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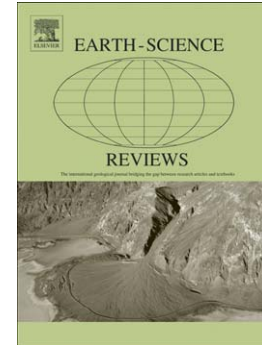
Tolerable versus actual soil erosion rates in Europe

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# 1 **Tolerable versus actual soil erosion rates in Europe**

2

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10

11

## 12 **Abstract**

13 Erosion is a major threat to soil resources in Europe, and may impair their ability to  
14 deliver a range of ecosystem goods and services. This is reflected by the European  
15 Commission's Thematic Strategy for Soil Protection, which recommends an  
16 indicator-based approach for monitoring soil erosion. Defined baseline and threshold  
17 values are essential for the evaluation of soil monitoring data. Therefore, accurate  
18 spatial data on both soil loss and soil genesis are required, especially in the light of  
19 predicted changes in climate patterns, notably frequency, seasonal distribution and  
20 intensity of precipitation. Rates of soil loss are reported that have been measured,  
21 modelled or inferred for most types of soil erosion in a variety of landscapes, by  
22 studies across the spectrum of the Earth sciences. Natural rates of soil formation can  
23 be used as a basis for setting tolerable soil erosion rates, with soil formation consisting  
24 of mineral weathering as well as dust deposition. This paper reviews the concept of

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25 tolerable soil erosion and summarizes current knowledge on rates of soil formation,  
26 which are then compared to rates of soil erosion by known erosion types, for  
27 assessment of soil erosion monitoring at the European scale.

28

29 A modified definition of tolerable soil erosion is proposed as ‘any actual soil erosion  
30 rate at which a deterioration or loss of one or more soil functions does not occur’,  
31 actual soil erosion being ‘the total amount of soil lost by all recognised erosion types’.  
32 Even when including dust deposition in soil formation rates, the upper limit of  
33 tolerable soil erosion, as equal to soil formation, is ca.  $1.4 \text{ t ha}^{-1} \text{ yr}^{-1}$  while the lower  
34 limit is ca.  $0.3 \text{ t ha}^{-1} \text{ yr}^{-1}$ , for conditions prevalent in Europe. Scope for spatio-  
35 temporal differentiation of tolerable soil erosion rates below this upper limit is  
36 suggested by considering (components of) relevant soil functions. Reported rates of  
37 actual soil erosion vary much more than those for soil formation. Actual soil erosion  
38 rates for tilled, arable land in Europe are, on average, 3 to 40 times greater than the  
39 upper limit of tolerable soil erosion, accepting substantial spatio-temporal variation.  
40 This paper comprehensively reviews tolerable and actual soil erosion in Europe and  
41 highlights the scientific areas where more research is needed for successful  
42 implementation of an effective European soil monitoring system.

43

44 Key words: erosion tolerance; soil formation; climate change; soil protection;  
45 monitoring; dust deposition

46

47

## 48 **1. Introduction**

49 1.1 General

50 Soil loss occurs mostly through physical pathways but can also occur as a result of  
51 biochemical processes, including weathering of mineral particles in soil, which is  
52 known as chemical denudation. Removal of particles or even small aggregates from  
53 the in situ soil system then takes place in suspension or solution, as bed load or by  
54 gaseous export. Organic soil material is lost mainly through decomposition processes,  
55 except in the case of peat erosion where organic particles are removed and transported  
56 by water or wind. Physical pathways of soil loss predominate and fall within the  
57 domain of soil erosion, which is defined as “the wearing away of the land surface by  
58 physical forces such as rainfall, flowing water, wind, ice, temperature change, gravity  
59 or other natural or anthropogenic agents that abrade, detach and remove soil or  
60 geological material from one point on the earth's surface to be deposited elsewhere”  
61 (Soil Science Society of America, 2001; Jones et al., 2006, p.24-5). With respect to  
62 soil degradation, most concerns about erosion are related to ‘accelerated soil erosion’,  
63 where the natural (or ‘normal’, or ‘geological’) rate has been increased significantly  
64 by human activity.

65

66 The cause and extent of accelerated soil erosion are influenced by a number of factors  
67 (Morgan, 2005) and the most significant are:

- 68 • soil erodibility or susceptibility to erosive forces, as determined by soil  
69 physical, chemical and biological properties (Chepil, 1950; Bryan, 1968;  
70 Wischmeier and Mannering, 1969; Aspiras et al., 1971; Wischmeier et al.,  
71 1971; Tisdall and Oades, 1982; Rauws and Govers, 1988; Forster, 1989;  
72 Chenu, 1993; Oades, 1993; Marinissen, 1994; Edgerton et al., 1995; Le  
73 Bissonnais, 1996; Degens, 1997; Ketterings et al., 1997 ; Kiem and Kandeler,  
74 1997; Hallett and Young, 1999; Czarnes et al., 2000; Doerr et al., 2000;

- 75 Scullion and Malik, 2000; Boix-Fayos et al., 2001; Ritz and Young, 2004;  
76 Allton, 2006; Shakesby and Doerr, 2006)
- 77 • erosivity or energy of the eroding agent, e.g. rainfall, overland flow or wind  
78 (Wischmeier and Smith, 1958; Skidmore and Woodruff, 1968; Fournier, 1972;  
79 Zachar, 1982; Morgan et al., 1986; Knighton, 1998)
  - 80 • slope characteristics, gradient, length and form (Zingg, 1940; Musgrave, 1947;  
81 Kirkby, 1969; Horváth and Erödi, 1962; Chepil et al., 1964; Meyer et al.,  
82 1975; D'Souza and Morgan, 1976; Wischmeier and Smith, 1978)
  - 83 • land cover use and management (Wischmeier and Smith, 1978; Wiersum,  
84 1979; De Ploey, 1981; Dissmeyer and Foster, 1981; Laflen and Colvin, 1981;  
85 Foster, 1982; Temple, 1982; Lang and McCaffrey, 1984; Armstrong and  
86 Mitchell, 1987; Quinton et al., 1997; Lal, 2001; Gyssels et al., 2005; Zhang et  
87 al., 2007)

88

89 This paper reviews the dominant causes and rates of soil loss that occur in Europe via  
90 the process of detachment (e.g. water, wind, tillage, crop harvesting and land  
91 levelling), and subsequent transport and deposition of the detached soil material.

92 Whilst all pathways of soil loss need to be considered and monitored carefully, once  
93 detachment of soil particles occurs, the functionality of the remaining soil is impaired  
94 to a greater or lesser extent depending on the amount of soil lost. Thus prevention of  
95 the detachment phase of the erosion process (Meyer and Wischmeier, 1969) is crucial  
96 if the functionality of the soil system is to be safeguarded for future generations.

97

98 This review focuses on erosion of mineral soils in Europe, because this is the  
99 dominant type of soil loss on the continent (Boardman and Poesen, 2006). Mineral  
100 soils are here defined as those that consist predominantly of, and have properties  
101 mainly determined by, mineral matter, and usually contain less than 20% organic  
102 carbon (SSSA, 2001). Relatively recent research (Holden and Burt, 2002; McHugh et  
103 al., 2002; Holden, 2005) has shown that erosion processes also account for substantial  
104 losses from organic soils, for example by piping and gullyng in peatlands. However,  
105 organic soils are far less extensive than mineral soils in Europe (Montanarella et al.,  
106 2006) and constitute a different eco-system; thus consideration of their erosion is not  
107 included in this paper.

108

## 109 1.2 Scale

110 Soil erosion research has considered various spatial and temporal scales at which the  
111 different erosion processes operate. The experience and knowledge gained from these  
112 studies is generated by, and serves, a very wide audience, ranging from developers of  
113 sub-process, physically based erosion models, such as EUROSEM (Morgan et al.,  
114 1998) and WEPP (Nearing et al., 1989), through to regional planners and policy  
115 makers. Ciesiolka and Rose (1998) observe that smaller scale studies tend to focus on  
116 'on-site' impacts of soil erosion, whilst larger spatial-scale studies concentrate on the  
117 'off-site' impacts.

118

## 119 Table 1

120

121 The temporal scale variation in erosion processes is implicit in Table 1, with small  
122 spatial scale processes such as raindrop impact occurring in fractions of seconds, and

123 catchment scale processes usually being monitored over much longer time scales (i.e.  
124 seasons, years, decades or even geological timescales). Sediment delivery ratios are  
125 also time-dependent, ranging from effectively no sediment delivered at the exact  
126 moment of detachment to sediment delivery ratios at the catchment scale approaching  
127 100% over geological timescales (van Rompaey et al., 2005).

128

129 The comparison of, and connectivity between different spatial and temporal scales is a  
130 major challenge in erosion research currently. This complex spatio-temporal process  
131 and the lag times involved, make it intrinsically difficult to compare directly a series  
132 of plot scale measurements with data generated for the whole catchment. The results  
133 of soil loss and sediment delivery obtained at one spatial scale cannot and should not  
134 be extrapolated to another (Walling, 1990; de Vente and Poesen, 2005).

135

136 Simple 'scaling up or down' of erosion rates is not possible (Pierson et al., 1994).

137 According to van Noordwijk et al. (1998), there are no 'scaling rules' in erosion  
138 research. It appears that the mean value of erosion per unit area will change at  
139 different spatial scales, all other factors being equal. At small spatial scales (e.g.  
140 individual aggregate), better control of variables, ease of replication and understanding of  
141 erosion mechanisms can be gained, but such fragmenting or deconstructing of processes  
142 may exclude many of the factors affecting the true rates of erosion (e.g. slope topography) as  
143 observed at a larger spatial scale in the field. On small plots, the process of rainsplash  
144 detachment (especially) and transport will dominate erosion rates, due to the limited  
145 slope lengths over which erosive overland flow can generate. It follows that certain  
146 erosion processes such as gully erosion or mass movements cannot be simulated at  
147 small spatial scales, but they may dominate at larger scales. As spatial scale

148 increases, overland flow becomes the dominant agent of erosion, but different  
149 experimental conditions have shown rates of erosion per unit area to both increase  
150 and decrease with increasing slope length (Zingg, 1940; Meyer et al., 1975;  
151 Abrahams et al., 1991; Smith and Quinton, 2000). Morgan (2005) states “with such a  
152 great range of possible conditions, a single relationship between soil loss and slope  
153 length cannot exist”. Also, plot boundary / edge effects on erosion processes and  
154 rates are proportionately more significant at smaller spatial scales.

155

156 To improve understanding of the effect of spatial scale on erosion processes, the links  
157 or connectivity between different scales can be studied by applying experimental  
158 methods which encompass a range of spatial scales simultaneously. There has been  
159 some work on converting field-scale to catchment-scale erosion data, based on the  
160 concept of sediment delivery ratios (Osterkamp and Toy, 1997; Walling, 1983, 1990).  
161 Hudson (1993) reports on the ‘nested catchments’ approach in soil erosion research,  
162 which was developed from biological research methods, investigating biodiversity  
163 and species richness at different scales. Turkelboom and Trebuil (1998) developed a  
164 methodology for erosion process analysis at the field, farm and catchment scales, and  
165 ways of linking these different scales. Their multiscale approach involves the  
166 physical, economic and social aspects affecting erosion. Kirkby (2001) describes the  
167 hierarchical MEDRUSH model, which simulates erosion and runoff processes  
168 operating at a scale of  $1 \text{ m}^2$  in the first instance. These results are then ‘nested’ or  
169 ‘embedded’ within representative ‘flow strips’ of up to 100 m wide, oriented up/down  
170 the slope. Water and sediment generated at this scale are then ‘routed’ via computed  
171 linear transfer functions into the sub-catchment scale ( $1\text{--}10 \text{ km}^2$ ). Output from this  
172 scale then feeds the main catchment-scale channel network, which may be up to



173 2500 km<sup>2</sup> in area. Kirkby (2001) argues that MEDRUSH demonstrates that ‘coarse  
174 and fine scaled models can be linked together consistently with a sound physical  
175 basis’.

176

177 Until we understand the connections between the different spatial scales, soil erosion  
178 research should encompass as wide a range of scales as possible. This has the multiple  
179 benefits of linking soil erosion rates generated at varying spatial scales, supplying  
180 knowledge which will be of interest to many parties (from physically based erosion  
181 modellers through to policy makers) and identifying if there are any rules to be  
182 applied when upscaling or downscaling the results of soil erosion research.

183

184 This discussion on the effect of scale on erosion is intended for completeness, but the  
185 focus of this paper is on the plot-to-field scale, because this is the position in the  
186 landscape at which removal of the in situ soil takes place. As a result, it is here that  
187 soil functioning will be most adversely affected by soil erosion.

188

189 1.3 Consequences, mitigation, costs and monitoring

190 Soil erosion rates are known to increase significantly following anthropogenic  
191 activities such as stripping of natural vegetation, especially clearing of forests for  
192 cultivation; other changes in land cover through cultivation or urbanisation and  
193 infrastructural development; over-grazing; wildfires or controlled burning; re-  
194 sculpturing of the land surface for example terrace construction; inappropriate  
195 intensification of land use and management, for example cultivation of steep slopes  
196 beyond their inherent ‘capability’ (Klingebiel and Montgomery, 1961) or collapse of  
197 terrace structures through poor maintenance (Temple and Rapp, 1972). The

198 consequences of soil erosion for society can be severe, for example annual costs have  
199 been estimated to be £205 million in England and Wales alone (see Table 2) and \$44  
200 billion in the U.S.A. (Pimentel et al., 1995).

201

202 Table 2

203

204 As Table 2 demonstrates, the costs associated with soil erosion are often categorised  
205 into ‘on-site’, i.e. where the soil loss takes place, and ‘off-site’ impacts, the temporary  
206 or permanent destination of the eroded sediment. Over time, attitudes have changed  
207 with regard to the most damaging effects of soil erosion. Where crop productivity has  
208 been a significant driver of soil erosion, the on-site impacts of erosion are paramount  
209 through the loss of rooting medium, nutrients, seeds, seedlings, agro-chemicals,  
210 organic matter, microbial communities, trace elements and water holding capacity.  
211 The production function of soil is likely to become even more important, in view of  
212 the projected increase in global human population and consequent demands for food.  
213 More than 99% of food supplies (calories) for human consumption come from the  
214 land, whereas less than 1% comes from oceans and other aquatic ecosystems (FAO,  
215 2003).

216

217 However, where food security is not an issue, or any declines in crop yield can be  
218 masked by applications of agro-chemicals, the focus has often been on off-site  
219 impacts. These include flooding, often due to deposition of eroded sediments  
220 restricting the capacity of water channels to carry peak flows, and reductions in water  
221 quality, due to turbidity and preferential transport of contaminants on eroded sediment  
222 surfaces, which, in turn, have impacts on aquatic biota (Lloyd, 1987; Lloyd et al.,

223 1987; Newcombe and Macdonald, 1991; Cooper, 1993). The value of soil in situ (i.e.  
224 not eroded) is once again acknowledged (Vandekerckhove et al., 2004), as the concept  
225 of soil resources being able to deliver ecosystem goods and services gains acceptance  
226 as advocated in the EU draft Soil Framework Directive (European Commission,  
227 2006a,b).

228

229 To evaluate the impact of agricultural and other land use policies in Europe, Gobin et  
230 al. (2002, 2004) proposed selecting a set of soil erosion indicators that can be  
231 calculated objectively, validated against measurements or observations and evaluated  
232 by experts. This advice has been heeded in the design of a European soil monitoring  
233 system by the ENVASSO project - Environmental Assessment of Soil for Monitoring  
234 – funded under the European Commission's 6<sup>th</sup> Framework Programme (Morvan et  
235 al., 2008). Indicators for soil erosion proposed for implementation at the first tier  
236 (Eckelmann et al., 2006), are: i) estimated soil loss by water via rill, inter-rill and  
237 sheet erosion, ii) estimated soil loss by wind erosion, and iii) estimated soil loss by  
238 tillage erosion. Each of these indicators can be modelled and is accompanied by a  
239 measured indicator of soil loss for calibration and validation of modelled estimates. At  
240 the present time, there is no reliable model for estimating or predicting gully erosion  
241 in the same way as models for rill and inter-rill erosion (Poesen et al. 2006, p528-30).  
242 However, it is likely that advances in remote sensing and data processing technology  
243 will allow more reliable and accurate estimation of soil loss as a result of gully  
244 erosion in future (Jones et al., 2004).

245

246 The clear impact of erosion on society and individuals, combined with the political  
247 drive for developing a harmonised European system for monitoring erosion as a threat

248 to soil, has identified the need for scientifically sound and robust threshold values  
249 against which to appraise the monitoring data. This paper sets out to review tolerable  
250 soil erosion, as a concept and in rates, for European conditions, and assesses actual  
251 soil erosion rates by discussing all (known) types of erosion.

252

253

## 254 **2 Tolerable soil erosion rates**

255

256

### 257 **2.1 Concept**

258 Since soil loss includes the removal of soil material by both physical processes  
259 (erosion), and biochemical processes (solute/gaseous export of mineral matter and  
260 decomposition of organic matter), the term ‘tolerable soil erosion’ is preferable when  
261 referring to soil lost by erosion in the context of soil protection. A number of (near)  
262 synonymous terms are used in the literature: ‘soil loss tolerance’, ‘permissible soil  
263 loss’, ‘acceptable rates of erosion’, ‘allowable soil loss’, etc. (see Table 3). It is  
264 important to note the difference between concept and unit. ‘Tolerable soil erosion’ is a  
265 conceptual term, with judgements of affected soil functions etc., that can be quantified  
266 in ‘tolerable rates of soil erosion’ with units conventionally in  $\text{t ha}^{-1} \text{yr}^{-1}$ .

267 Table 3

268

269 Reviewing the different definitions for tolerable soil erosion in the literature (Table 3),  
270 two themes emerge. The first interpretation is to view tolerable soil erosion as  
271 maintaining the dynamic equilibrium of soil quantity (mass/volume) in any location  
272 under any circumstances. The second interpretation takes a functional approach by

273 relating soil erosion tolerance to the biomass production function of soil. Roose  
274 (1996) highlighted difficulties with both interpretations. The first interpretation  
275 ignores soil quality by focusing only on soil quantity. The second approach ignores  
276 many soil functions by focusing only on the biomass (particularly crop) production  
277 function of soil (see also Table 4). In addition, it creates temporal ambiguity: 'a long  
278 time', 'indefinitely', 'an extended period of time', and '20-25 years'. Interestingly, the  
279 Soil Quality Vocabulary of the SSSA (2001) lists both interpretations, without  
280 indicating the conditions under which these should apply.

281

282 Both interpretations incorporate value judgements of how much soil erosion human  
283 societies should tolerate. The first interpretation judges that it is tolerable to ensure  
284 that the rate of soil formation exceeds the rate of soil loss by erosion, but that it is not  
285 tolerable for the soil erosion rate to exceed the soil formation rate. The value  
286 judgement in the functional approach links the soil erosion tolerated to the  
287 performance of one particular soil function, for example the crop production function.

288

289 At the end of the Second World War much of Europe was in ruins and crop  
290 production systems were destroyed or at best seriously malfunctioning in many areas.  
291 International aid, through the Marshall Plan in the 'western' world, focused on food  
292 supplies, which were scarce and insecure. It was during this period that the concept of  
293 tolerable soil erosion was developed most actively, which may explain the focus on  
294 the crop production function of soil. The agricultural surpluses of the 1980s led in  
295 the 1990s to a more comprehensive/holistic concept of soil functions (e.g. Blum,  
296 1993; Sombroek and Sims, 1995; Brady and Weil, 2002; De Groot, 2002; Blum,

297 2005; Nikitin, 2005; and the European Commission, 2006a,b). These are generally  
298 based on five primary soil functions (see Table 4).

299

300 Table 4

301

302 The need to include the regulation function in establishing tolerable rates of soil  
303 erosion was realised by Mannering (1981) and Skidmore (1982), who included it in a  
304 function of 'soil loss tolerance' (modified from Stamey and Smith, 1964), although  
305 only as secondary to the production function. Roose (1996) stated that tolerable soil  
306 erosion should consider "respect for the environment in terms of water quality,  
307 especially runoff sediments". Despite these appeals, definitions for tolerable soil  
308 erosion that were published later only incorporated the crop production function (see  
309 Table 3).

310 The remaining three soil functions (i.e. information, engineering and habitat) do not  
311 appear to have been considered in 'tolerable soil erosion' definitions in the literature.

312 This can probably be explained by the relatively recent development of the holistic  
313 soil function concept, compared to the development of the tolerable soil erosion  
314 concept. Sparovek and De Maria (2003) point out that tolerable soil erosion is the  
315 most multidisciplinary field of soil erosion research and that only contemplation of  
316 this multi-perspective nature may be successful. It appears, therefore, that the time has  
317 come to integrate both concepts. Tolerable soil erosion may then be defined as 'any  
318 mean annual cumulative (all erosion types combined) soil erosion rate at which a  
319 deterioration or loss of one or more soil functions (Table 4) does not occur'.

320

321 Clearly, this definition still leaves the problem of value judgement and scale: at what  
322 stage is a soil function considered to have deteriorated, and at what scale is this  
323 assessed? Also, it is a rather negative approach, where action is only required when a  
324 tolerable rate of soil erosion in a specific location is reached. This approach also  
325 assumes that no technological advances may occur over time, such as the invention of  
326 'super-fertilisers', which could (albeit unsustainably) mask declines in crop yield due  
327 to loss of soil through erosion processes. It may be a more effective policy to provide  
328 incentives to land owners and managers to ensure that actual soil erosion rates remain  
329 much closer to, or preferably equal to or below, the soil formation rate. This would be  
330 an exemplary application of the precautionary principle (i.e. to preferably err on the  
331 side of caution), and ensure that soil functions were maintained for the benefit of  
332 current and future generations.

333  
334 Rates of soil formation provide an invaluable benchmark to use as a 'basis' for  
335 determining tolerable rates of soil erosion, that is soil functions can generally be  
336 judged not to deteriorate as long as soil erosion does not exceed 'natural' or  
337 'geological' (or 'normal') erosion rates. At present, this assumption remains largely  
338 untested, but applying the precautionary principle appears to be a reasonable starting  
339 point. A second assumption is that 'natural' soil erosion rates equate to soil formation  
340 rates. This implies a meta-stable situation where all soils are in dynamic equilibrium  
341 in terms of quantity (mass/volume). Clearly, young soils or any soil that could  
342 accumulate under current conditions, and thereby improve the soil regulation,  
343 production, and habitat functions, would not be in dynamic equilibrium. Nevertheless,  
344 soil formation rates form the best basis upon which to establish tolerable rates of soil  
345 erosion.

346

347 **2.2 Current evidence for soil formation rates**

348 The natural process of soil accumulation at any location has been described as soil  
349 production, soil formation, soil genesis, pedogenesis, or soil renewal (Brady and Weil,  
350 2002). The term ‘soil formation’ is used here for reasons of general acceptance, noting  
351 that this includes both dust deposition and parent material weathering.

352

353 Ideally, soil formation models (e.g. Hoosbeek and Bryan, 1992; Minasny and  
354 McBratney, 2001) would have been developed and validated to such an extent that for  
355 any soil type, under any land use, soil management practice, in any region, accurate  
356 estimates of soil formation rates could be derived. Better still would be a degree of  
357 model development that could also estimate soil formation rates for future climate  
358 change scenarios. It is generally acknowledged that ‘natural’ erosion rates have varied  
359 significantly throughout geological history as the climate changed (Wilkinson and  
360 McElroy, 2007). However, fundamental scientific knowledge on soil formation  
361 processes is still insufficient at present to support the use of mechanistic soil  
362 formation models for establishing tolerable rates of soil erosion in the context of  
363 environmental protection. Therefore, the most useful contribution that science can  
364 make to the policy process would be to arrive at a consensus on mean rates of soil  
365 formation and soil erosion.

366

367 **2.2.1 Soil formation rates by weathering**

368 Very few direct measurements of soil formation rates are available. This is due in part  
369 to the extremely slow rate of soil formation in relation to the human life span, and  
370 consequent difficulties in accurate field measurement. However, from studies using



371 different methodologies over different scales, an overall picture of the range of soil  
372 formation rates can be built up (Table 5), although differentiation of these rates by  
373 dominant factors remains elusive. Mass balance measurement studies have been  
374 performed to investigate soil formation rates. Alexander (1988a) determined soil  
375 formation rates for 18 small, non-agricultural, non-carbonate substrate watersheds  
376 (located in North America, Europe, Australia (Victoria) and Zimbabwe) with shallow  
377 to moderately deep soils, by measuring values of silica inputs and outputs and relating  
378 these to soil formation. The range for non-peaty soils was from 0.02 to 1.27  
379 (mean=0.49) t ha<sup>-1</sup> yr<sup>-1</sup>. If, and to what extent, these soil formation rates would  
380 increase under agricultural land use is not known. Wakatsuki and Rasyidin (1992)  
381 used similar geochemical mass balance methodologies on seven elements (Al, Fe, Ca,  
382 K, Mg, Na and Si) to calculate soil formation at a global scale as ranging from 0.37 to  
383 1.29 (mean=0.7) t ha<sup>-1</sup> yr<sup>-1</sup>. Much greater rates were calculated for well draining, high  
384 precipitation watersheds in southwestern Japan, but environmental conditions there  
385 are not typical for the rest of the world. Soil formation rates by weathering in  
386 limestone-dominated catchments, or those with a mainly igneous lithology, have been  
387 estimated at < 0.1 t ha<sup>-1</sup> yr<sup>-1</sup> (Alexander, 1985). Soil chronosequence studies can be  
388 used as an alternative method for deriving soil formation rates, although most appear  
389 to focus on processes that are responsible for specific soil parameters rather than  
390 overall soil formation rates. See Huggett (1998) and Yoo and Mudd (2008) for  
391 discussions of methodological issues of classic soil chronosequence work.

392

393 Table 5

394

395 Landscape scale 'soil formation functions' (i.e. the relationship between soil  
396 formation and soil depth) have been derived from studies in the disciplines of geology  
397 and geomorphology. Humphreys and Wilkinson (2007) describe a useful overview of  
398 this theme and recommend that the basic idea of soil formation may be used for the  
399 determination of tolerable soil erosion rates. Heimsath et al. (1997) used  
400 measurements of in situ produced cosmogenic  $^{10}\text{Be}$  and  $^{26}\text{Al}$  concentrations with  
401 measured soil depths to show an inverse relationship between soil formation rates and  
402 soil depth in northern California. Soil formation rates ranged from ca.  $0.39 \text{ t ha}^{-1} \text{ yr}^{-1}$   
403 for deeper soils (ca. 50 cm) to ca.  $0.91 \text{ t ha}^{-1} \text{ yr}^{-1}$  for shallower soil (ca. 5 cm),  
404 assuming a bulk density of  $1.3 \text{ t m}^{-3}$ . Shakesby and Doerr (2006) reviewed evidence in  
405 the literature of fire weathering, that is where wildfire 'weathers' rocks by spalling  
406 (detachment of lensoid-shaped rock flakes) and other fracturing effects, and showed  
407 that where fires are relatively frequent this may be an important additional weathering  
408 process, although erosion rates are likely to increase concomitantly.

409  
410 Natural soil erosion rates, assumed to be equivalent to soil formation rates (see section  
411 1) when studied over geological time scales, have been estimated by studying  
412 continental erosion and sedimentation. Wilkinson and McElroy (2007) gave an  
413 exhaustive analysis of rates of subaerial denudation in the Phanerozoic, a period of  
414 542 million years spanning the Lower Cambrian to the Tertiary Pliocene. They  
415 estimate that erosion averaged  $5 \text{ Gt yr}^{-1}$  during this period.. The global land area  
416 fluctuated throughout the Phanerozoic, but using a continental area of 118 million  
417  $\text{km}^2$ ,  $5 \text{ Gt yr}^{-1}$  equates to an average natural erosion rate of  $0.4 \text{ t ha}^{-1} \text{ yr}^{-1}$  (over 542  
418 million years. Schaller et al. (2001) measured in situ produced radionuclides ( $^{10}\text{Be}$ ) in  
419 the bedload of middle European rivers to infer average soil erosion rates, over the last

420 10,000-40,000 yr, at 0.26-1.3 t ha<sup>-1</sup>yr<sup>-1</sup> (assuming a bulk density of 1.3 t m<sup>-3</sup>). Mabit et  
421 al. (2008) discusses the advantages and limitations of fallout radionuclides for  
422 assessing soil erosion. Bennett (1939) reported that soil formation rates in the USA  
423 range from 0.3-1.1 t ha<sup>-1</sup>yr<sup>-1</sup> (assuming a bulk density of 1.3 t m<sup>-3</sup>), although he did  
424 not specify the methodology used. However, in areas where aeolian deposition occurs,  
425 the picture of soil formation is more complex.

426

#### 427 2.2.2 Soil formation rates by dust deposition

428 Simonson (1995) reviewed the significance of air-borne dust to soils and discussed  
429 that when dust is deposited onto a soil from a desert source area, it may be regarded as  
430 'more valuable' for soil functions in its new location, in a similar way that Sahelian  
431 dust boosts biomass production in Amazonian forests (e.g. Swap et al., 1992).

432 Although this is a contentious view, wind erosion of fine particles in the Sahel may  
433 contribute to not allowing local vegetation cover development. In the present paper  
434 Simonson's suggestion is accepted as long as the amount deposited is of an order of  
435 magnitude that enables the soil to incorporate it (i.e. not being buried by it).

436

437 Research into dust transport and deposition has increased substantially over the last  
438 decade (Engelstaedter et al., 2006). Satellite imagery and isotopic composition  
439 analyses have revealed that the Sahara is the main source of dust deposited in Europe  
440 (Middleton and Goudie, 2001), although dust originating from China has also been  
441 recorded in the French Alps (Grousset et al., 2003). Remote sensing analysis,  
442 employing the Total Ozone Mapping Spectrometer absorbing Aerosol Index (TOMS  
443 AI), has identified dust pathways from North Africa to the Mediterranean Basin  
444 (Middleton and Goudie, 2001; Israelevich et al., 2002).

445

446 North Africa is considered to be the largest source of dust on Earth with estimates of  
447 the strength of the Saharan source to be 130 to 760 million t yr<sup>-1</sup>, compared to 1000 to  
448 3000 million t yr<sup>-1</sup> globally (Engelstaedter et al., 2006). The greater part of Saharan  
449 and peri-Saharan or Sahelian dust is delivered to the North Atlantic, but substantial  
450 amounts are estimated to be deposited on the European continent. D'Almeida (1986)  
451 used sun-photometer readings taken in the early 1980s to estimate Saharan dust  
452 delivery to Europe at 80-120 million t yr<sup>-1</sup>. Löye-Pilot et al. (1986) extrapolated their  
453 field data from Corsica to estimate dust delivery to the western Mediterranean at 3.9  
454 million t yr<sup>-1</sup>.

455

456 Field measurements of dust deposition are summarised in Table 6. As Middleton and  
457 Goudie (2001) and Engelstaedter et al. (2006) observed, both the frequency of dust  
458 deposition and the mean annual quantity of deposited dust are greater for southern  
459 than for northern Europe. For Mediterranean Europe, up to the Pyrenean, Alpine, and  
460 Carpathian mountain ranges, dust deposition rates range from 0.05 to 0.39 t ha<sup>-1</sup> yr<sup>-1</sup>.  
461 North of this mountain divide, dust deposition rates are below 0.01 t ha<sup>-1</sup> yr<sup>-1</sup>. For the  
462 purpose of setting soil formation rates as thresholds for soil erosion (i.e. tolerable  
463 rates), it seems a reasonable generalisation to set dust deposition rates at ca. 0.2 t ha<sup>-1</sup>  
464 yr<sup>-1</sup> south of the trans-European mountain divide, and to regard dust deposition rates  
465 as negligible relative to soil erosion rates north of the divide, accepting potentially  
466 substantial but presently unquantifiable local variation to this.

467

468 Table 6

469

470 The value of  $0.2 \text{ t ha}^{-1} \text{ yr}^{-1}$  for southern Europe is of the same order of dust deposition  
471 rates found in California, where Reheis and Kihl (1995) measured dust deposition  
472 rates to range from  $0.04\text{-}0.16 \text{ t ha}^{-1} \text{ yr}^{-1}$  in southern Nevada and south-eastern  
473 California, and determined an average value of  $0.30 \text{ t ha}^{-1} \text{ yr}^{-1}$  in south-western  
474 California. Simonson (1995) reviewed the significance of dust deposition to soils and  
475 quoted estimates of approximately  $3.0 \text{ t ha}^{-1} \text{ yr}^{-1}$  of dust deposition on average for  
476 soils between the Rocky Mountains and the Mississippi River. This is a much greater  
477 value than those reported for Europe or California, and may be explained by the  
478 source area in the semi-arid south west U.S.A. delivering most of its dust eastward.

479

#### 480 2.2.3 Overall soil formation rates

481 For the purpose of deriving overall soil formation rates in the evaluation and  
482 monitoring of soil erosion and its impacts, it appears to be reasonable to estimate dust  
483 deposition at no more than  $0.2 \text{ t ha}^{-1} \text{ yr}^{-1}$  in southern Europe and at  $0.0 \text{ t ha}^{-1} \text{ yr}^{-1}$  in  
484 northern Europe. By contrast, estimated soil formation rates (by weathering) for  
485 current conditions in Europe range on average from ca.  $0.3 \text{ t ha}^{-1} \text{ yr}^{-1}$  to ca.  $1.2 \text{ t ha}^{-1}$   
486  $\text{yr}^{-1}$ . Much lower rates (e.g.  $0.004 \text{ t ha}^{-1} \text{ yr}^{-1}$  for basaltic parent material in semi-arid  
487 Australia – Pillans, 1997) and greater rates (e.g.  $5.7 \text{ t ha}^{-1} \text{ yr}^{-1}$  for a very well draining  
488 high precipitation watershed in southwestern Japan – Wakatsuki and Rasyidin, 1992)  
489 have been reported for environmental conditions generally not found in Europe.

490 Therefore, considering soil formation rates by both weathering and dust deposition, it  
491 is estimated that for the majority of soil forming factors in most European situations,  
492 soil formation rates probably range from ca.  $0.3 - 1.4 \text{ t ha}^{-1} \text{ yr}^{-1}$ . Although the current  
493 agreement on these values seems relatively strong, how the variation within the range  
494 is spatially distributed across Europe and how this may be affected by climate, land

495 use and land management change in the future remains largely unexplored. It may be  
496 expected that dust deposition rates in the Mediterranean will increase in a climate  
497 change scenario that brings increasing droughts to the Sahel region, but if this will  
498 also mean that more dust will be deposited further northwards in Europe is more  
499 uncertain, as is the regional/local scale variation in dust deposition rates. Chemical  
500 weathering can be expected to increase where precipitation increases, particularly  
501 where the parent material is well draining, although soil erosion rates may  
502 concomitantly increase at the same or a greater rate (particularly when the rainfall  
503 intensity increases). Soils formed in limestone or granitic lithology are reported to  
504 have formation rates towards the smaller part of the range, although the body of  
505 evidence is relatively small and more experimental research is urgently needed into  
506 soil formation rates for these lithologies, since they cover a substantial area in Europe.  
507 Soil formation by sedimentation in water is only significant in the floodplains of large  
508 river systems, and is, therefore, omitted from this paper.

509

#### 510 2.2.4 Tolerable rates of soil erosion in Europe

511 Although reported rates of soil formation suggest an upper limit of approximately 1.4  
512  $\text{t ha}^{-1} \text{ yr}^{-1}$  for mineral soils (see also Alexander, 1988b), it would be advisable to apply  
513 the 'precautionary principle' to any policy response to counteract soil erosion,  
514 otherwise soils with particularly slow rates of formation will steadily disappear, even  
515 when subjected to low erosion rates. Therefore, future differentiation of soil formation  
516 rates for soil–landuse–climate combinations is needed, and quantitative pedogenesis  
517 modelling (e.g. Hoosbeek and Bryan, 1992; Minasny and McBratney, 2001) may  
518 provide an appropriate methodology.

519

520 In some cases, rates of soil erosion greater than those of soil formation have been  
521 regarded as tolerable only from the wider perspective of society as a whole, for  
522 example because of a perception that certain crops (such as some vines) favour eroded  
523 soil profiles. In Switzerland, the threshold tolerated for soil erosion is generally  $1 \text{ t ha}^{-1}$   
524  $\text{yr}^{-1}$ , though this threshold is increased to  $2 \text{ t ha}^{-1} \text{ yr}^{-1}$  for some soil types (Schaub and  
525 Prasuhn, 1998). In Norway,  $2 \text{ t ha}^{-1} \text{ yr}^{-1}$  is adopted as the threshold for tolerable soil  
526 loss (A. Arnoldussen, personal communication.). However, the data reviewed here  
527 confirm that a precautionary approach to environmental protection should regard soil  
528 erosion losses of more than  $1 \text{ t ha}^{-1} \text{ yr}^{-1}$  in Europe as unsustainable in the long term  
529 (Jones et al., 2004). In the USA, soils have been assigned tolerable rates (so-called ‘T  
530 values’) by using a range of methodologies, mainly the USLE model and expert  
531 judgement, and differentiated mainly by soil depth and crop productivity. Approaches  
532 and assumptions for deriving T values have been revised (e.g. Mannering, 1981;  
533 Pierce et al., 1984) and continue to be discussed (Johnson, 1987; Mirtskhulava, 2001;  
534 Johnson, 2005; Montgomery, 2007). Another way of expressing tolerable soil erosion  
535 is to calculate the ‘life span’ of soil. This is the number of years it will take, at current  
536 soil formation/erosion rates, for a soil to reach its finite point (i.e. the minimum soil  
537 depth required before it becomes economically unsustainable to maintain the current  
538 land use - Stocking and Pain, 1983). For commercial farming the finite point has been  
539 defined at which yields fall to 75% below the maximum possible (Morgan, 1987).  
540 However, this value is highly dependent on socio-economic conditions and available  
541 technology and these factors are notoriously difficult to predict accurately in the  
542 future. For other soil functions this approach has not been applied, possibly in part  
543 because of some (components of) soil functions do not allow for straightforward  
544 economic sustainability assessments (e.g. soil biodiversity).

545

546 Setting a limit of  $1 \text{ t ha}^{-1} \text{ yr}^{-1}$  is also supported when considering the impact of soil  
547 erosion / sediment production rates on water quality. Eroded soil, delivered to water  
548 bodies can be a physical and chemical pollutant in terms of water turbidity and as a  
549 carrier of contaminants which may have detrimental effects on aquatic ecosystems.  
550 Qualitative limits for eroded sediment in water bodies are advocated in policy drivers  
551 such as the EU Water Framework Directive, which states that surface waters should  
552 be kept in 'good ecological status'. EU Member States are currently deciding on the  
553 level of sediment, which will give such a status, but it is unlikely that absolute  
554 standards for biological quality will be set across the whole community, because of  
555 ecological variability. It is expected that the specified controls will allow "only a  
556 slight departure from the biological community which would be expected in  
557 conditions of minimal anthropogenic impact". Quantitative targets have also been set  
558 to control pollution from sediment (e.g. the United States Department of Agriculture  
559 uses a target of  $1 \text{ t ha}^{-1} \text{ yr}^{-1}$  to maintain water quality).

560

561

### 562 **3. Actual soil erosion rates**

563 Section 3.1 introduces the main types of soil erosion while section 3.2 reviews the  
564 erosion rates reported in the literature.

565

#### 566 **3.1 Soil erosion types**

567 Soil loss by coastal and riparian erosion is not reviewed in this study, because this  
568 constitutes the loss of land, which is not directly linked to human activities although it  
569 constitutes a 'permanent' loss of soil. Furthermore, it is not clear that human influence



570 through land management and land use practices has any significant effect on  
571 increasing or decreasing coastal erosion, although a number of studies have shown  
572 that attempts to mitigate by erecting engineering structures (e.g. impervious sea walls  
573 and breakwaters) can actually aggravate the problem elsewhere along the coastline  
574 (McInnes et al., 2000; Lee and Clark, 2004; Lee and Jones, 2004; Bromhead and  
575 Ibsen, 2006).

576

### 577 3.1.1 Soil loss by water erosion

578 Water erosion takes place through rill and/or inter-rill (sheet) erosion, and gullies, as a  
579 result of excess surface runoff, notably when flow shear stresses exceed the shear  
580 strength of the soil (Kirkby et al., 2000; Jones et al., 2004; Kirkby et al., 2004). This  
581 form of erosion is generally estimated to be the most extensive form of erosion  
582 occurring in Europe. De Ploey (1989) identified different domains where these  
583 processes take place, as a function of soil, slope and land cover characteristics in any  
584 location. Sheet and rill erosion will cause surface soil to be removed from the in situ  
585 soil mass. Assuming this surface soil has not been disturbed previously (e.g. by  
586 inversion tillage or preceding erosion events), it will contain considerable amounts of  
587 organic matter and plant nutrients that are crucial to perform effective soil functions  
588 (Fullen and Brandsma, 1995). This eroded soil material may not necessarily travel  
589 very far and may remain in the same field from where it was eroded. Indeed, the area  
590 of deposition may benefit from the accumulation of highly fertile, eroded surface soil,  
591 in the same way that river flood plains receive substantial depositions of highly fertile  
592 sediment. However, this accumulation of eroded soil may only be temporary, until the  
593 next erosion event, especially as the recently deposited sediments often lack  
594 aggregation and remain highly erodible.

595

596 Where there is little vegetative cover or root network below the surface, and slopes  
597 are steep, the eroded soil from these surface processes can move into the stream  
598 network and thus cause further detrimental off-site impacts (Cerdan et al., 2006). The  
599 transport of eroded material will be enhanced further by erosion features such as  
600 gullies which provide a conduit for the eroded surface soil (Blong et al., 1982), as  
601 well as being a source of sediments in their own right. Long term field plots are often  
602 used for direct measurement of soil loss by rill and inter-rill erosion; as demonstrated  
603 by Boix-Fayos (2005). Models of rill erosion have been shown by some researchers to  
604 be in disagreement with current experimental evidence (Govers et al., 2007; De Vente  
605 et al., 2008), but direct measurements of soil erosion are both scarce and do not fully  
606 represent the soil-climatic landscapes that experience rill erosion in Europe.

607

608 Gully erosion is common in Mediterranean Europe, in particular, Spain, Italy and  
609 Greece (Vandekerckhove et al., 2000). These areas are characterised by long-term  
610 gullies (i.e. that cannot be obliterated by ploughing), which have been described as  
611 relatively deep, recently formed, eroding channels that form on valley sides and on  
612 valley floors where no well-defined channel previously existed (Schumm et al., 1984).  
613 Ephemeral gullies (i.e. that can be obliterated by ploughing) commonly occur in the  
614 arable loess soil, as seen in the loess belt of Belgium and the sandy soils of the South  
615 and West Midlands of England. These gullies develop rapidly, are ploughed in and  
616 often reappear the following year. The occurrence of gullies, and variations in the type  
617 of gully erosion, are related to particular soil properties, climate and topography of  
618 these areas (Nachtergaele and Poesen, 1999; Nachtergaele et al., 2001). It is  
619 notoriously difficult to predict where and when gully erosion will occur in the

620 landscape by the extension of an existing gully or a new gully forming, as well as  
621 associated rates of sediment production (Poesen et al., 2003).

622

### 623 3.1.2 Soil loss by wind erosion

624 Wind erosion occurs predominantly on the North European Plain (northern Germany,  
625 eastern Netherlands and eastern England) and in parts of Mediterranean Europe (De  
626 Ploey, 1989; Evans, 1990, 1996; Chappell, 1999; Chappell and Thomas, 2002;  
627 Warren, 2002; Barring et al., 2003; Breshears et al., 2003; Riksen et al., 2003; Jones  
628 et al., 2004; Quine et al., 2006). Wind erosion is caused by the simultaneous  
629 occurrence of three conditions: high wind velocity; susceptible surface of loose  
630 particles; and insufficient surface protection. The transport of soil material (between  
631 erosion and sedimentation) can occur in three main modes: saltation, creep and  
632 suspension. Factors that exacerbate wind erosion are similar to those for erosion by  
633 water: namely soil erodibility, as determined by physical, chemical and biological  
634 properties including texture, organic matter content, moisture content, land use and  
635 cover, and energy of the force causing the erosion (wind erosivity). Riksen et al.  
636 (2003) point out that wind erosion is not as significant or as widespread a problem in  
637 Europe as in drier parts of the world, which might explain the relatively limited  
638 research on wind erosion to date compared to water erosion studies. The present  
639 review concludes that there are few accurate data on the extent and magnitude of the  
640 problem, or the costs of the remediation (Owens et al., 2006a,b,c). Goossens et al.  
641 (2001) studied the dynamics of Aeolian dust emitted from agriculture in northwest  
642 Germany, over a 15 month period. The dust emission was caused by wind erosion  
643 combined with tillage activities and the dust emitted consisted of mineral as well as  
644 organic particles.

645

## 646 3.1.3 Soil loss by tillage erosion

647 This erosion type has been recognised for several decades, but the magnitude of soil  
648 lost by this process in Europe has only been appreciated and documented during the  
649 last 10-15 years (Lindstrom et al., 1992; Govers et al., 1993; Lobb et al., 1995; Govers  
650 et al., 1996; Lobb et al., 1999; Van Muysen et al., 1999; Lindstrom et al., 2000; Van  
651 Oost et al., 2000a,b; Quine and Zhang, 2004a,b; Van Oost et al., 2005a,b; Owens et  
652 al., 2006a,b; Quine et al., 2006; Van Muysen et al., 2006; Van Oost et al., 2006; Van  
653 Oost et al., in press). Mech and Free (1942) concluded that soil movement by tillage  
654 was far from insignificant and that its intensity was related to slope gradient. Soil  
655 translocation by tillage results in soil loss from convex slope positions, such as crests  
656 and shoulder slopes, because of an increase in slope gradient and a consequent  
657 increase in soil translocation. Spatial patterns of tillage erosion differ from those of  
658 water erosion, because the principal agent is different. Soil loss by tillage can be  
659 greatest from landscape positions where water erosion is minimal (i.e. in concavities  
660 and near upslope field boundaries), whereas soil deposition by tillage can occur in  
661 areas where water erosion is often maximal (i.e. on slope convexities). Measurements  
662 on the magnitude of tillage erosion are few, but studies in Europe highlight the  
663 importance of the magnitude of tillage erosion relative to water erosion (Govers et al.,  
664 1993; Quine et al., 1994; Owens et al., 2006a). Van Oost et al. (2005a) have compared  
665 rates of soil erosion by tillage with those by water. By comparing two time periods,  
666 they found that there has been a shift from water-dominated to tillage-dominated  
667 erosion processes in agricultural areas during the past few decades. This reflects the  
668 increase in mechanized agriculture and the authors concluded that where soil is  
669 cultivated, tillage erosion may lead to larger losses than overland flow.

670

## 671 3.1.4 Soil loss by crop harvesting

672 This erosion type refers to soil removed during crop harvesting, for example of root  
673 crops, mainly in northern Europe. Soil can be removed from a location or field by  
674 adhering to farm machinery (e.g. wheels, tines, ploughs and discs). Much larger  
675 amounts of soil can be removed by soil co-extraction with a root crop, particularly .  
676 sugar beet, potatoes, carrots and chicory) (Jaggard et al., 1997; Ruyschaert et al.,  
677 2005). This mechanism of soil loss is known as ‘soil loss due to crop harvest (SLCH)’  
678 in the scientific literature (Ruyschaert et al., 2004, 2005), and as ‘soil/dirt tare’ in the  
679 agricultural industry. SLCH is a particular problem in areas growing early potatoes in  
680 northern Europe because harvesting normally takes place when the topsoil is moist or  
681 very moist and soil particles readily adhere to the surface of the potatoes. However,  
682 preparation of the crop for marketing usually involves cleaning (washing) and  
683 removing the soil but returning it to the fields from whence it came is not always  
684 advised by the agricultural extension services, because of the possibility of spreading  
685 disease.

686

## 687 3.1.5 Soil loss by slope engineering

688 Slope engineering is the mechanical translocation of soil by bulldozers and other earth  
689 moving equipment to adapt slope surfaces to mechanised agriculture. Some authors  
690 refer to this practice as ‘land levelling’, which implies a reduction of slope gradient,  
691 which in turn would actually reduce erosion risk. However, as is seen in the  
692 construction of bench terraces for example, whilst the bench of the terrace is levelled,  
693 the ‘riser’ or back wall component of the terrace has to compensate for this, and is  
694 constructed at an angle which is steeper than the original land slope. This back slope

695 is thus highly susceptible to surface erosion and mass movement. During terrace  
696 construction, soil loss can be aggravated as natural vegetation is mechanically  
697 removed from the land to enable soil to be cultivated, often in the form of modern  
698 specialised orchards, vineyards and olive groves. Often, marginal land with poor  
699 quality soils is used, so deep ploughing to about 1 m depth is required to ensure a  
700 sufficient depth of rootable soil (Jones et al., 2004). Such soil disturbance can destroy  
701 any soil structure, and increase soil erodibility and exacerbate soil losses. This form of  
702 erosion is common in many parts of Europe, especially in Italy, where it is widespread  
703 in the Apennines and hilly pre-alpine regions. Such techniques are also practised in  
704 southern Spain, where intensive horticulture under polythene canopies has spread onto  
705 the foothills of Andalusia. The climate there is arid to semi-arid. Thus, when heavy  
706 rain falls soil losses are exacerbated by steep slopes, lack of natural vegetation cover  
707 and the unstable disturbed soil (Kibblewhite et al., 2007).

708

709

### 710 **3.2 Current evidence for actual soil erosion rates**

711 There have been attempts to map soil erosion rates and risk in a number of EU  
712 Member States (De Ploey, 1989; Schaub and Prasuhn, 1998; Sanchez et al., 2001;  
713 Ministry of Environment of the Slovak Republic and Slovak Environmental Agency,  
714 2002; Van der Knijff et al., 2002; Hennings, 2003; Øygarden, 2003; Kirkby et al.,  
715 2004; Dostal et al., 2004; Boardman and Poesen, 2006; Kertész and Centeri, 2006), but  
716 to establish an accepted overall baseline for erosion in Europe remains a challenging  
717 task. Rates of soil erosion have been determined using several approaches: i) plot and  
718 field measurements, ii) soil erosion modelling, iii) mass/energy balance modelling, iv)  
719 radionuclide measurement, v) suspended sediment load in rivers and streams, vi)

720 chronosequence studies, and vii) geological (sedimentological) studies. Trimble and  
721 Crosson (2000a,b) reviewed soil erosion rates in the U.S. and concluded that models  
722 should only be used with caution, taking account of all the assumptions and potential  
723 inaccuracies of the model chosen. These authors recommended that it would be better  
724 if resources were directed more towards measurements of soil erosion.

725

726 In this review, the focus is placed on measured soil erosion rates where available, and  
727 validated modelled rates for important but relatively unexplored soil erosion types.  
728 Publications on mean soil erosion rates refer mostly to water erosion, yet baseline  
729 values for other forms of erosion, for example by wind and tillage, are also needed.

730

731 3.2.1 Rates of soil loss by water (sheet, rill and gully) erosion

732 Pimentel et al. (1995) have reviewed erosion rates around the world and suggested an  
733 average of  $17 \text{ t ha}^{-1} \text{ yr}^{-1}$  for arable soils in Europe. This is a crude approximation since  
734 it is based on plot data, which only exist for very small areas where measuring  
735 equipment has been installed and monitored. Furthermore, data from plot experiments  
736 are known to be a poor basis for regional generalisation (Boardman, 1998). This is  
737 because to obtain long-term estimates of soil erosion, plot estimates must be scaled up  
738 by integrating over time and surface runoff generated locally may not reach the base  
739 of a slope to deliver sediment to a channel (Kirkby et al., 2008). Thus, some soil  
740 removed from an experimental plot may be deposited downslope but not lost  
741 completely from the regional parcel or catchment. In addition, the location of soil  
742 erosion plots across Europe may not be representative, because erosion plots tend to  
743 be selected in places where erosion is known to occur and where resources are  
744 available to measure it. Yang et al. (2003) applied the RUSLE model on a  $0.5^\circ$  global

745 grid using a 1 km resolution DEM to estimate rates of soil erosion by water, and  
746 found an average value of  $11.1 \text{ t ha}^{-1} \text{ yr}^{-1}$  for Europe compared to  $10.2 \text{ t ha}^{-1} \text{ yr}^{-1}$   
747 globally. In addition Yang et al. (2003) evaluated the human induced proportion of the  
748 soil erosion by modelling the difference between current land cover and potential land  
749 cover without human activity. Human-induced erosion was estimated to be ca. 60%  
750 globally, but ca. 88% for Europe.

751

752 The occurrence and rate of water erosion processes are influenced by regional climate,  
753 local soil properties, and past and present land use. A number of localised erosion  
754 rates are given for various plots around Europe, some containing only one or two  
755 forms of erosion, depending on the spatial scale of the plots (Morgan, 2005). Cerdan  
756 et al. (2006) extensively reviewed the experimental data for soil loss by sheet and rill  
757 erosion in Europe, and compiled a database of 208 plots on 57 experimental sites in  
758 13 countries. The mean erosion rate was  $8.8 \text{ t ha}^{-1} \text{ yr}^{-1}$ , although aggregation of the  
759 data by land use showed large variations. Geographical comparisons, (i.e.  
760 Mediterranean versus the rest of Europe) showed no significant overall difference and  
761 no large differences between most land uses, except for bare soil (ca.  $32 \text{ t ha}^{-1} \text{ yr}^{-1}$  for  
762 the Mediterranean zone and ca.  $17 \text{ t ha}^{-1} \text{ yr}^{-1}$  for the rest of Europe).

763

764 Poesen et al. (2006) present a comprehensive list of published rates for gully erosion,  
765 including both ephemeral and permanent gullies. Ephemeral gully rates derived from  
766 studies conducted in the loess belt of Belgium while the majority of permanent gully  
767 erosion rate estimates are from the Mediterranean region of Europe. These rates vary  
768 from 1.1 to  $455 \text{ t ha}^{-1} \text{ yr}^{-1}$  (Poesen et al., 2006). This wide range gives an indication of  
769 the complexities of quantifying soil loss by gully erosion owing to the episodic and



770 highly variable nature of soil loss within these eroded channels; variable regional  
771 climatic effects; the haphazard nature of gully distribution in the landscape;  
772 propensity of vertically variable soil properties to exacerbate gully erosion; the stage  
773 at which the gully is in its erosion cycle (active or stable); current or previous  
774 topographic position in the landscape; and the historical and present land use  
775 influencing the gully (Valentin et al., 2005).

776

777 Martinez-Casasnovas et al. (2003) highlighted the complexities of measuring gully  
778 erosion rates in a study of one gully system located in north eastern Spain. Using  
779 aerial photographs and a detailed digital elevation model (DEM), they estimated the  
780 annual average sediment production rate of the gully from 1975 to 1995 to be  $846 (\pm$   
781  $40) \text{ t ha}^{-1} \text{ yr}^{-1}$ . The net erosion, taking account of some eroded material being  
782 deposited, was  $576 (\pm 58) \text{ t ha}^{-1} \text{ yr}^{-1}$ , averaged over the 20-year period. During the  
783 study the authors measured and analysed a 1 in 100 year rainfall event when 205 mm  
784 fell over the study area in 2h 15 min leading to a net soil loss of  $207 (\pm 21) \text{ t ha}^{-1}$  with  
785 a sediment production rate of  $487 (\pm 13) \text{ t ha}^{-1}$  by ephemeral gully, rill and inter-rill  
786 erosion (Martinez-Casasnovas et al., 2003). The authors see this comparison as good  
787 evidence that gully erosion accounts for 1.7 times more soil loss than the other forms  
788 of erosion in this study area. However, averaging gully erosion on an annual basis  
789 probably gives an unrealistic rate, owing to the episodic nature of the gully forming  
790 process (Betts and De Rose, 1999)

791 Few studies have considered erosion from gullies at a regional or catchment scale.  
792 However, Nachtergaele and Poesen (1999) considered ephemeral gullies at four sites  
793 in Belgium (ranging from 216 to 1095 ha), using sequential aerial photographs from  
794 1952 to 1996. Each site contained 18 to 38 gullies on average and it was estimated

795 that the reasonably long-term (44 yr) average for soil loss was between 3.2 and 8.9 t  
796  $\text{ha}^{-1} \text{yr}^{-1}$ . These figures are considerably different to those given by Martinez-  
797 Casasnovas et al. (2003), even though the measurement methods were similar  
798 (interpretation of sequential aerial photographs), and reveal the importance of  
799 differentiating between type of gully erosion and regional influences (Mediterranean  
800 versus western Europe) when assessing gully erosion rates.

801 Jones et al. (2004) report a number of other soil erosion studies which provide a  
802 European overview, but these are based mostly on models or expert judgement  
803 (including observation). These approaches more commonly produce assessments of  
804 erosion risk rather than estimates of actual soil loss, without reference to baseline  
805 and/or threshold values.

806

### 807 3.2.2 Rates of soil loss by wind erosion

808 Recent work in Eastern England reported mean wind erosion rates of 0.1-2.0  $\text{t ha}^{-1} \text{yr}^{-1}$   
809 (Chappell and Thomas, 2002), although severe events can move much larger  
810 quantities ( $>10 \text{ t ha}^{-1} \text{yr}^{-1}$ ) of soil. Böhner et al. (2003) estimated average soil loss at  
811 1.6  $\text{t ha}^{-1} \text{yr}^{-1}$ , and a mean maximum of 15.5  $\text{t ha}^{-1} \text{yr}^{-1}$  from simulation modelling.

812 Despite research studies in these areas, Chappell and Warren (2003) report that little  
813 is known about the true extent and magnitude of wind erosion in Europe.

814

815

### 816 3.2.3 Rates of soil loss by tillage erosion

817 Mean gross rates of tillage erosion have been reported to be in the order of 3  $\text{t ha}^{-1} \text{yr}^{-1}$   
818 for Belgium, the north of France, and the east of England (Govers et al., 1996; Owens  
819 et al., 2006a). Boardman and Poesen (2006) reviewed measurement data for tillage

820 erosion rates in Europe and concluded that it often exceeds  $10 \text{ t ha}^{-1} \text{ yr}^{-1}$ , particularly  
821 on fields with complex topography. Van Oost et al. (2005a) estimated that the average  
822 erosion and soil redistribution rate, over the last ca. 35-40 years due to tillage, is ca. 9  
823  $\text{t ha}^{-1} \text{ yr}^{-1}$ . Long-term erosion rates based on soil profile truncation data demonstrated  
824 that, over the longer term, erosion has been dominantly by water by overland flow.

825

826 Hinz (2004) reported rates of soil loss between  $18.6$  and  $29.5 \text{ kg ha}^{-1}$  for harvesting  
827 operations, and between  $0.8$  and  $1.4 \text{ kg ha}^{-1}$  for normal tillage operations. The latter  
828 data are for the production of cereals but they may give a good idea of the order of  
829 magnitude for other adjacent crops. Funk and Reuter (2004) investigated emissions  
830 for various tillage operations and arrived at values of between  $3$  and  $6 \text{ kg ha}^{-1}$ , that is  
831 about 3 times greater than those of Hinz (2004).

832

833 At Dalicott Farm in Shropshire (UK),  $^{137}\text{Cs}$  data and a numerical erosion model were  
834 used to estimate erosion on a hillslope (Govers et al., 1993; Quine et al., 1994). The  
835 proportions of overall erosion that was caused by water or tillage erosion were  
836 estimated to be similar for the last ca. 6 centuries (57% and 43%, respectively), and  
837 greater for water erosion over the last 40 years (76% and 24%, respectively), based on  
838  $^{137}\text{Cs}$  data.

839

#### 840 3.2.4 Rates of soil loss by crop harvesting

841 Ruyschaert et al. (2004) provided an excellent review of the research on soil loss due  
842 to crop harvesting (SLCH) in Europe. They reported mean losses ranging from  $1.3$  to  
843  $19 \text{ t ha}^{-1} \text{ yr}^{-1}$  for a variety of crops. SLCH was greatest for chicory, sugar beet and  
844 potatoes. Boardman and Poesen (2006) also reviewed soil loss by crop harvesting,

845 confirming the variation in Europe, according to crop types and climate, concluding  
846 that average values of  $2 \text{ t ha}^{-1} \text{ yr}^{-1}$  for a potato crop and  $9 \text{ t ha}^{-1} \text{ yr}^{-1}$  for a sugar beet  
847 crop can be expected. Soil moisture content at harvest is the driving factor.

848

849

850

### 851 3.2.5 Rates of soil loss by slope engineering

852 Recently, P. Bazzoffi (pers.com.) estimated that in Italy the area highly prone to risk  
853 of land levelling is about 10% of the area under permanent crops. After levelling, land  
854 is in a vulnerable condition and a few storms can easily cause severe soil losses.

855 Bazzoffi et al. (1989) measured  $454 \text{ t ha}^{-1} \text{ yr}^{-1}$  of water erosion with the formation of a  
856 gully after six rainfall events of medium intensity in central Italy.

857

858 In Norway during the late 1970s, extensive land levelling was stimulated by subsidies.

859 This led to a two- to three-fold increase in soil erosion. The increase was especially

860 large when former ravine landscapes used for pasture were levelled and turned into

861 arable land that was ploughed in autumn. The clearly visible erosion and increasing

862 negative offsite effects on water quality, together with overproduction, put an end to

863 the subsidies for land levelling, but not before 13% of the agricultural area had been

864 levelled with the support of these subsidies. The most visible effect was erosion

865 caused by concentrated flow, including severe ‘gullying’ resulting from reduced

866 infiltration, longer slopes and inadequate measures to handle concentrated flow (Jones

867 et al., 2004). Now, land levelling is only allowed in Norway with special permission.

868

### 869 3.2.6 Overall soil erosion rates

870 Breshears et al. (2003) researched the relative importance of soil erosion by wind and  
871 by water in a Mediterranean ecosystem and found wind erosion to exceed water  
872 erosion from shrubland and forest sites, but not from a grassland site. Wind-driven  
873 transport of soil material from horizontal flux measurements were projected to annual  
874 timescales for shrubland (ca. 55 t ha<sup>-1</sup> yr<sup>-1</sup>), grassland (ca. 5.5 t ha<sup>-1</sup> yr<sup>-1</sup>) and forest (ca.  
875 0.6 t ha<sup>-1</sup> yr<sup>-1</sup>). In a similar study, Goossens et al. (2001) found lower values (ca. 9.5 t  
876 ha<sup>-1</sup> yr<sup>-1</sup>) for arable fields in lower Saxony, Germany.

877

878 Owens et al. (2006a) proposed a tentative comparison between the various forms of  
879 soil loss, including water erosion processes in England and Wales. The rates quoted  
880 suggest that the likely range of annual soil loss rates may be similar for all forms of  
881 erosion. There will be temporal and spatial variations in the relative magnitude and  
882 extent of the different processes, with arable land being susceptible to all forms of  
883 erosion, and uncultivated land only at risk of water and, to some extent (i.e. exposed  
884 sandy and peaty soils), wind erosion.

885

### 886 3.2.7 Soil erosion rates for Europe

887 In the context of soil erosion, the true baseline is the amount of soil that is lost from a  
888 defined spatial unit under current environmental conditions. However, to determine a  
889 universal baseline it is not practicable to measure the actual loss of soil caused by  
890 erosion processes over the whole of Europe. It is more realistic to estimate baseline  
891 data for Europe by modelling the factors known to cause erosion, validating estimated  
892 baseline soil losses using actual measurements from the few experimental sites that  
893 currently exist, and augmenting by measurements from additional 'benchmark' sites.  
894 This leaves the spatial unit over which any baseline would apply undefined.

895

896 For soils under arable land use, several researchers quote soil erosion rates in Europe  
897 of between 10 and 20 t ha<sup>-1</sup>yr<sup>-1</sup> (Richter, 1983; Lal et al., 1998; Yang et al., 2003),  
898 whereas Arden-Clarke and Evans (1993) report that water erosion rates in Britain vary  
899 from 1-20 t ha<sup>-1</sup> yr<sup>-1</sup> but that the higher rates are rare events and localised. Boardman  
900 (1998) challenged the usefulness of an average rate of soil erosion for Europe,  
901 concluding that the rates vary too much in time and space to specify precise amounts.  
902 This variation is evident in Table 7 which shows ranges of the mean rates of soil lost  
903 by the recognised erosion types for agricultural land, and the actual soil erosion rates  
904 in tilled, arable agriculture by different combinations of erosion types (ca. 3-40 t ha<sup>-1</sup>  
905 yr<sup>-1</sup>). Although soil type, slope and climate are important factors, the greater part of  
906 the actual soil erosion rates relate to soil cover, soil management, and crop  
907 management. These factors can all be influenced by policy measures.

908

909 Table 7

910

911

912

#### 913 **4. Summary and conclusions**

914

915 Figure 1

916

917 Tolerable soil erosion is a concept that has been developed over the last 60 years. Its  
918 definition has been related to the production function of soil by numerous authors.  
919 Inclusion of the regulation function of soil was realised, but not implemented in these  
920 definitions. Over the last 15 to 20 years a more holistic concept of soil functions has

921 been developed, which this paper suggests should be applied to defining tolerable soil  
922 erosion: ‘any actual soil erosion rate at which a deterioration or loss of one or more  
923 soil functions (Table 4) does not occur’, with actual soil erosion meaning ‘the  
924 cumulative amount of soil lost by all recognised erosion types’.

925

926 Soil formation rates are proposed as a basis for establishing tolerable soil erosion. For  
927 Europe, the current state of scientific knowledge indicates that tolerable soil erosion  
928 rates range from ca. 0.3 – 1.4 t ha<sup>-1</sup> yr<sup>-1</sup> depending on the driving factors of weathering  
929 (e.g. parent material, climate, land use) and dust deposition (e.g. geographic position;  
930 distance to source). Relevant local components of soil functions that are impacted by  
931 soil erosion (e.g. surface water turbidity effects on aquatic wildlife or siltation of  
932 reservoirs) can be used to set tolerable soil erosion rates below the upper limit  
933 determined by soil formation rates.

934

935 Soil erosion research has focused traditionally on erosion by water (rill, gully etc.)  
936 and, to a lesser extent, by wind. However, over the last 10 - 15 years, the focus has  
937 broadened to include other important types of erosion, namely tillage erosion, crop  
938 harvesting and slope engineering or land levelling. Estimates of soil erosion rates for  
939 evaluation in a soil monitoring system need to consider all types of erosion, although  
940 mitigation should focus on the dominant type in any particular location. For all types  
941 of soil erosion, and particularly wind erosion and land levelling, there is a need for  
942 more spatially differentiated evidence of current rates.

943

944 The range of reported erosion rates for tilled arable soils is many times greater than  
945 the range of reported soil formation rates. This can be because soil formation is

946 affected little by human activities, whereas today most soil erosion is  
947 anthropogenically induced. It should also be noted that soil erosion only appears to  
948 exceed tolerable rates when the soil is under cultivation or affected by other human  
949 disturbance. Furthermore, Boardman and Poesen (2006) estimated that arable  
950 agriculture accounts for ca. 70% of soil erosion in Europe, while Yang et al. (2003)  
951 developed a coarse-scaled global model from which they estimated that ca. 88% of  
952 soil erosion in Europe to be human-induced. Figure 1 gives an overview of the  
953 concept and rates of tolerable soil erosion and actual soil erosion (i.e. ‘the total  
954 amount of soil lost by all recognised erosion types’), and suggests directions for  
955 developing more detailed tolerable rates by applying the soil function concept and  
956 numerical soil formation modelling. The right side describes the components of soil  
957 erosion and the reported variation in their rates (mean and maximum). Tolerable soil  
958 erosion rates and approaches for deriving them are described on the left. At present,  
959 best estimates for mean rates in Europe are ca.  $0.3-1.4 \text{ t ha}^{-1}\text{yr}^{-1}$  for soil formation and  
960 ca.  $3-40 \text{ t ha}^{-1}\text{yr}^{-1}$  for actual soil erosion. These results are comparable with the 10-40  
961 times greater than tolerable global estimate reported by Pimentel (2006). The figure  
962 also highlights areas for more research. Apart from the need for more detailed and  
963 differentiated values for soil erosion and formation rates (experimentally), it is also  
964 needed to identify yet unknown erosion types and further develop concepts such as  
965 the soil function system and numerical soil formation models, to implement soil  
966 erosion mitigation policies at appropriate spatial scales (differentiated by dominant  
967 factors). In addition, soil erosion work and policies should include a wide range of  
968 spatial and temporal scales until the connections between scales are better understood.  
969 Clearly, the spatial and temporal variation of tolerance-exceeding soil erosion is  
970 substantial and is likely to change, or possibly intensify, when climate and land use



971 change. Therefore, the recommendation from Trimble and Crosson (2000a,b) and  
972 Brazier (2004), that resources should focus more on monitoring soil erosion by field  
973 measurements than on modelling, is supported by this review. Ideally, the approaches  
974 to field measurement (e.g. considering scale and spatial heterogeneity) would be  
975 developed in conjunction with process-based models.

976

977 However, if these measured and estimated ranges for soil formation and erosion are  
978 correct, and current conditions and management persist (a 'business as usual'  
979 scenario), then topsoils of tilled arable land on hill slopes (i.e. not flood plains) in  
980 Europe could be ca. 2 to 30 cm thinner in 100 years time (assuming a blanket  
981 tolerable rate of  $1 \text{ t ha}^{-1} \text{ yr}^{-1}$  and a bulk density of  $1.3 \text{ t m}^{-3}$ ) than today. Where in the  
982 range an area will be, depends on physical factors (e.g. climate, drainage, soil texture  
983 and structure) and on land management factors (see Table 7). For many topsoils in  
984 Europe this would mean a substantial deterioration in their production, regulation,  
985 habitat, and information functions (Table 4), if not a cessation of some of them. For  
986 areas where slope engineering and/or gully erosion occurs, even more soil could be  
987 lost. Thus, the status quo is not compliant with the intergenerational equity argument,  
988 i.e. that future generations should have the same rights to natural resources as those  
989 enjoyed by the current generation. A substantial effort is required to reduce soil  
990 erosion losses closer to tolerable levels, particularly in tilled, arable agriculture. In the  
991 future, climate change looks likely to increase rainfall intensity, if not annual totals,  
992 thereby increasing soil erosion by water, although there is much uncertainty about the  
993 spatio-temporal structure of this change as well as the socio-economic and agronomic  
994 changes that may accompany them (e.g. Boardman and Favis-Mortlock, 1993;  
995 Phillips et al., 1993; Nearing et al., 2004). Similarly, as a response to climate change,

996 soil formation rates may change and the development of ‘moving tolerable rates’ with  
997 climate change scenarios may be required to support the policy sector with sound  
998 scientific guidelines.

999

1000 This review of rates of soil loss by erosion, in the mineral soils of Europe, has  
1001 clarified the tolerable rate of soil erosion to which modern land use systems should  
1002 aspire. Furthermore, the evidence of well-founded tolerable rates of soil erosion,  
1003 evaluated against actual soil erosion rates, is vital for developing policies to ensure  
1004 that soil receives a level of protection comparable to that accorded to water and air in  
1005 Europe.

1006

1007

1008

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1014

1015

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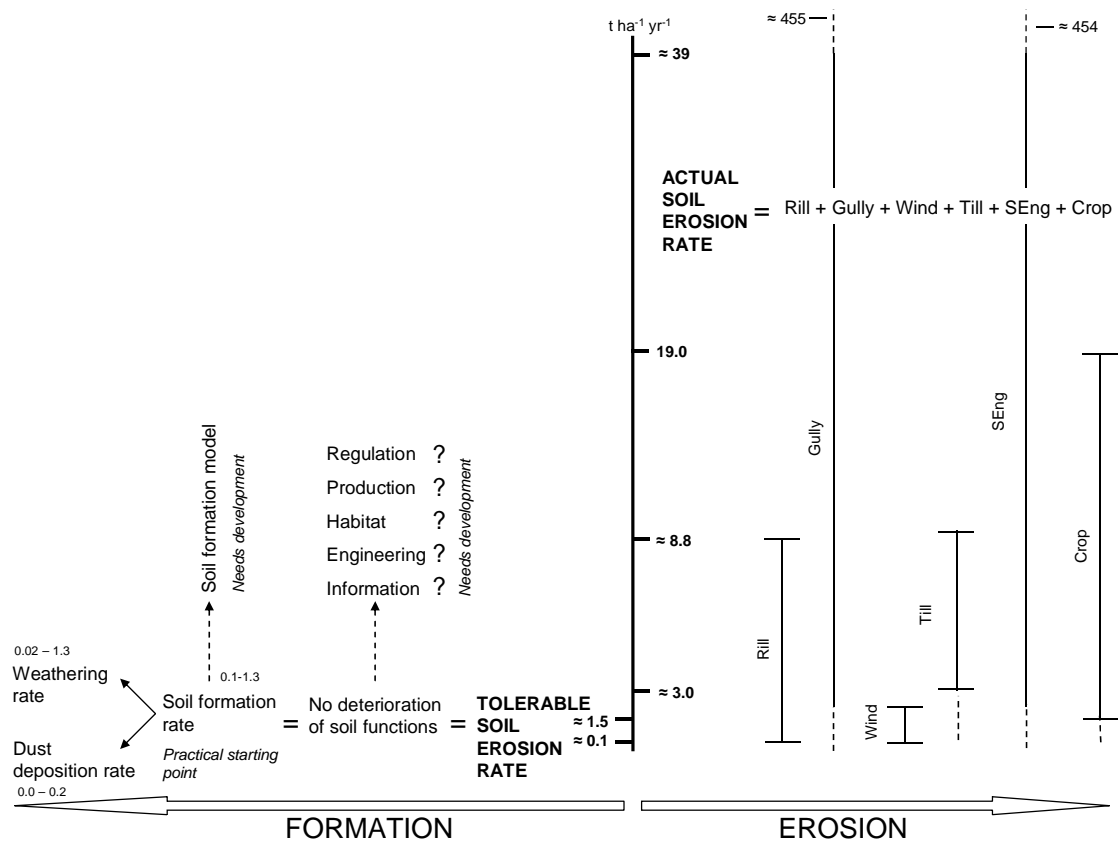
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Tolerable vs. actual soil erosion, concept and rates. See the text for a detailed explanation. All numbers are in  $t\ ha^{-1}\ yr^{-1}$ . Please see relevant sections of this paper for more detailed information and references. Rill=rill and sheet erosion; Gully=gully erosion; Wind=wind erosion; Till=tillage erosion; SEng=erosion by slope engineering; Crop=erosion by crop harvesting.

Range of spatial scales of soil erosion research (Rickson, 2006; after Wickenkamp et al., 2000).

Erosion research technique	Area	Dimension descriptors (Wickenkamp et al., 2000)		Dominant processes operating	Selected References
Splash cup	mm <sup>2</sup>	Nanoscale	Subtope	Rain splash dominant; overland flow/deposition limited. No gullies, stream bank erosion or mass movements.	Ellison (1944); Kinnell (1974); Morgan et al. (1988); Salles, C. and Poesen, J. (2000)
Laboratory tray	cm <sup>2</sup>	Nanoscale	Subtope	Rain splash dominant?; overland flow/deposition limited. No gullies, stream bank erosion or mass movements.	Idowu (1996)
Runoff rig	m <sup>2</sup>	Microscale	Tope	Rain splash and overland flow; some deposition possible. No gullies, stream bank erosion or mass movements.	Kamalu (1993); Govers (1989)
Field plot	m <sup>2</sup>	Microscale	Tope	Rain splash and overland flow; some deposition. Some gullying and mass movements possible; no stream bank erosion.	Wischmeier and Smith (1978); Ciesiolka and Rose (1998); Pierson et al. (1994)
Field	ha	Mesoscale	Chore	Rain splash, overland flow and deposition. Gullying and mass movements possible. No stream bank erosion.	Evans and Boardman (1994); Walling and Quine (1991)
Sub-catchment	ha – km <sup>2</sup>	Mesoscale	Chore	Rain splash, overland flow and deposition. Gullying possible. Some stream bank erosion.	Hudson (1981); Rapp et al. (1972)
Catchment/landscape	km <sup>2</sup>	Macroscale	Region	Rain splash, overland flow and deposition. Some gullying and mass movement possible. Stream bank erosion.	Dickinson and Collins (1998)

Estimated annual costs of soil erosion to UK economy in £million (2000 prices)

	£ million	% contribution from agriculture
Soil organic matter loss, leading to increased emissions of carbon dioxide	74	95%
On-farm costs (additional fertilisers, etc.)	8	100%
Accidents/stream channels (i.e. off-site costs mainly related to clean-up operations)	8.2	95%
Effects of flooding	115	14%
<b>TOTAL ANNUAL COST (£ million)</b>	<b>205</b>	

Source: Environment Agency (2002).



## Interpretations and definitions for 'tolerable soil erosion'

Tolerable soil erosion - definition	Reference
The maximum volume of erosion-removed topsoil that provides high, or economically feasible, fertility for a long time	Patsukevich et al., 1997.
Soil loss balanced by soil formation through weathering of rocks	in Roose (1996)
Erosion that does not lead to any appreciable reduction in soil productivity	in Roose (1996)
The maximum rate of soil erosion that permits an optimum level of crop productivity to be sustained economically and indefinitely	ISSS (1996)
The average annual soil loss a given soil type may experience and still maintain its productivity over an extended period of time (permissible soil loss)	Kok et al. (1995)
The maximum permissible rate of erosion at which soil fertility can be maintained over 20-25 years	Morgan (2005)
(i) The maximum average annual soil loss that will allow continuous cropping and maintain soil productivity without requiring additional management inputs. (ii) The maximum soil erosion loss that is offset by the theoretical maximum rate of soil development which will maintain an equilibrium between soil losses and gains	SSSA (2001)
Rate of soil erosion is not larger than the rate of soil production (acceptable rates of soil erosion)	Boardman and Poesen (2006)

## Harmonised primary soil functions scheme.

Primary soil functions	Components
Habitat	Refugium function; nursery function; medicinal resources; gene pool; seed bank
Information	Cultural information (archaeological and palaeontological); science and education; spiritual and historic; recreation; aesthetic information
Production	Food; fodder; fibre; raw materials; renewable energy
Engineering	Technical, industrial and socio-economic structures
Regulation	Gas regulation; climate regulation; disturbance resistance; disturbance resilience; water supply; water filtering; pH buffering; biotransformation of organic carbon; soil retention; soil formation; nutrient regulation; biological control; waste and pollution control

Reported soil formation rates by weathering (large scale); na=not available.

Methodology	Spatial scale	Temporal scale	Lower limit	Upper limit	Reference
Mass balance (Si)	Non-carbonate; non-arable; North America, Europe, Australia (Victoria), Zimbabwe	na	0.02	1.27	Alexander (1988a)
Mass balance (Al, Fe, Ca, K, Mg, Na, Si)	Global		0.37	1.29	Wakatsuki and Rasyidin (1992)
In situ cosmogenic $^{10}\text{Be}$ and $^{26}\text{Al}$	Northern California	na	0.39	0.91	Heimsath et al. (1997)
In situ cosmogenic $^{10}\text{Be}$	Middle European rivers	10-40 Kyr	0.26	1.3	(Schaller et al. (2001)
Continental scale erosion/sedimentation	Global	542 Myr	0.4	1.4	Wilkinson and McElroy (2007)
Na	USA	na	0.3	1.1	Bennett (1939)

## Soil formation rates by dust deposition

(adapted from Goudie and Middleton,

2001)

Location	Dust deposition (t ha <sup>-1</sup> yr <sup>-1</sup> )
Aegean Sea	0.112 - 0.365
Southern Sardinia	0.06 - 0.13
Swiss Alps	0.004
French Alps	0.002
NE Spain	0.051
Corsica	0.12
Corsica	0.125
Central France	0.01
Crete	0.1 - 1.0
Crete	0.195
Pyrenees	0.30 - 0.39

Actual soil erosion rates in Europe (tolerable rate  $< 1.0 \text{ t ha}^{-1} \text{ yr}^{-1}$ ). For references, please see relevant sections in this paper.

Erosion type	Mean rates ( $\text{t ha}^{-1} \text{ yr}^{-1}$ )	Maximum rates ( $\text{t ha}^{-1} \text{ yr}^{-1}$ )	comment	Main factors
Rill, sheet erosion	0.1 - 8.8	23.4		Land use, soil cover, slope
Gullies	na	455		Climate, land use
Wind erosion	0.1 - 2.0	15		Soil type, soil cover, climate
Tillage erosion	3.0 - 9.0	na		Soil management
Slope engineering	na	454		Soil management
Crop harvesting	1.3 - 19.0	na	For a variety of crops	Crop type (Table 6); soil moisture content at time of harvesting
Cumulative mean soil erosion rates in tilled agriculture	3.0 - 10.0 3.2 - 19.8 4.5 - 38.8	na	Tillage only Water + wind + tillage Water + wind + tillage + crop harvesting	

na = not available

# Tolerable versus actual soil erosion rates in Europe

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