, which can lead to increases in soil erosion even where rainfall is expected to decrease; the importance of vegetation biomass productivity in these regions is highlighted. However, these studies were constrained to the slope scale and agricultural fields; possible impacts on rangelands, gully erosion or catchment sediment yield were not studied, and should not be inferred from the results due to the complex nature of the processes involved.

15.4.2 Continuous modelling at the catchment scale

Another model used to assess the impacts of climate change on soil erosion has been SWAT – Soil and Water Assessment Tool (Neitsch *et al.*, 2002). Like WEPP, SWAT simulates hillslope erosion processes, sediment transport and deposition, vegetation growth and residue processes, and agricultural operations. Unlike WEPP, however, SWAT was designed to simulate mesoscale catchments, trading detail at the slope scale for the ability to represent more complex catchment and river network structures, including large reservoirs and irrigation schemes. The following SWAT applications were focused on processes linking hillslopes to the river network to take advantage of these features. In contrast with the single-slope WEPP applications detailed above, SWAT was applied to complex catchments.

The first example is an application of SWAT to a watershed in Finland by Bouraoui *et al.* (2004). In contrast with the usual approach for climate change impact assessment, the authors looked at the impacts of recent climate change (1965 to 1998) on river flow and sediment yield, by comparing model results with observed climate and a synthetic climate series where rainfall and temperature increases were removed using non-parametric methods. The model results pointed to an increase in winter runoff and suspended sediment caused by a combination of increasing rainfall and decreasing snow cover. These results indicate the likely trend for future climate change impacts in this region. Another example is given by Chaplot (2007), who applied SWAT to two watersheds in the US, one with a humid climate and agricultural land (in Iowa), and the other with a semi-arid climate and a significant proportion of pasture (in Texas). The author simulated the impacts on runoff and soil erosion of two CO_2 and temperature change scenarios, combined with rainfall changes from −40% to +40%; the scenarios were stochastically generated using CLIGEN. Model results point to a dominant impact of rainfall in soil erosion rates at the humid watershed, with the wettest scenario leading to an increase of 157%, and similar decreases for the drier scenarios. Soil erosion in the semi-arid watershed, however, did not show great sensitivity to changes in climate, except by decreasing for the −40% rainfall scenario; surprisingly, soil erosion decreased in the wetter scenarios, possibly due to improved conditions for vegetation cover in the winter.

A final example is given by Nunes *et al.* (2008), who applied SWAT to two groups of watersheds in Portugal, also with humid and semi-arid climates. Climate change scenarios were generated using CLIGEN with the intention of simulating the range of climate change predictions by GCMs for this area, with temperature increases from 2°C to 6°C and rainfall decreases from 2.5% to 40%. The authors simulated changes to each parameter separately; they also simulated two sets of scenarios of combined rainfall and temperature change with wetter and drier conditions (rainfall decreasing by 1.6% and 6.2% respectively per 1°C increase in temperature). The results point to rainfall changes as the main driving forces for soil erosion in all landcovers except in wheat croplands, where temperature increases were more important due to the negative impact on biomass production and soil cover. For the combined changes, model results varied significantly between vegetation cover types; rangelands and managed forests showed a decrease in soil erosion in all scenarios, while agricultural lands (wheat croplands and vineyards) responded differently according to the combination of rainfall and temperature changes. For the drier scenarios, soil erosion decreased in both agricultural landcovers; for the wetter scenarios, soil erosion decreased slightly in vineyards (–25%) and increased in wheat croplands (up to 149%). These results are important since these landcover types represent the most important sediment sources in the study area. The authors also found greater responses in the humid watershed, as in the previous study, and note that in one of the test sites the shallow soils (c. 10 mm) were responsible for a relatively low sensitivity of surface runoff to rainfall decreases.

In short, these studies are not as comprehensive as those presented in the previous section, but they do provide additional information at the large catchment scale. The simulated areas are quite large (up to 1000 km^2 in all studies), and include different vegetation cover and soil types, which impact differently upon similar climate change scenarios; these different impacts combine to determine changes to watershed sediment yield. In particular, these results confirm one of the conclusions of the previous case studies, namely that the impact of decreasing rainfall rates on soil erosion is complex and depends upon the impact on vegetation biomass growth; however, these results also indicate that croplands in drying climates are particularly vulnerable to increases in soil erosion rates.

A final note should be made on the robustness of both this and the previous modelling approaches. While the SWAT approach has a larger spatial domain, there was in all cases a lack of data for validating the erosion simulations; the model was assessed using sediment yield measurements in the channel network, which is not sufficient to ensure that sediment sources and sinks are being correctly simulated (Jetten *et al.*, 2003). The WEPP approach was more robust, since it was applied to heavily monitored slopes with data available for calibration and validation. This difference illustrates how the lack of measured erosion data may hamper climate change impact studies using watershed-scale models.

15.4.3 Grid-based continuous modelling

A different example of erosion modelling at the slope scale was performed using the PESERA – Pan-European Soil Erosion Risk Assessment model (Kirkby *et al.*, 2004). PESERA simulates erosion at the slope scale in a similar way to SWAT and WEPP, including a vegetation growth component; however, the model has been applied using a 1 × 1 km grid for western and central Europe, taking into account the spatial variability of rainfall, relief, soil and vegetation properties. This grid-based approach allows an estimation of soil erosion for large areas while taking into account some degree of spatial variability, although the processes represented are still at the slope scale (e.g. gully erosion and channel processes are not taken into account by PESERA). This approach could also be used to generate global predictions for the impacts of climate change on soil erosion, similar to the work done for surface runoff in recent years (e.g. Manabe *et al.*, 2004).

This approach was performed by Mantel *et al.* (2003) using the A2b climate scenario based on the HadRM3 RCM. The study was performed for two windows in northwestern and southwestern Europe, with contrasting climates (humid and dry, respectively) and land uses. Land-use change scenarios (switching other arable crops to maize) were also assessed. The results for northwestern Europe indicate an increase in soil erosion ranging from 1 to 15 t ha^{-1} y^{-1}, due in a large part to an increase in winter and spring rainfall, but with very significant spatial variability which can be partially explained by different topography and land-use patterns. In southwestern Europe, the results point to a change in the spatial patterns of soil erosion, leading to an increase in the area for which significant erosion risk is expected (especially sparsely vegetated areas), coupled with a great decrease in soil erosion rates for the rest of the study area. Nevertheless, the overall erosion rates remain low, of the order of 0.5 to 1 t ha^{-1} y^{-1}. No significant differences were found for the land-use change scenarios. These results illustrate how a grid-based approach can analyse the superimposition of different spatial patterns – climate, topography, land use and soil – which when combined lead to complex patterns of soil erosion change that do not directly correlate with the spatial patterns of climate change.

This study also illustrates an important limitation on soil erosion model application: the lack of long-term soil erosion measurements at the slope scale (Boardman, 2006). Van Rompaey *et al*. (2003) evaluated the PESERA model for several areas in Europe; while the model gives acceptable results for agricultural areas in northern and central Europe, results for Mediterranean Europe have a poor correlation with estimates based on sediment yield. Part of this uncertainty is due to the difficulty in accurately determining the relationship between hillslope erosion and sediment yield due to the importance of gully and channel erosion processes in Mediterranean regions. Again, the lack of erosion data at the field scale makes a grid-based approach less robust than the modelling studies on highly monitored slopes described earlier; in many regions there are insufficient data to assess the robustness of upscaling model results from the slope to the regional scale.

15.4.4 Modelling channel processes

A number of studies have also focused specifically on suspended sediment transport and deposition in channels, which requires different models from the ones used in the previously described applications. Thodsen *et al*. (2008) looked at the impacts of combined land-use and climate change scenarios (A2 scenario from the HIRHAM RCM) on suspended sediment transport in two Danish rivers, using sediment rating curves adjusted for rainfall, runoff and season (to take into account vegetation cover inside the catchment). They found that a warmer and rainier scenario led to increases of 9% to 27% for the 2080s, mostly due to increased river flow in winter with greater sediment transport capacity; the longer growing season for annual crops had a minor impact on these predictions. Finally, the non-alluvial river was more sensitive to changes in climate than the alluvial river, possibly due to the greater irregularity of the flow regime.

A different approach was tested by Zhu *et al*. (2008), who used artificial neural networks (ANNs) instead of the process-based modelling approaches that dominate climate change impact studies; ANNs, while constrained to observations under current climate patterns, may take into account interactions between climate, hydrology and soil erosion not represented in models. The authors tested hypothetical scenarios of rainfall changes, from −20% to +20%, combined with temperature changes from −1 to +3°C, evaluating the impacts on sediment flux in the Yangtze river basin, China. The ANN predicts higher sediment flux with higher rainfall, while for higher temperatures the response is more complex, with lower runoff and therefore lower sediment flux, but higher sediment concentration in rivers thanks to increased soil erosion and sediment delivery. A combination of warmer and wetter climates is expected to lead to greater sediment flux due to higher soil erosion and sediment transport in the study area.

Another modelling approach was applied to US catchments by Istanbulluoglu and Bras (2006). They applied a river sediment dynamics model with a stochastic model linking rainfall amount and frequency, soil moisture and within-catchment vegetation dynamics to study the relationship between climate, vegetation cover and soil loss potential. The results indicate that soil erosion is not only dependent upon changes to mean annual rainfall, but also that an increase in soil erosion can be expected under lower storm frequency, especially in humid catchments, when considering lower rainfall rates. The relationship between climate and soil loss appears to be controlled by soil texture characteristics in shape and magnitude. This is one of the few studies focusing specifically on the impacts of drought frequency and length on soil erosion processes within the context of climate change.

Finally, Lane *et al*. (2007) used a more detailed modelling approach to study the feedback between impacts of climate change on flood frequency and sedimentation in Britain. The modelling framework included a detailed inundation model coupled with an estimate of channel aggradation from suspended sediment deposition; the model was applied using the A2 climate change scenario for the 2050s and 2080s using the HADRM3 RCM. Results point to an increase in inundated area, due to rainfall changes alone, of 12.2% to 14.7% during relatively frequent floods (1-in-0.5 and 1-in-2 year events). When considering also the impact of sedimentation in the river bed, the inundated area increases by 38.2% to 52.1%. The results indicate that in-channel sedimentation increases the sensitivity of flood inundation to climate change, and measures to prevent streambank erosion might aggravate this problem as the river would require enlargement to compensate for the rising channel bed. This study highlights one possible off-site effect of increased soil erosion rates, a subject which has not received much attention in recent research.

15.4.5 Modelling extreme events

The previous examples focused on long-term continuous modelling; there are fewer case studies specifically focusing on individual extreme events. This can be attributed in part to the complexity of the processes involved, particularly when compared with the low spatial and temporal resolution of current climate prediction approaches. Furthermore, studies at the extreme event scale are dependent on longer-term predictions for vegetation cover and land use.

Nevertheless, there are a number of examples in the literature. One case study is the Soil Erosion Network's model intercomparison exercise (Nearing *et al*., 2005), aimed at investigating the response of different soil erosion models, with different methods and levels of process representation, to key variables expected to be impacted by climate change: precipitation and vegetation. Seven different models were applied to two watersheds, one humid (in Belgium) and one semi-arid (in Arizona, US); they utilize different approaches to erosion process description, and temporal and spatial discretization, and include continuous as well as event-based models. This modelling approach was used to study the response of three storms per catchment to hypothetical changes in storm rainfall, vegetation cover and ground cover, from –20% to 20%.

The model response to these changes was coherent, with all models responding more strongly to changes in rainfall. The median ratio of sensitivity of sediment yield to rainfall changes was around 8 in the humid catchment, and around 5 in the semi-arid catchment, with models responding more strongly to changes in rainfall amount and intensity than to changes in rainfall amount alone. For vegetation and ground cover, the sensitivity was around –2 in both catchments. The coefficients of variation between models are significant, but most models responded within a similar range, especially for stronger storms; these results indicate that the tested models give, in relative terms, similar responses to climate forcings, which increases the credibility of the different modelling approaches.

Another extreme event study was made by Nunes (2007), who applied the MEFIDIS model (Nunes *et al*., 2005) to one humid and one semi-arid catchment in Portugal. MEFIDIS is a model optimized for extreme events, with a high process discretization in space and time. The author performed a first approach using hypothetical scenarios of rainfall and vegetation cover change, similar to the one presented above. The results for sediment yield sensitivity were similar, but the author also analysed differences in erosion response with spatial scale. Catchment-scale sediment yield and gully erosion were found to be more sensitive to changes in rainfall than erosion at the slope scale, due to non-linear relationships with changes to surface runoff rates and channel peak flow rates; however, changes to vegetation cover had similar impacts on soil erosion at all scales. The author also analysed the impact of changes to soil water deficit (–20 to +20%), which can have important consequences for water and sediment connectivity between hillslopes and the river network. While erosion at the slope scale showed a relatively low sensitivity to this parameter, gully erosion and sediment yield were significantly more sensitive. Finally, the author noted the relationship between low soil depth and increased sensitivity of soil erosion to climate change, as a low water-holding capacity of soils increases the response of water runoff generation to storm rainfall characteristics.

Nunes (2007) also applied the MEFIDIS model for the A2 and B2 climate change scenarios, downscaled with the PROMES RCM; scenarios for changes to vegetation cover and average soil water deficit were created by applying the SWAT model (described above). For the study areas, the scenarios combine higher temperatures (+2 to +4°C) with lower rainfall (–30 to –40%) and higher rainfall intensity in extreme events (10 to 20% in the A2 scenario, for winter and spring). The SWAT model indicates that this would lead to slightly higher vegetation cover (from c. 5% for wheat and vineyards to c. 30% for Mediterranean oaks and shrubs) and lower soil water content (–40% in winter and spring, –80% in autumn). These scenarios combine to cause different impacts on soil erosion according to climate scenario and season. Soil erosion is expected to decrease in both catchments (–20 to –60%), due to the combined impacts of higher vegetation cover, lower soil moisture and modest increases in rainfall intensity. However, this decrease is more marked for gully erosion and sediment yield due to the lower water and sediment connectivity; at the slope scale, erosion decreases are expected to be halved (–10 to –30%). Also, this decrease is mostly under forests and Mediterranean vegetation cover types; wheat croplands experience little or no reduction in soil erosion rates for the A2 scenario. These changes are coupled with increased seasonal differences in soil erosion; in the humid catchment, erosion is expected to increase by 20% in winter and spring. These results highlight how different soil erosion processes have different responses to climate change, and the role of soil moisture in determining changes to sediment connectivity as well as to soil erosion, an issue which is not explored in most studies. However, an analysis of these results must take into account the lack of data to validate gully erosion simulations in the study watersheds, a problem which is widespread in erosion studies (Boardman, 2006).

A final example of extreme event modelling approaches was given by Michael *et al*. (2005), who applied the EROSION 2D model (Schmidt, 1990) to two agricultural slopes in Germany. The authors used GCM scenarios for the B2 emission scenario, 2030–2050, downscaled to 5 min rainfall data using a statistical approach driven by prevailing weather types; the scenario points to an increase of 23% in the intensity of the most extreme events, but a 38% decrease in frequency. The results point to an increase in soil erosion between 22% and 66%, but it should be noted that changes to vegetation cover were not taken into account.

Overall, these studies highlight the complexity and potential of an event-based modelling approach for climate change impact assessment. The models are often difficult to parameterize and evaluate, and require both high-resolution climate change scenarios and predictions for longer-term impacts (in these examples, vegetation cover and soil moisture). However, predictions can be made for within-storm processes dependent upon surface runoff concentrations (gully erosion) or peak flow rates (sediment transport) with more detail than that achieved by continuous models.

15.5 Conclusions, Limitations and Research Needs

The case studies presented in the previous section are representative of the typical modelling approaches used to study the impacts of climate change on soil erosion. It should be noted that the most complete studies were applied using continuous models at the slope scale, possibly due to the availability of data to evaluate these models; studies at the watershed scale and using extreme event models are rarer and appear, in comparison, to be less developed. Despite the higher number of slope applications, current modelling approaches are still limited in space and scope, and therefore it is difficult to extrapolate the results to more general conclusions. It can perhaps be said that this branch of climate change impact science is not yet fully developed, and that modelling approaches still need further testing, refinement and discussion before robust results can be presented.

However, one overall conclusion indicated by the results of the different studies is that the relationship between soil erosion and climate change is complex and depends upon a number of impacts highlighted at the start of this chapter. Furthermore, soil erosion processes are themselves highly sensitive to changes in driving forces, making it difficult to exclude complexity from the analysis without invalidating the main conclusions. These issues should be taken into account when designing a modelling approach to be applied in a particular case study. Two broad conclusions emerging from this work relate the patterns of changes in climate with erosion response, at least at the slope scale:

- where rainfall is expected to increase significantly, this dominates erosion response; and
- where rainfall is not expected to change or is expected to decrease, more complex processes take hold, with the dominant processes involving a relationship between changes to rainfall and vegetation biomass.

The results are not sufficient for a quantitative estimate of these impacts, and there are still many knowledge gaps surrounding these estimates, especially when transferring results from slope-scale studies to larger scales. Some of these gaps are related to more general issues in soil erosion science, such as the lack of data and the uncertainties surrounding estimates in erosion magnitude, location of hotspots, on- and off-site impacts and conservation measures (Boardman, 2006). The knowledge gaps on the impacts of climate change on soil erosion can be, in broad terms, systematized in a few questions:

- Can we upscale model results at the individual hillslope and watershed scales to regional and global scales?
- What is the uncertainty surrounding the estimates?
- Which are the links and feedbacks between soil erosion and land use/land cover that can be affected by climate change, and which adaptation measures can be taken?

15.5.1 Upscaling results to the regional and global scales

Most of the studies presented earlier in the chapter focus on single hillslopes or, at most, watersheds. While these applications have been extremely useful to increase our understanding of the processes behind the impacts of climate change, one can question whether the results can be upscaled. Soil erosion is a phenomenon with high variability in space and time, and different processes intervening at different scales. The PESERA study (Mantel *et al.*, 2003) highlighted the high spatial variability of climate change impacts on soil erosion, even at the hillslope scale; the within-watershed results by Nunes (2007) showed how impacts may vary with spatial scale. Both studies have been hampered by the lack of data to evaluate the modelling approach used.

These issues, especially the lack of erosion data, appear to limit the feasibility of grid-based impact assessment studies at the regional or global scale, such as those currently done for surface runoff (e.g. Nohara *et al.*, 2006). The lack of regional or global-scale erosion estimates for current conditions (Boardman, 2006) should be overcome before attempting to upscale climate change impacts. Furthermore, the studies presented in this chapter are not evenly distributed throughout the globe. Most studies have focused on the mid-latitudes, with temperate humid and semi-arid climates; subtropical regions and the high latitudes are poorly represented by comparison, which could limit the understanding of particular interactions between climate change, runoff, vegetation cover, and so on, which are required to upscale model predictions in these regions. It can therefore be argued that more slope-scale studies are still needed in order to increase our understanding of the processes linking climate change and soil erosion, thereby increasing our confidence in subsequent upscaling exercises.

15.5.2 Uncertainty in climate change impact estimates

Knowing the uncertainty of a climate change impact assessment is necessary to provide robust adaptation measures, i.e. measures that can be expected to provide acceptable results under a large range of conditions. While sources of uncertainty in soil erosion studies have been discussed since the first modelling experiments (e.g. Favis-Mortlock & Guerra, 1999), published studies usually only quantify uncertainty due to model errors; even the assessment of this kind of uncertainty may be hampered by the lack of soil erosion data, an issue which is a broader problem in soil erosion modelling (Boardman, 2006).

An example of other sources of uncertainty which can significantly hinder modelling results can be taken from the water resources sciences (e.g. Dessai & Hulme, 2007). These include uncertainties in: greenhouse gas emission scenarios, different GCM results for a similar emission scenario, downscaling (particularly important for extreme event predictions), model results for surface runoff generation and vegetation response, and future land-use changes; these uncertainties may propagate through the modelling approach. Some of these sources of uncertainty have been taken into account in the studies presented in this chapter, for example by driving erosion models with outputs from different GCMs or different climate change scenarios; the remaining sources of uncertainty are rarely taken into account. While progress has been made on quantifying and reducing these uncertainties, such as the PRUDENCE project (Déqué *et al*., 2005) which provided downscaled climate change estimates for Europe, soil erosion is downstream from a number of climate change studies (e.g. changes to the hydrological cycle and vegetation patterns) and therefore this issue is likely to remain a problem in the near future.

Furthermore, it is doubtful if some sources of uncertainty can be quantified since they can be defined as 'deep uncertainties': processes which are not yet fully understood (Dessai & Hulme, 2007) and therefore not well simulated. The studies shown in this chapter focus mainly on long-term hillslope erosion rates and, to a lesser degree, channel processes. Gully erosion and sediment connectivity issues are poorly represented; however, the current lack of data and knowledge on these processes has limited their integration in soil erosion models (Boardman, 2006), which may severely hamper progress in this area. Disturbances are also poorly represented in these studies. While continuous models can represent the impacts of drought on vegetation cover, other important impacts of severe droughts – such as woody plant mortality, changes in vegetation patterns, desertification – are not well described; this issue might potentially be addressed by associating erosion models with more detailed vegetation models. The impacts on soil erosion of increased wildfire frequency are also poorly represented; in this case, while links between climate change and wildfires have been studied, the impacts upon soil erosion are still not well understood (Shakesby & Doerr, 2006) and require additional research before being included in climate change impact studies. Finally, the relationships between climate change, soil carbon processes and erodibility have been studied mainly through space-for-time approaches (e.g. Lavee *et al*., 1998), as described earlier in this chapter. Soil structure processes are poorly represented in erosion models, and some attention to this issue is required in order to obtain improved predictions, including more data on climate–soil structure relationships.

15.5.3 Links and feedbacks between erosion and land use/land cover

Links between soil erosion, land use/land cover and socio-economic issues are also barely touched by the studies presented in this chapter. Future land-use changes are not usually considered in climate change studies, but existing scenarios can be taken into account by models, as shown in a few examples in this chapter. Feedbacks between soil erosion, agricultural productivity and land-use changes (e.g. Bakker *et al*., 2004, 2005; Avni, 2005) are less well known and more difficult to take into account; for example, Nunes (2007) suggested that in regions of degraded soils, long-term soil erosion might have as much impact on vegetation productivity as changes in climate, with a possible feedback relation with soil erosion. In particular, one poorly understood subject is the relationship between desertification and climatic or land degradation thresholds; more data and research on this issue would allow its inclusion in soil erosion studies. This will be particularly important when the focus is on semi-arid 'threshold regions', with dry climates tending to become drier. One possible approach to consider these interactions is to link physical erosion models with socio-economic models; however, interdisciplinary models of this nature are still rare, and existing approaches (e.g. Wu *et al*., 2007) are still not developed enough to be combined with relatively complex erosion models.

Furthermore, most of the studies do not consider adaptation to climate change. The studies that did tested different adaptation methods (e.g. conservation and no tillage) to assess whether they are efficient tools to counterbalance the negative impacts of climate change. A further issue that needs to be addressed is the interaction between measures to adapt to different climate change impacts. For example, the study by O'Neal *et al.* (2005), reported above, shows that agricultural adaptations to future climate aimed at increasing productivity might also lead to increased erosion. On the other hand, Lacombe *et al*. (2008) showed how the adoption of extensive soil and water conservation measures in the past has led to a decrease in available water downstream. These issues need to be addressed, particularly at the watershed scale and in light of proposing integrated watershed management methods to adapt to multiple impacts of climate change on water resources, floods, agricultural productivity, soil erosion, nutrient exports, and so on.

These and other limitations must be addressed before the impacts of climate change can be evaluated with some measure of confidence. Some ongoing research projects are proposing modelling strategies that take these issues into account; one such example is the ongoing MESOEROS21 project, aiming to study the impact of global climate change on soil erosion in the Mediterranean (MESOEROS21, 2006). The modelling approach takes into account soil erosion drivers such as land-use changes, intensification of irrigation and desertification, as impacted by climate change, as well as direct impacts on soil erosion; in some cases, more complex vegetation models are used to generate vegetation cover scenarios. Changes to erosion processes are explored with complex models in intensively monitored small catchments, but results are also upscaled to the regional scale using simpler models validated with long-term soil erosion databases for the region. Finally, this project also studies the vulnerability to soil erosion – the expected impact of changes to soil erosion rates on soil water storage, crop productivity, and so on. MESOEROS21 shows an example of how more complex, and hopefully more robust, approaches can tackle a number of the research gaps outlined above.

In summary, this chapter has hopefully shown how climate change can impact soil erosion through a number of processes, many of which are not linearly dependent upon changes to rainfall patterns. Current soil erosion modelling approaches have been developed and applied to test the impacts of climate change for different case studies involving different climate scenarios and locations, providing an insight into the processes linking climate and soil erosion. However, a significant number of research gaps are still present, including the upscaling of results for larger spatial scales; uncertainties in climate change scenarios and their impacts, particularly on soil erosion drivers not fully taken into account by current models; and the links between climate change, soil erosion and land-use changes involving socio-economic as well as biophysical processes. More complex modelling approaches can be developed to address these limitations; however, some effort in other areas such as data collection and process understanding are still needed to improve our knowledge of how soil erosion can be affected by changes in climate. This issue is critical to provide robust adaptation measures, especially when considering that global change is currently one of the greatest challenges for soil and water conservation (Garbrecht *et al*., 2007).

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