

Accepted Manuscript

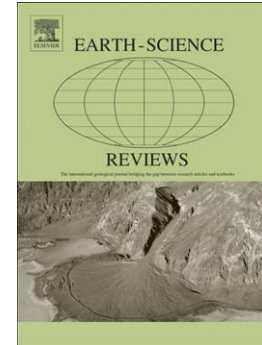
Tolerable versus actual soil erosion rates in Europe

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PII: S0012-8252(09)00035-X
DOI: doi: [10.1016/j.earscirev.2009.02.003](https://doi.org/10.1016/j.earscirev.2009.02.003)
Reference: EARTH 1558

To appear in: *Earth Science Reviews*

Received date: 13 March 2008
Accepted date: 19 February 2009



Please cite this article as: Verheijen, F.G.A., Jones, R.J.A., Rickson, R.J., Smith, C.J., Tolerable versus actual soil erosion rates in Europe, *Earth Science Reviews* (2009), doi: [10.1016/j.earscirev.2009.02.003](https://doi.org/10.1016/j.earscirev.2009.02.003)

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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

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 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 km² 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 6th 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⁻¹ yr⁻¹. 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⁻¹ yr⁻¹. 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⁻¹ yr⁻¹ (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}Be and ^{26}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 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 Gt yr^{-1} during this period.. The global land area
416 fluctuated throughout the Phanerozoic, but using a continental area of 118 million
417 km^2 , 5 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}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 $0.26-1.3 \text{ t ha}^{-1}\text{yr}^{-1}$ (assuming a bulk density of 1.3 t m^{-3}). 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 $0.3-1.1 \text{ t ha}^{-1}\text{yr}^{-1}$ (assuming a bulk density of 1.3 t m^{-3}), 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⁻¹, compared to 1000 to
448 3000 million t yr⁻¹ 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⁻¹. 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⁻¹.

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⁻¹ yr⁻¹.
461 North of this mountain divide, dust deposition rates are below 0.01 t ha⁻¹ yr⁻¹. 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⁻¹
464 yr⁻¹ 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 t ha^{-1}
486 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 t ha^{-1}
524 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; Kertéz 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° 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 kg ha^{-1} for harvesting
827 operations, and between 0.8 and 1.4 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 kg ha^{-1} , that is
831 about 3 times greater than those of Hinz (2004).

832

833 At Dalicott Farm in Shropshire (UK), ^{137}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}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⁻¹ yr⁻¹), grassland (ca. 5.5 t ha⁻¹ yr⁻¹) and forest (ca.
875 0.6 t ha⁻¹ yr⁻¹). In a similar study, Goossens et al. (2001) found lower values (ca. 9.5 t
876 ha⁻¹ yr⁻¹) 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⁻¹yr⁻¹ (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⁻¹ yr⁻¹ 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⁻¹
905 yr⁻¹). 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⁻¹ yr⁻¹ 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 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

1009 **Acknowledgements**

1010 The authors acknowledge the contribution of the Consortium of the ENVASSO
1011 Project (contract 022713) funded by the European Commission under the 6th
1012 Framework Programme of Research. We are grateful for the valuable comments made
1013 by two anonymous reviewers.

1014

1015

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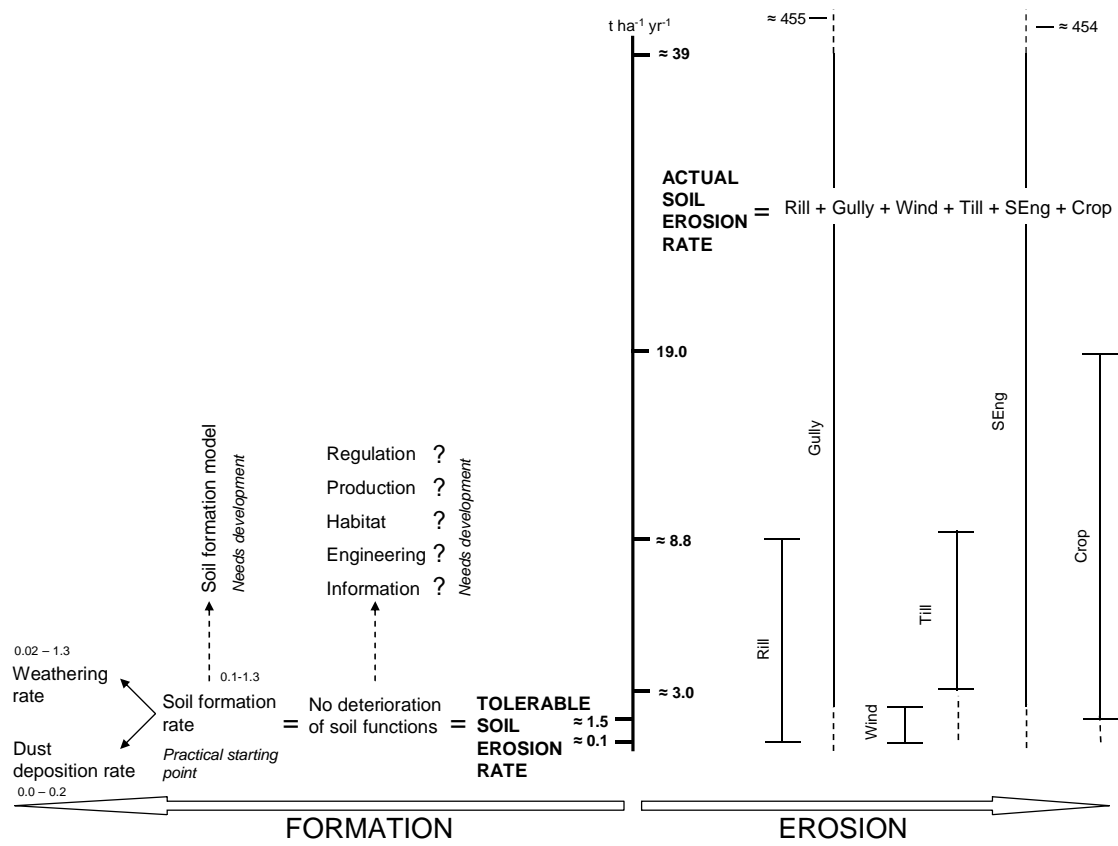
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Tolerable vs. actual soil erosion, concept and rates. See the text for a detailed explanation. All numbers are in $\text{t ha}^{-1}\text{yr}^{-1}$. Please see relevant sections of this paper for more detailed information and references. Rill=rill and 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 ²	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 ²	Nanoscale	Subtope	Rain splash dominant?; overland flow/deposition limited. No gullies, stream bank erosion or mass movements.	Idowu (1996)
Runoff rig	m ²	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 ²	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 ²	Mesoscale	Chore	Rain splash, overland flow and deposition. Gullying possible. Some stream bank erosion.	Hudson (1981); Rapp et al. (1972)
Catchment/landscape	km ²	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%
TOTAL ANNUAL COST (£ million)	205	

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}Be and ^{26}Al	Northern California	na	0.39	0.91	Heimsath et al. (1997)
In situ cosmogenic ^{10}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 ⁻¹ yr ⁻¹)
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 t ha⁻¹ yr⁻¹). For references, please see relevant sections in this paper.

Erosion type	Mean rates (t ha ⁻¹ yr ⁻¹)	Maximum rates (t ha ⁻¹ 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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2009-05

Verheijen FGA, Jones RJA, Rickson RJ, Smith JC. (2009) Tolerable versus actual soil erosion rates in Europe. *Earth-Science Reviews*, Volume 94, Issues 1-4, May 2009, pp. 23-38

<http://dx.doi.org/10.1016/j.earscirev.2009.02.003>

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