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1 **Modelling the impact of land use change and rainfall seasonality on sediment export**
2 **from an agricultural catchment of the northwestern European loess belt**

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14 **Abstract**

15
16 Soil erosion leads to important environmental problems (e.g. muddy floods, reservoir sedimentation)
17 in cultivated areas of the European loess belt. This study aimed to determine the impact of rainfall
18 seasonality and land use change on soil erosion over the last 40 years in a 94-ha cultivated catchment
19 of Normandy (France). To this end, scenarios representative of the different land use conditions were
20 simulated using the STREAM expert-based erosion model. A 13-yr long sequence of rainfall events
21 was run with this model. Results showed that erosion increased dramatically after land consolidation
22 (+168% on average). Interannual variability of erosion is important. After land consolidation, 79% of
23 erosion was observed in summer and autumn, even though these seasons only accounted for 58% of
24 annual rainfall kinetic energy. The bulk of erosion was hence produced by a few intense thunderstorms
25 during this period. Thunderstorms correspond to 5% of rainfall events and to 15% of the total rainfall
26 depth, but they generate 51% of total annual erosion after land consolidation (and up to 57% of
27 erosion before land consolidation). Confrontation of the STREAM model outputs with the erosion
28 rates modelled based on Cs-137 measurements suggested that soil redistribution within the catchment
29 was very high but that sediment exports from the catchment remained limited (sediment delivery ratio
30 between 1 – 10%). Erosion rates derived from Cs-137 measurements showed an important and
31 organised spatial variability, but erosion rates integrated over larger areas remained in the same order
32 of magnitude as those simulated by the STREAM model or were slightly higher. Water erosion would

33 hence not be the only process generating erosion within this catchment. In this context, our results
34 show that tillage erosion cannot be neglected to calculate the sediment budget over several decades.

35
36 **Keywords:** Agricultural landscape; erosion; rainfall seasonality; Cesium-137; expert-based
37 model.

38 39 40 **1. Introduction**

41
42 During the last decades, a significant increase in environmental problems such as
43 eutrophication, pollution of water bodies and reservoir sedimentation has been observed in
44 Europe, as a result of soil erosion on agricultural land (Boardman and Poesen, 2006). Among
45 these off-site impacts, muddy floods affect numerous villages of northwestern Europe
46 (Boardman et al., 2006) and induce high costs (e.g. $16 - 172 \times 10^6$ € each year in central
47 Belgium; Evrard et al., 2007a). Regions of intensive agricultural production of the European
48 loess belt, e.g. in Normandy, France (Souchère et al., 2003a), on the South Downs, UK
49 (Boardman et al., 2003) and in central Belgium (Evrard et al., 2007a) are regularly affected by
50 erosion and muddy floods. A severe decline in biodiversity is also outlined in agricultural
51 landscapes of northwestern Europe, as a consequence of agriculture intensification (e.g.
52 Robinson and Sutherland, 2002; Berger et al., 2006).

53 It is now well established that soil sensitivity to erosion depends on the coincidence of
54 two distributions, namely the driving force of erosion (i.e. rainfall and induced runoff
55 erosivity) and the system resistance (i.e. soil erodibility; Morgan, 2005; Nearing, 2006).
56 Rainfall erosivity depends on the climate area, the seasonal pattern of rainfall and the random
57 occurrence of storms. Soil erodibility, i.e. the sensitivity of soil to detachment by the impact
58 of raindrops and the shearing action of runoff, results from the combination of soil resistance
59 and infiltrability (Knapen et al., 2007a; Knapen et al., 2007b). On the plateaus of the
60 European loess belt, soil erodibility greatly varies throughout the year, because of the
61 decrease in infiltration rate of cultivated soils after tillage/sowing due to surface crusting
62 processes, vegetation growth and the evolution of soil moisture content (Auzet et al., 1990; Le
63 Bissonnais et al., 1998, 2005; Evrard et al., 2009).

64 The major role played by the interaction between rainfall erosivity and land use on soil
65 erosion at the scale of agricultural catchments has been outlined in several studies (e.g.
66 Cerdan et al., 2002b; Nearing et al., 2005; Evrard et al., 2008a; Valentin et al., 2008). This
67 interplay results in a strong seasonality of erosion during the year. However, to our
68 knowledge, the studies outlining erosion seasonality were restricted to a period of a few years

69 or to the impact of storms or extreme events (e.g. Papy and Douyer, 1991; Souchère et al.,
70 2005; Nearing et al., 2005). Furthermore, the few studies that investigated erosion seasonality
71 focused on Mediterranean regions, rather than on northwestern Europe (e.g. Gallart et al.,
72 2005; Lana-Renault, et al., 2007).

73 Still, in the current context of climate change, there is a need to evaluate the relative
74 contribution of rainfall erosivity and land use change on soil erosion in intensively cultivated
75 areas of northwestern Europe at the scale of several decades. Furthermore, the agricultural
76 regions of northwestern Europe have been characterised by important environmental changes
77 during the last decades. The implementation of the European Common Agricultural Policy
78 (CAP) has, for instance, led to important changes in farming practices, the selection of crop
79 varieties and the landscape structure (e.g. ditch network, field size and shape). Souchère et al.
80 (2003a) outlined that, in certain areas (e.g. Normandy), these modifications occurred very
81 rapidly, within a few years only. These changes greatly modified both the pathways and
82 quantities of runoff and erosion generated in cultivated areas (Van Oost et al., 2000).
83 Operations of land consolidation have particularly modified the pattern of runoff and its lag
84 time to flow across cropland (Evrard et al., 2007b).

85 When applied over the short-term studies (i.e. from the event to the annual scale),
86 investigations about the driving factors of soil erosion in agricultural land are typically carried
87 out by simulating scenarios using spatially-distributed models, and by comparing the model
88 outputs to field measurements. However, two problems arise when such a methodology is
89 used for several decades. First, it is difficult to find an appropriate erosion model. The model
90 must indeed be spatially-distributed, continuous and require limited input data. Second, field
91 measurements of erosion are rarely available at the catchment scale over such a long period.
92 In order to overcome the modelling problem, we used the STREAM erosion expert-based
93 model (Cerdan et al., 2002a). Even though different types of erosion models have been
94 developed in the past (see e.g. Jetten and Favis-Mortlock, 2006, for a review of models), the
95 ability of empirical models (e.g. USLE) to integrate the dominant processes at the catchment
96 scale is uncertain (Imeson and Kirkby, 1996), whereas process-based models require
97 numerous input data that are generally not available and difficult to measure (Takken et al.,
98 1999). In such a context, it has been shown that expert-based models (e.g. STREAM) offer an
99 alternative and reliable solution in regions where hortonian runoff dominates (Evrard et al.,
100 2009). This type of model focuses on the driving factors of erosion which can be combined by
101 developing tables of decision rules. Furthermore, the application of the selected expert-based
102 model to the catchment where it was initially designed and validated (i.e. the Blosseville

103 catchment in Normandy for the STREAM model; Cerdan et al., 2002a) should limit the
104 uncertainties associated with modelling. Various scenarios representative of the different land
105 use and rainfall conditions need to be modelled to derive ranges of sediment export, given
106 long term databases of input data are difficult to derive .

107 To overcome the lack of field surveys in the past, we used ^{137}Cs measurements to
108 estimate the spatial patterns of erosion and deposition since the 1960s in the Blosseville
109 cultivated catchment. Even though this method is associated with large uncertainties, it can
110 provide an “order of magnitude” of the soil erosion that occurred in intensively cultivated
111 areas over the last four decades (e.g. Sogon et al., 1999; Walling et al., 2002; Van Oost et al.,
112 2005). We also hypothesised that water erosion is the dominant erosion process in this area,
113 and that tillage erosion remains limited.

114 The main objective of this paper is to model the relative impact of rainfall seasonality
115 and land use change on soil erosion over the last 40 years, in an intensively cultivated
116 catchment of northwestern Europe. First, erosion rates over the whole period are derived from
117 ^{137}Cs measurements. Then, local databases of rainfall, land use and associated soil surface
118 characteristics are analysed to construct various scenarios. These scenarios are then simulated
119 using the STREAM model in order to test the impact of rainfall seasonality and land use
120 change (e.g. land consolidation) on soil erosion, and to compare the simulated erosion rates
121 with the ones derived from ^{137}Cs measurements. Finally, the implications of the reconstructed
122 history of erosion for landscape management within this catchment are discussed.

123 124 **2. Materials and methods**

125 126 *2.1. Study site*

127
128 The Blosseville catchment (94.4 ha) is located in northwestern France (49°50' N,
129 0°47' W; Normandy; Fig. 1) and is characterised by a humid temperate climate. Mean annual
130 rainfall in the catchment varies between 800 and 900 mm, with a high frequency of low to
131 moderate rainfall in winter (Papy and Douyer, 1991). Mean annual temperature reaches 13°C,
132 and annual potential evapotranspiration is ca. 500 mm. The catchment has an undulating
133 topography (mean slope of 4.6%), the slopes with a gradient between 5-10% covering less
134 than 10% of the total surface. Soils are mainly Orthic Luvisols (World Reference Base, 1998)
135 and surface horizons contain at least 60% silt and 11% clay (Le Bissonnais et al., 1998).

136 Today, main land uses in the catchment are cropland (96%) and grassland (4%). The water

137 table is rather deep (> 7 m) and is therefore unlikely to generate saturation-excess flow. The
138 catchment is a dry valley, and the fields are undrained.

139

2.2 Modelling the erosion rates over a 40 yrs-period based on ¹³⁷Cs measurements

141

142 ¹³⁷Cs activity was measured on 60 soil profiles sampled along 5 transects within the
143 catchment in 1998-1999 in order to characterize recent soil redistribution within the
144 catchment. These transects were selected in order to take account of the various topographic
145 settings observed within the catchment (i.e. transects carried out parallel to the principal
146 thalweg directions; transects parallel to the field boundaries and transects along the steepest
147 slope direction). Undisturbed soil cores (having 9-cm diameter) were sampled in the field up
148 to a soil depth of 70 cm. All 60 cores were immediately cut in the field. The first section
149 corresponded to the uppermost 30 cm of the core (i.e. the ploughed mixed layer). The rest of
150 the cores was then cut in 5-cm sections. All the samples were air-dried during 48 h at 40 °C,
151 weighted, sieved through a 2 mm mesh and ground to a fine powder.

152 ¹³⁷Cs activity was then measured at 661 keV using Germanium gamma-ray detectors
153 (Germanium hyperpure – GeHP, N-type, coaxial model; Eurisys, Lingolsheim, France) during
154 a counting time of 10⁴-10⁵ s. An initial qualitative assessment was performed on successive
155 sub-samples of each core to determine the maximum depth of the ¹³⁷Cs signal. Total ¹³⁷Cs
156 inventory (A_S ; Bq m⁻²) of each core was finally calculated according to Eq. (1).

$$A_S = \sum_i A_i \times \frac{M_i}{S} \quad (1)$$

157 where A_i is the ¹³⁷Cs concentration of each sub-sample i of the core containing ¹³⁷Cs (Bq kg⁻¹); M_i is
158 the mass (kg) of the soil fine fraction of each sub-sample i ; S is the surface area (m²) of the soil core
159 cylinder.

161

162 In order to estimate whether soil deposition or erosion occurred in the investigated area, ¹³⁷Cs
163 inventories were compared with the inventories obtained by sampling in a neighbouring
164 undisturbed site (i.e. an orchard). ¹³⁷Cs reference value and erosion rates (t ha⁻¹ yr⁻¹ or mm
165 yr⁻¹) were calculated using the Cs model developed by Walling and He (1997). The erosion
166 rates derived using the Cs model were then averaged over larger areas in order to compare
167 them with the outputs of the STREAM erosion model.

168

2.3. Description of the STREAM model

170 STREAM (Sealing and Transfer by Runoff and Erosion related to Agricultural
171 Management) is an expert-based runoff and erosion model at the small catchment scale (10 –
172 1000 ha). It is spatially-distributed, and lumped at the event-scale (Cerdan et al., 2002a). The
173 model assumes that the following surface characteristics are the main determinants of
174 infiltration and runoff at the field scale: soil surface crusting, surface roughness, total cover
175 (crops and residues) and antecedent moisture content (Cerdan et al., 2002a). These
176 characteristics are set for each field using classification rules developed by Le Bissonnais et
177 al. (2005). A table is then used to assign a steady-state (i.e. the constant infiltration rate that is
178 reached during prolonged rainfall) infiltration rate value to each combination of these soil
179 surface characteristics. A runoff/infiltration balance (B_α) is then computed for each pixel α
180 (Eq. 2).

$$181 \quad B_\alpha = R - IR - (I_\alpha \times t) \quad (2)$$

182 Where R is the rainfall depth (mm); IR the amount of rainfall needed to reach soil saturation (mm)
183 derived from rainfall depth during the 48 hours before the event; I_α is the steady-state infiltration rate
184 (mm h⁻¹) of the pixel α and t is the rainfall duration (h). Note that negative values of B_α correspond to
185 infiltration and positive values to runoff.

187 For each event, the runoff flow network is then derived by combining two models: (i) a
188 standard topographic runoff model (Moore et al., 1988) based on a DEM and redirecting
189 runoff from one cell to the lowest of its eight neighbours and (ii) a tillage direction model
190 developed by Souchère et al. (1998). Based on the infiltration/runoff balance (Eq. 2)
191 calculated for each pixel, a Visual Basic Application (VBA) programme is then run in
192 ArcGIS to determine flow accumulation at the catchment scale (Cerdan et al., 2002a).

193 Interrill and concentrated erosion modules have also been integrated into STREAM.
194 Within the interrill erosion module, a table is used to assign a potential sediment
195 concentration value (SC) to each combination of surface characteristics (Cerdan et al., 2002b).
196 At the catchment scale, sediment is transported in proportion of the runoff volumes computed
197 with the STREAM runoff module, and is deposited as a function of topography (vertical
198 curvature, slope gradient), or vegetation cover (see Cerdan et al., 2002c for details).

199 The module calculating gully erosion within the catchments (Souchère et al., 2003b) is
200 based on slope gradient and parameters influencing runoff velocity or soil resistance
201 (vegetation type, crop cover, soil roughness, soil surface crusting). The performance of the
202 STREAM model to predict erosion was evaluated by Evrard et al. (2009). In this study, the

203 Nash-Sutcliffe efficiency criterion varied between 0.85 – 0.95 for erosion predictions.

204 Furthermore, Evrard et al. (2009) showed that errors on sediment export predictions provided
205 by the STREAM model can be estimated as $\leq 30\%$.

206

207 2.4. Model input dataset

208

209 STREAM requires four datasets to compute runoff and erosion at any point of the
210 catchment. First, a land cover dataset, associating each field of the catchment with the
211 appropriate soil surface characteristics, is needed. Then, the slope and the flow directions are
212 calculated by combining the DEM of the catchment and the tillage direction model. A DEM
213 with 5 m grid cells is available for the Blosseville catchment. Third, a decision table is
214 required to associate the soil surface characteristics observed in the different fields of the
215 catchment with a steady-state infiltration rate (I_a) and a single potential sediment
216 concentration (SC_a) value. Finally, four parameters characterising the simulated rainfall
217 events must be introduced into the model:

- 218 • total rainfall amount (RA ; mm);
- 219 • total rainfall effective duration (RD ; h) – we therefore removed the rainfall periods
220 with an intensity lower than 2 mm h^{-1} ;
- 221 • total rainfall amount during the 48 h before the beginning of the event (ARA_{48h} ; mm);
- 222 • maximum 5-min rainfall intensity ($I_{max5min}$; mm h^{-1}).

223

224 2.5. Deriving STREAM input data from local databases

225 *Rainfall data*

226 Rainfall has been collected between October 1992 and January 2006 by a 0.2-mm
227 resolution raingauge located at the catchment outlet. We distinguished two rainfall events
228 when there is a period without precipitation of at least 150 minutes between them. A threshold
229 of 1 mm rainfall was also applied to remove the lowest events from the database.

230 A k -means clustering was then used to classify the rainfall events that occurred within the
231 Blosseville catchment ($n=1948$) into several groups, based on the four parameters required by
232 STREAM (RA ; RD ; ARA_{48h} ; $I_{max5min}$).

233 The homogeneity of the groups created by the k -means clustering was then checked using
234 a non-parametric Kruskal-Wallis test, given the tested variables were not normal.

235 Finally, given Salles et al. (2002) state that rainfall kinetic energy is often used as an
236 indicator of rainfall erosivity, kinetic energy (KE ; $J m^{-2}$) of each rainfall event was calculated
237 using Eq. 3. This equation was selected because it was based on a raindrop size distribution
238 representative for a wide range of environments.

$$KE_{mm} = \sum_i 8.95 + 8.44 \log_{10} I_i \quad (3)$$

240 where KE_{mm} is the volume-specific kinetic energy ($J m^{-2} mm^{-1}$) and I is the rainfall intensity at the one-
241 minute time step ($mm h^{-1}$).

242 Thirteen hydrologic years (starting in October and ending in September) were
243 extracted from the database (October 1992 – September 2005). We checked if these data were
244 representative for the last 40 years in the region using rainfall data available for four
245 neighbouring meteorological stations operated by Météo France and located within a radius of
246 10 km around the catchment. Non-parametric Kruskal-Wallis tests were carried out to
247 compare the rainfall regimes of the different periods.

248 *Land use and associated soil surface characteristics*

249
250
251 The field pattern (i.e. their limits and shapes), the crop types and the soil surface
252 characteristics [soil surface crusting; surface roughness; total cover of crops and residues]
253 required by STREAM were determined each month by visual observations in the Blosseville
254 catchment and in neighbouring sites between 1992 and 2002. In total, a database of 4255 field
255 surveys has been compiled (Joannon, 2004; Le Bissonnais et al., 2005; Souchère et al., 2007).
256 This database was used to associate soil surface characteristics with the most common crops
257 in Upper Normandy. Steady-state infiltration rates (I_a) and potential sediment concentrations
258 (SC_a) were attributed to these combinations of soil surface characteristics using the tables
259 proposed by Cerdan et al. (2002a, 2002b) for Normandy. A classification of runoff risk and
260 interrill erosion risk at the field scale was then applied to the common crops of Upper
261 Normandy, based on these I_a and SC_a values.

262 Land consolidation in the Blosseville catchment occurred in 1965. The former field
263 pattern was mapped from a digitised aerial photograph taken on 15 September 1947 (French
264 National Geographical Institute). A visual observation of the photograph allowed the
265 recognition of most land uses at the end of summer within the catchment. The proportions of
266 the different land cover classes were then checked using the available agricultural statistics
267 (French General Agricultural Census) in the neighbouring municipalities.

268

269 2.6 Deriving the erosion rates from STREAM simulations

270 The relative impact of (i) rainfall seasonality, (ii) land use (e.g. land consolidation) on soil
271 erosion were investigated, by simulating two series of scenarios:

- 272 (i) At the annual scale, we chose to simulate all the sequence of rainfall events
273 (October 1992 – September 2005) recorded by the raingauge located in the
274 catchment. This provided us a reliable order of magnitude of annual erosion. At
275 the interannual scale, we outlined the impact of seasonality and heavier storms
276 during these years, to determine their relative contribution to the total annual
277 erosion. A single heterogeneous crop distribution representative for the crop
278 rotations implemented after the land consolidation and the associated soil surface
279 characteristics was used to perform this first set of simulations.
- 280 (ii) We also compared the land use situation before (a) and after (b) the land
281 consolidation of the catchment carried out in 1965, by simulating the same 13 yrs-
282 rainfall sequence (October 1992- September 2005) with the land use situation
283 observed before land consolidation and by comparing the output erosion rates with
284 those obtained in (i).

285 3. Results and discussion

286 3.1. Modelling the erosion rates over a 40 yrs-period based on ^{137}Cs measurements

287
288
289
290
291 In Blosseville, the ^{137}Cs reference value reached $2184 \pm 128 \text{ Bq m}^{-2}$ in 2000 (mean
292 activity and standard deviation derived from the analysis of 6 reference cores). The pattern of
293 soil redistribution within the catchment is highly complex and is not directly influenced by
294 slope steepness and convexity (Fig. 2a-b). Erosion within the catchment is the most intense
295 upslope or in the vicinity of the field boundaries, reaching up to -3 mm yr^{-1} . However, a
296 succession of erosion and accumulation areas is observed along the different hillslope
297 transects. In contrast, erosion on the footslopes as well as in the thalweg is lower (up to -1.2
298 mm yr^{-1}), given sedimentation also takes place at those locations. An area of important soil
299 accumulation is observed in the lower part of the catchment thalweg (between 2.3 and 4 mm
300 yr^{-1}). This accumulation is also influenced by the former land use pattern. This accumulation
301 area is located just upstream of a former field boundary between arable land and grassland
302 (Fig. 2b). Sediments settle typically in such locations. At the catchment outlet, erosion starts

303 again, at rather severe local rates ($-2 - -3.1 \text{ mm yr}^{-1}$). These high rates are explained by runoff
1 304 concentration in the thalweg, close to the catchment outlet. Overall, ^{137}Cs measurements
2 305 outline the variability of erosion and accumulation patterns within the catchment. This
3 306 variability is also due to the combination of processes of interrill and rill erosion. Important
4 307 soil redistribution occurs within the catchment. Three areas are delineated in the vicinity of
5 308 the transects and a mean erosion rate is calculated for each area to compare it with the
6 309 STREAM model outputs (Fig. 2a).

13 310 3.2. Rainfall seasonality in the Blosseville catchment

14 311
15 312
16 313
17 314 In total, 1948 rainfall events ($> 1 \text{ mm}$) occurred in the catchment between October
18 315 1992 and September 2005. This rainfall sequence can be considered as representative for the
19 316 last 40 years. No significant statistical difference (for monthly, seasonal and annual cumulated
20 317 rainfall) has been identified when comparing the Blosseville dataset (Table 1) to the ones
21 318 from the neighbouring Météo France stations using Kruskal Wallis tests.

22 319 Rainfall is rather evenly widespread throughout the year (Fig. 3a). There are no
23 320 important seasonal trends associated with the monthly rainfall depth, except a peak of rainfall
24 321 in October and a slightly lower rainfall depth in summer (particularly in July). When we focus
25 322 on rainfall erosivity, clearer seasonal differences can be outlined (Fig. 3b). October is clearly
26 323 the most erosive month of the year, the average kinetic energy reaching 6113 J m^{-2} in
27 324 October, compared to a monthly average of 3492 J m^{-2} during the rest of the year. Overall, the
28 325 4-months period from September to December concentrates 45% of the total annual erosivity.
29 326 February and March are rather dry (ca. 50 mm of monthly rainfall) and characterised by the
30 327 lowest rainfall erosivity of the year (ca. 2500 J m^{-2}).

31 328 These trends can be refined by characterising the different types of rainfall events
32 329 occurring each month. The k -means classification allows differentiating three types of events
33 330 (Fig. 3a; Table 2): (i) rainfall on wet soils; (ii) intense thunderstorms and (iii) low-intensity
34 331 rainfall on dry soils. (i) Rainfall on wet soils is mostly observed between October and January
35 332 (33% of the total rainfall depth during this period), even though similar events are also
36 333 recorded in the remainder of the year (22% of the total annual rainfall). Rainfall events
37 334 occurring on wet soils are generally characterised by a low to moderate intensity (RA of 6.5
38 335 mm; $I_{max5min}$ of 10.8 mm h^{-1} ; Table 2). These events, falling mostly on wet soils, are
39 336 associated with oceanic fronts coming from the Atlantic. (ii) Intense thunderstorms contribute
40 337 significantly to the cumulative rainfall depth between May and October (25% of rainfall

338 during this period and 15% of total annual rainfall). They can be considered as ‘extreme’ in
1 339 numerous cases (RA of 15.4 mm; $I_{max5min}$ of 48.1 mm h⁻¹; Table 2). These storms are
2 340 associated with the development of convective cells at the end of spring and in summer. (iii)
3 341 Finally, rainfall on dry soils corresponds to the bulk of annual rainfall (63%; Fig. 3b). These
4 342 long-lasting events are characterised by low intensities (RA of 4.5 mm; $I_{max5min}$ of 8.2 mm h⁻¹
5 343¹; Table 2). They correspond in a certain way to the low “background” rainfall signal.

10 344 The contribution of these three classes of events to the annual erosivity is somewhat
11 345 different (Fig. 3b). For instance, the large contribution of thunderstorms to the average
12 346 monthly erosivity is particularly important between July and October (29%), even though
13 347 these storms are rather infrequent (only 9% of the events occurring during this period).

18 348 19 349 3.3. Land cover and associated soil surface characteristics

20 350
21 351 The risk of runoff and interrill erosion was derived from data for the period 1992-2002
22 352 for the common crops in Upper Normandy, based on the monthly surveys of soil surface
23 353 characteristics (Table 3a). For simplicity reasons, the common crops have been regrouped in
24 354 three classes (winter crops; early spring crops and late spring crops). The class of winter crops
25 355 mostly consists of winter wheat - *Triticum aestivum* L. (80%) and in much lower proportions
26 356 of oilseed rape (*Brassica napus* L.) and winter barley (*Hordeum vulgare* L.); the class of
27 357 early spring crops regroups proteaginous pea (*Pisum arvense* L.) and textile flax (*Linum
28 358 usitatissimum* L.); and the class of late spring crops represents corn (*Zea mays* L.), potatoes
29 359 (*Solanum tuberosum* L.) and sugar beets (*Beta vulgaris* L.).

30 360 It must be outlined that this monthly evaluation consists in a simplification of the
31 361 actual situation observed in the field, given the soil surface characteristics at a given time
32 362 result from the interaction of the rainfall conditions and the crop system at this time.
33 363 Furthermore, farming operations modifying soil surface conditions are not distributed
34 364 randomly throughout the year. Certain farming practices are indeed concentrated during
35 365 certain periods of the year (e.g. succession of harvests and sowings between mid-July and
36 366 mid-November). They lead to important modifications of soil surface characteristics during
37 367 these periods. In contrast, farming operations are more limited during other periods of the
38 368 year (e.g. from mid-November to mid-February, because of wet and cold conditions) and
39 369 rainfall erosivity is therefore the driver of the degradation of the soil surface characteristics
40 370 during this period.

371 The sowing date of the different crops is a very important event, which is
1 372 unfortunately often undocumented in the field surveys. This date, which depends itself on the
2 373 local meteorological conditions (i.e. the farmer takes advantage of a dry weather to sow the
3 374 crops) coincides indeed with the beginning of the soil surface degradation by the action of
4 375 cumulative rainfall (Table 3a). Soil degradation in autumn is particularly high, given the soil
5 376 surface is not protected by vegetation. The sowing of wheat generally occurs early in October.
6
7 377 The rainfall depth needed for the transition of one soil crusting stage to the next has been
8 378 determined based on the database compiled. The transition from the initial soil fragmentary
9 379 structure (i.e. F0 stage) to an altered state (i.e. F11 stage) requires ca. 28 mm rainfall. The
10 380 local formation of depositional crusts (i.e. F12 stage) is then observed after ca. 87 mm
11 381 additional rainfall. Finally, reaching a continuous state with depositional crusts (i.e. F2 stage)
12 382 requires ca. 110 mm additional rainfall. A similar analysis has been performed for spring
13 383 crops, even though the documented soil surface characteristics are not as homogeneous as for
14 384 winter cereals (Joannon, 2004).

25 385 This evaluation allows outlining the periods sensitive to runoff and soil erosion
26 386 throughout the year (Table 3c-d). The high risk of interrill erosion is restricted to the period
27 387 following the crop sowing, whereas a high risk of runoff is widespread all throughout the
28 388 year.

32 389 Land use has undergone important modifications since the 1940s (Fig. 4). Land use in
33 390 1947, identified by a visual observation of the aerial photograph, consisted in grassland
34 391 (64.6%), winter cereals (28.4%) and late spring crops (7%). After the consolidation in 1965,
35 392 the mean size of the fields increased by 120%, from 1.0 ha in 1947 to 2.2 ha in 2000. A
36 393 dramatic decrease of the surface covered by grassland has rapidly occurred in the 1970s. An
37 394 increase in the variety of crops has also been observed at this time, with the planting of early
38 395 spring crops (Fig. 4). The proportion of the different land covers remained rather constant
39 396 between 1979-2000.

47 397 48 398 *3.4. Impact of rainfall seasonality on erosion*

51 399
52 400 To remain consistent with the progressive degradation of soil surface characteristics
53 401 after crop sowing outlined in section 3.3, we simulated the 13-yrs sequence of rainfall,
54 402 starting in October and ending in September, to coincide with the annual growth cycle of
55 403 wheat, which is commonly the most widespread crop in the Blossenville catchment.
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404 The mean erosion rate reached 276.6 t yr⁻¹ for the heterogeneous crop pattern observed
1 405 after land consolidation and the 13-yrs study period (Table 4a). Summer and autumn were the
2
3 406 most erosive seasons (79% of the total annual erosion; Table 5a) and erosion was primarily
4
5 407 triggered by thunderstorms (51% of erosion; Table 5b).
6

7 408 Inter-annual variability of erosion was high (Table 6; Fig. 5). Annual erosion at the
8
9 409 catchment outlet ranged between 133 t in 2003-2004 and 389 t in 2000-2001. There was no
10
11 410 correlation between total annual rainfall and total annual erosion ($R^2=0.03$). This was
12
13 411 illustrated by the situation observed during certain years, e.g. 1995-1996. This hydrologic
14
15 412 year was the driest of the entire study period (Fig. 5a). Winter rainfall accounted for only 21%
16
17 413 of the total annual rainfall, but generated 89% of the annual erosion (Fig. 5b). In contrast,
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19 414 1994-1995 was the wettest year of the study period (Fig. 5a). Winter rainfall accounted for
20
21 415 45% of annual rainfall but generated only 18% of total erosion (Fig. 5b). These two examples
22
23 416 illustrate the crucial importance of simulating a sequence of events, and not only isolate
24
25 417 storms. This is particularly true in an agricultural region where erosion results from the
26
27 418 combination of soil erodibility, which strongly varies all throughout the year, and rainfall
28
29 419 erosivity. The high erosion observed in winter in 1995-1996 is due to the occurrence of
30
31 420 rainfall on very crusted soils. Such an important issue could not have been outlined if we
32
33 421 worked at the event or even at the annual scale.

34 422 Intra-annual variability of erosion is also important (Fig. 5a-b). When correlations are
35
36 423 calculated between cumulative rainfall and erosion for the different seasons, it is particularly
37
38 424 low during winter ($R^2=0.09$), low in summer ($R^2=0.24$), but higher in spring ($R^2=0.51$) and in
39
40 425 autumn ($R^2=0.62$). This means that cumulative rainfall is only partly relevant to describe
41
42 426 erosion extent in spring and autumn, when rain falls on a soil sparsely covered by vegetation,
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44 427 which can directly lead to erosion. In contrast, in winter, erosion mainly depends on the
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46 428 presence of a soil surface crust, which is formed by cumulative rainfall in autumn. In summer,
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48 429 erosion is triggered by thunderstorms, which is badly reflected by cumulative rainfall. The
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50 430 mean contribution to erosion per storm is indeed the highest in summer (up to 45 t per event;
51
52 431 Table 4a). It is important to note that, compared to the mean annual rate, erosion generated by
53
54 432 a single event can be very important during certain years (e.g. a single event that occurred in
55
56 433 September 1998 generated 164.4 t). Given these results, it is really questionable to envisage
57
58 434 the creation of a representative mean hydrologic year to investigate erosion in a given area.

59 435 60 436 *3.5. Impact of land consolidation on erosion* 61 437

438 Before land consolidation, mean erosion rate reached 103 t yr⁻¹ (Table 4b). Overall,
1 439 erosion increased importantly after land consolidation (+ 168% on average; Table 6). Before
2 440 land consolidation, summer was already the principal contributing season to erosion (45.8%;
3 441 Table 4c). Winter erosion was also more important before land consolidation (23.8%).
4 442

5 443 The contribution of thunderstorms to total erosion was also higher before land
6 444 consolidation, triggering 57% of erosion (Table 5b). This result confirms that runoff and
7 445 sediment connectivity within a catchment characterised by a small field pattern was already
8 446 achieved during heavy rainfall. Muddy floods were indeed already reported in Normandy
9 447 before 1965 (Papy and Douyer, 1991), but they were less frequent. However, sediment export
10 448 during extreme events was much lower before land consolidation because of the higher
11 449 proportion of grassland trapping sediment (Fig. 2a). For instance, according to our model
12 450 simulations, a 53-mm storm occurring in 5 hours and falling on a dry soil in September
13 451 generates 41.2 t with the field pattern before land consolidation (vs. 152.7 t afterwards).
14 452

15 453 Crop pattern before land consolidation was run with the soil surface characteristics
16 454 observed currently. However, the farming machinery used in the 1950s (e.g. horses pulling
17 455 ploughshares) induced a lower compaction of the soil. Furthermore, soil loosening was less
18 456 pronounced at this time. Given the formation of a soil surface crust was probably less rapid
19 457 and less widespread in the past, the infiltration rate and the potential sediment concentration
20 458 were probably higher, because of a lower soil cohesion in surface. It is likely that this
21 459 simplification leads to an overestimation of runoff and an underestimation of interrill erosion.
22 460 Tillage direction was systematically determined as parallel to the longest length of the fields,
23 461 which appears to be reasonable.
24 462

25 463 This means that, even though it is probably overestimated, erosion generation was
26 464 much lower before the land consolidation. This is due to the very large proportion of
27 465 grassland within the catchment which mostly infiltrated runoff and rainfall, as well as to the
28 466 heterogeneous pattern of small fields prevailing during this period (Fig. 2b). However, it is
29 467 important to note that erosion in the area was not negligible before 1965.
30 468

31 469 *3.6. Comparison with Cs measurements*

32 470 If we compare the erosion rates simulated by the model (taking account of 30%
33 471 uncertainties on erosion predictions) to the ones derived from the ¹³⁷Cs measurements, we
34 472 observe that the erosion rates derived from the Cs measurements are in the same order of
35 473 magnitude, although their mean values are systematically higher than the ones derived from
36 474 the STREAM model outputs (Table 7). We hypothesised that water erosion dominates in
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473 Normandy and the STREAM model simulates only this process. However, the slight
1 474 underestimation of erosion by modelling compared to ^{137}Cs measurements suggests that
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3 475 tillage erosion also needs to be taken into account if we want to reconstruct the history of
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5 476 erosion within a catchment, at the scale of several decades. If we apply this reflection to our
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7 477 results in the Blosseville catchment, it would mean that even though water erosion generates
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9 478 the bulk of erosion within the catchment, tillage erosion cannot be neglected to calculate the
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11 479 sediment budget over 40 years. Tillage erosion could even locally reach 40%. These figures
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13 480 remain consistent with the ones reported for the whole of Europe by Van Oost et al. (2009).

14 481 Overall, the Cs analysis demonstrates that the soil redistribution within the catchment
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16 482 is much higher than sediment export. Sediment delivery ratio of the catchment is indeed
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18 483 rather low (1-10 %). Erosion rates calculated based on Cs measurements constitute local rates
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20 484 of soil loss. In contrast, STREAM outputs provide soil losses at the outlet. This sediment is
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22 485 exported and delivered to the river network. Local redistribution of sediment (up to 50 t ha^{-1}
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24 486 yr^{-1}) exceeds by far the sediment export rate (a maximum of $4 \text{ t ha}^{-1} \text{ yr}^{-1}$ after land
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26 487 consolidation, and even $2 \text{ t ha}^{-1} \text{ yr}^{-1}$ before the field pattern reorganisation).

27 488 28 489 *3.7. General discussion and implications for landscape management*

29 490
30 491 Our results clearly show that significant erosion mostly occurs when both runoff
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32 492 potential (Table 3c) and rainfall erosivity (Fig. 3b) are the highest, which explains that
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34 493 summer and autumn constitute the most erosive seasons in all the simulated scenarios. We
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36 494 demonstrate the necessity to simulate entire years of rainfall (or at least a sequence of events)
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38 495 to obtain reliable erosion predictions for a given catchment.

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40 496 To calculate the sediment export from the catchment between 1963 (maximum of
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42 497 radionuclide fallout due to test of thermonuclear bombs) and 2000 (period of soil coring in the
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44 498 field), we can subdivide this period into two parts: (1) the period before land consolidation
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46 499 (that occurred in 1965) and (2) the post-1965 period. For the first period (1963-1965), our
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48 500 simulations give a sediment export of 206 t (given the modelled annual mean reaches 103 t
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50 501 yr^{-1} and this first period covers two years; Table 6). For the second period (1965-2000), our
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52 502 simulations give 9958 t (taking account of a mean annual erosion reaching 276.6 t yr^{-1}). In
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54 503 total, 10,164 t of sediment would hence have been exported from the Blosseville catchment
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56 504 during the entire period. STREAM model outputs do not take account of tillage erosion.
57
58 505 However, even though tillage erosion mostly generates soil redistribution within the
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60 506 catchment, it should contribute only very slightly to sediment export from the catchment. If
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62 507 we convert the sediment export into soil loss, the mean value reaches -0.2 mm yr^{-1} after 1965
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508 and -0.1 mm yr^{-1} before this period. Over a period of 40 years, the mean soil loss would then
509 reach -9 mm (Table 6). A sediment export from a catchment corresponding to a soil layer of
510 less than 1 cm over 4 decades can seem to be low. However, when it is exported, this fertile
511 layer leads to numerous problems downstream (e.g. sedimentation in reservoirs, transport of
512 pollutants, eutrophication). Given soil cannot be regenerated at the human life scale, it is
513 important to prevent this soil loss. Consequently, on-site conservation measures should be
514 encouraged to limit soil redistribution within a catchment.

515 Furthermore, it is demonstrated that sediment exports increased by 168% after land
516 consolidation, because of the decrease in the area covered by grassland and by the increase in
517 field size (Fig. 2). Erosion is particularly important in the thalweg and close to the field
518 borders. In this context, besides on-site erosion control measures, it is important to promote
519 the installation of small-scale dams, grass buffer strips and grassed waterways along the field
520 borders or across runoff and sediment concentration pathways. These measures allow
521 buffering and releasing gradually runoff and sediment when the infiltration rates of the fields
522 are exceeded (e.g. Fiener et al., 2005; Evrard et al., 2008b). This type of mitigation measures
523 precisely allow coping with erosion during heavy rainfall, to prevent downstream damage.
524 Their installation can also be designed to protect or enhance biodiversity in areas of intensive
525 farming (e.g. Berger et al., 2003). The implementation of these measures should
526 systematically be coordinated by catchment agencies similar to the ones existing in central
527 Belgium and Normandy (e.g. Evrard et al., 2008b).

4. Conclusions

531 This case study in a small cultivated catchment (ca. 100 ha) of the European loess belt
532 (Normandy, France) shows that, over a period of 40 years, soil erosion is very intense within
533 the catchment. It can reach local rates of up to $50 \text{ t ha}^{-1} \text{ yr}^{-1}$. However, the bulk of erosion
534 consists of sediment redistribution within the catchment and sediment export to the river
535 network remains limited (up to $4 \text{ t ha}^{-1} \text{ yr}^{-1}$). Model simulations run for a 13-yr rainfall
536 sequence allow outlining the increase in erosion (+ 168%) that occurred after land
537 consolidation carried out in 1965. Furthermore, the bulk of annual erosion is systematically
538 generated by thunderstorms (51-57 %) and in summer and autumn (69 – 79%). Simulations
539 also show the high variability of erosion, both throughout the year as well as from one year to
540 another. This phenomenon is due to the complex interaction between rainfall erosivity and
541 soil surface characteristics during a storm. It is hence crucial to simulate a long sequence of
542 rainfall events to investigate erosion in a catchment at the scale of several decades.

543 Confrontation of the model results with the erosion rates derived from Cs-137 measurements
1 544 suggests that water erosion may not constitute the only significant erosion process in this area.
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3 545 Tillage erosion cannot hence be neglected to establish sediment budgets in intensively
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5 546 cultivated catchments at the scale of several decades. An adaptation of the model to integrate
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7 547 topographical changes due to erosion could hence be usefully envisaged. These findings
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9 548 outline the need to apply on-site soil conservation measures to limit soil redistribution within
10
11 549 the catchment and to install buffer elements (e.g. small-scale dams, grassed waterways)
12
13 550 within the landscape to store sediment and release runoff gradually during storms to protect
14
15 551 downstream areas.

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Table 1[Click here to download Tables: Blosseville_Table1-revised.doc](#)

Table 1. Monthly characteristics of rainfall in Blosseville.

	Blosseville (1992-2006)	
	Rain(mm)	Rainy days
January	70	19
February	56	17
March	53	15
April	62	16
May	58	14
June	58	12
July	50	13
August	59	14
September	74	16
October	99	19
November	81	20
December	100	20
Year (mean \pm SD)	818 \pm 120	193 \pm 29

Table 2[Click here to download Tables: Blosseville_Table2-revised.doc](#)Table 2. Coordinates of the gravity centres of the rainfall groups as classified by the *k*-means clustering.

Rainfall group	RA (mm)	RD (h)	ARA _{48h} (mm)	Imax-5min (mm/h)
Low intensity rainfall on dry soils (<i>n</i> =1462)	4	5	3	8
Low intensity rainfall on wet soils (<i>n</i> =382)	6	6	21	11
Thunderstorms (<i>n</i> =104)	15	5	7	48

RA is the rainfall amount; *RD* is the total rainfall duration; *ARA*_{48h} is the antecedent rainfall amount during the 48h before the event; *Imax-5min* is the 5-min maximum rainfall intensity.

Table 3. Classification of runoff /interrill erosion risk for the common crops in Upper Normandy, and associated STREAM input parameters (steady-state infiltration rates – $I\alpha$ – and potential sediment concentration – $SC\alpha$).

(a) **Soil surface characteristics (*)**

Crop	October	November	December	January	February	March	April	May	June	July	August	September
Winter cereals	C1-F0-R2	C1-F11-R1	C1-F12-R0	C1-F2-R0	C1-F2-R0	C2-F2-R0	C3-F2-R0	C3-F2-R0	C3-F2-R0	C3-F2-R0	C2-F2-R0	C1-F2-R0
	Sowing	Soil crusting	Soil crusting								Harvest	
Early spring crops	C2-F2-R0	C2-F2-R0	C2-F2-R0	C1-F0-R4	C1-F11-R3	C1-F0-R2	C2-F0-R1	C3-F12-R1	C3-F12-R0	C3-F2-R0	C3-F2-R0	C2-F2-R0
					Sowing	Soil crusting	Soil crusting	Soil crusting			Harvest	
Late spring crops	C3-F2-R0	C3-F2-R0	C3-F2-R0	C3-F2-R0	C3-F2-R0	C3-F2-R0	C1-F0-R2	C1-F0-R2	C1-F11-R1	C2-F2-R0	C3-F2-R0	C3-F2-R0
		Harvest					Sowing	Soil crusting	Soil crusting	Soil crusting		

(b) **Risk quantification**

	$I\alpha$ (mm/h)	$SC\alpha$ (g/l)	
Very low risk	> 25	1 - 10	Soil crusting depends on rainfall depth after sowing (mm)
Low risk	15 - 25	10 - 15	F0 > F11 28
Medium risk	5 - 15	15 - 25	F11 > F12 115
High risk	1 - 5	25 - 35	F12 > F2 225

(c) **Runoff risk**

Crop	October	November	December	January	February	March	April	May	June	July	August	September
Winter cereals	Light	Dark	Very Dark	Very Dark	Very Dark	Very Dark	Very Dark	Very Dark	Very Dark	Very Dark	Very Dark	Very Dark
Early spring crops	Very Dark	Very Dark	Very Dark	Light	Dark	Dark	Dark	Dark	Dark	Dark	Dark	Dark
Late spring crops	Very Dark	Very Dark	Very Dark	Very Dark	Very Dark	Very Dark	Light	Light	Dark	Very Dark	Very Dark	Very Dark

(d) **Interrill erosion risk**

Crop	October	November	December	January	February	March	April	May	June	July	August	September
Winter cereals	Dark	Dark	Light	Light	Light	Light	Light	Light	Light	Light	Light	Light
Early spring crops	Light	Light	Light	Dark	Very Dark	Dark	Light	Light	Light	Light	Light	Light
Late spring crops	Light	Light	Light	Light	Light	Light	Dark	Dark	Dark	Light	Light	Light

(*) The following soil surface characteristics are documented for each field:

- Soil surface roughness state (height difference between the deepest part of micro-depressions and the lowest point of their divide). R0: 0-1 cm; R1: 1-2 cm; R2: 2-5 cm; R3: 5-10 cm; R4: > 10 cm;
- Crop cover classes (defined after the soil surface percentage covered by canopy or litter). C1: 0-20%; C2: 21 – 60%; C3: 61-100%;
- Soil surface crusting stage. F0: initial fragmentary structure; F11: altered fragmentary state with structural crusts; F12: local appearance of depositional crusts; F2: continuous state with depositional crusts.

Table 4[Click here to download Tables: Blosseville_Table4-revised.doc](#)

Table 4. Total erosion at the outlet simulated by the STREAM model for the different land use scenarios [(a) after land consolidation and (b) before land consolidation] for all the rainfall events of the period 1992-2006 (n=1948).

(a) Crop pattern after land consolidation

Month	Erosion (t)	% of total	Mean erosion per storm
January	160	4.3	8
February	318	8.6	24
March	69	1.9	5
April	1.2	0	0
May	111	3.0	7
June	108	2.9	7
July	204	5.5	11
August	732	19.8	46
September	727	19.7	25
October	406	11.0	9
November	217	5.9	7
December	643	17.4	17

Annual mean (t yr⁻¹) 276.6

Standard deviation 76.3

(b) Crop pattern before land consolidation

Month	Erosion (t)	% of total	Mean erosion per storm
January	65	4.7	4
February	219	16.0	18
March	41	3.0	5
April	1	0.0	0
May	43	3.2	11
June	57	4.2	7
July	143	10.5	10
August	262	19.2	11
September	219	16.1	8
October	38	2.8	8
November	58	4.2	7
December	217	15.9	6

Annual mean (t yr⁻¹) 103.0

Standard deviation 44.6

Table 5[Click here to download Tables: Blosseville_Table5-revised.doc](#)

Table 5. (a) Seasonal contributions and (b) contribution of different rainfall types to the total erosion simulated at the catchment outlet by the STREAM model (% of total erosion for all the rainfall events of the period 1992-2006; $n = 1948$).

(a)

Contribution of
season to total
erosion (%)

Crop pattern

after land consolidation

Crop pattern

before land consolidation

Winter	14.8	23.8
Spring	6.0	7.4
Summer	45.0	45.8
Autumn	34.3	23.0

(b)

Contribution of
Rainfall type (%)

Crop pattern

after land consolidation

Crop pattern

before land consolidation

Thunderstorms	51	57
Low intensity rainfall on dry soils	27	25
Low intensity rainfall on wet soils	22	18

Table 6[Click here to download Tables: Blosseville_Table6-revised.doc](#)

Table 6. Interannual variability of erosion at the Blosseville catchment outlet, as simulated by the STREAM model for the two different field patterns and for the rainfall events of the period 1992-2005 ($n=1948$).

Year	Erosion ($t\ yr^{-1}$) $t\ ha^{-1}yr^{-1}$				$mm\ yr^{-1}$		$mm\ 40\ yr^{-1}$	
	ALC	BLC	ALC	BLC	ALC	BLC	ALC	BLC
1992-1993	207	67	2.2	0.7	0.2	0.1	7	2
1993-1994	201	61	2.1	0.7	0.2	0.1	7	2
1994-1995	325	152	3.4	1.6	0.3	0.1	11	5
1995-1996	260	184	2.8	1.9	0.2	0.1	8	6
1996-1997	346	141	3.7	1.5	0.3	0.1	11	5
1997-1998	313	81	3.3	0.9	0.3	0.1	10	3
1998-1999	356	105	3.8	1.1	0.3	0.1	12	3
1999-2000	235	77	2.5	0.8	0.2	0.1	8	2
2000-2001	390	146	4.1	1.5	0.3	0.1	13	5
2001-2002	218	90	2.3	1.0	0.2	0.1	7	3
2002-2003	257	56	2.7	0.6	0.2	0.0	8	2
2003-2004	135	41	1.4	0.4	0.1	0.0	4	1
2004-2005	354	137	3.8	1.5	0.3	0.1	12	4
Mean	276.6	103.0	2.9	1.1	0.2	0.1	9.0	3.4
St. Deviation	76.3	44.6	0.8	0.5	0.1	0.0	2.5	1.5

ALC: after land consolidation.

BLC: before land consolidation.

$mm\ 40\ yr^{-1}$ corresponds to the estimation of total erosion over a period of 40 years.

Table 7. Comparison of annual erosion rates derived from ^{137}Cs measurements and STREAM outputs for the three areas located within the Blosseville catchment and delineated in Fig. 2.

# of area	Mean annual erosion (mm yr^{-1})	
	derived from ^{137}Cs measurements	derived from STREAM outputs
1	0.6 ± 0.6	0.4 ± 0.1
2	1.3 ± 0.4	1.1 ± 0.3
3	1.7 ± 0.4	1.0 ± 0.3

Fig. 1. Location of the Blosseville catchment in France.

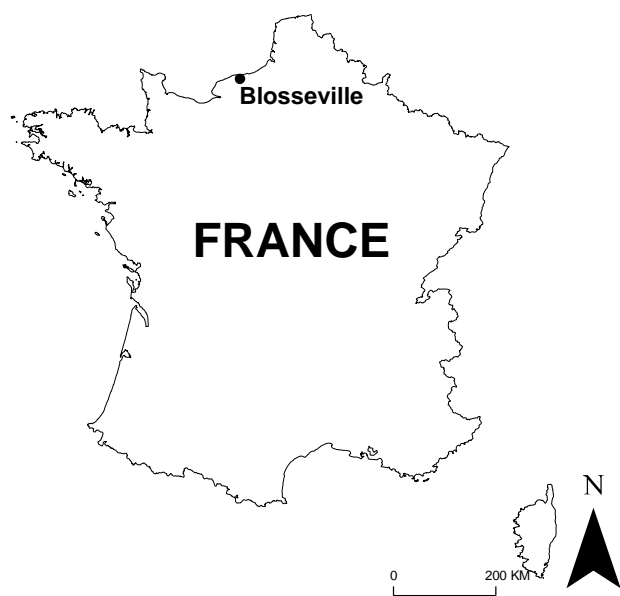
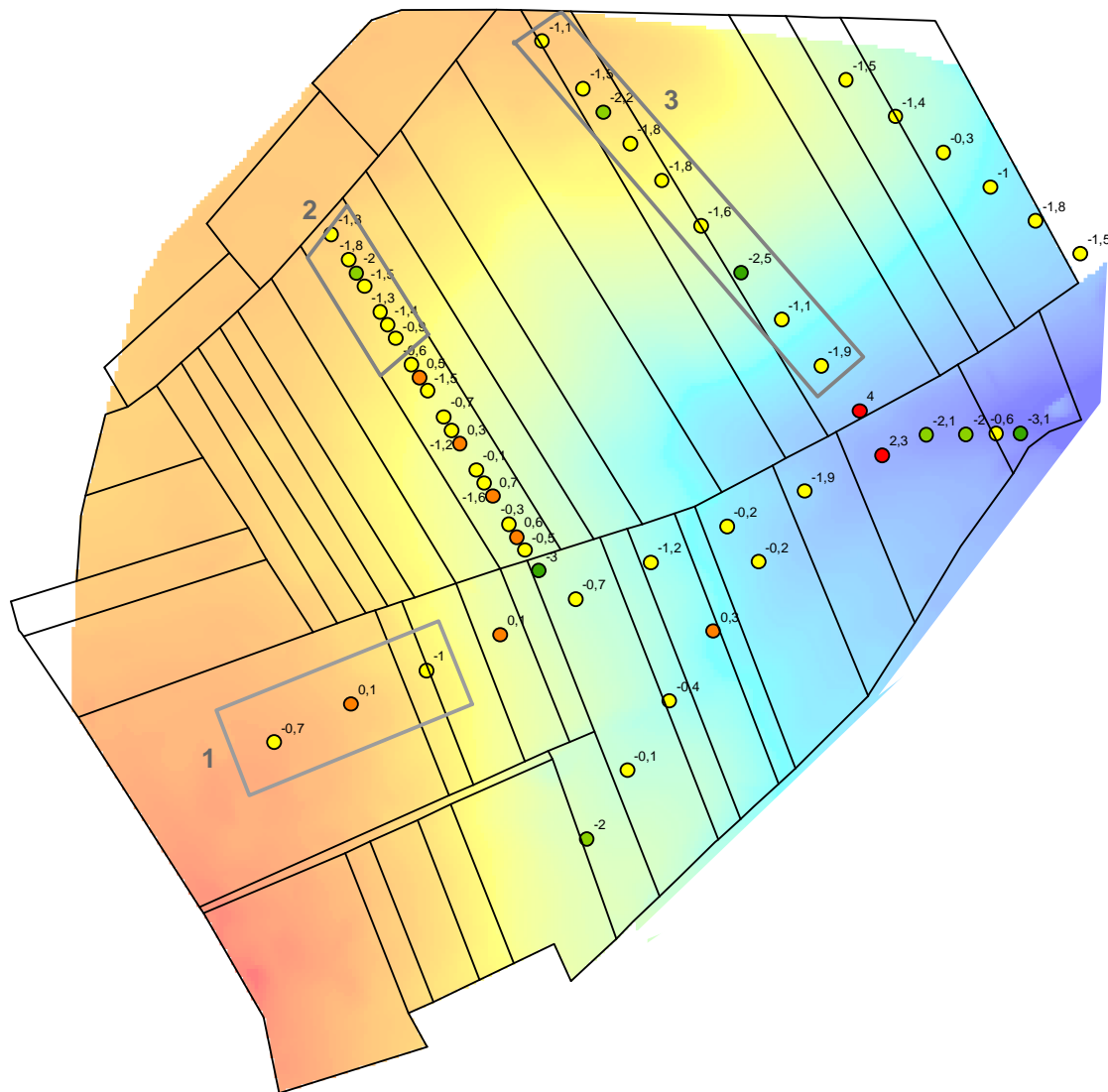


Figure 2

[Click here to download Figure: Blosseville_Fig2-revised.pdf](#)

Fig 2. Map of mean annual soil erosion and deposition derived from ^{137}Cs analysis of the 60 soil cores sampled in the Blosseville catchment, as simulated using the Cs model of Walling and He (1997).

- (a) Field pattern after land consolidation (situation in 2002). Several areas are delineated to compare the erosion rates derived from ^{137}Cs analysis with the averaged STREAM model outputs.
- (b) Field pattern and location of grassland before land consolidation (situation in 1947).



Comparison areas

Soil cores

Soil movement (mm/yr)

- -3.1 - -2.5
- -2.4 - -2.0
- -1.9 - 0.0
- 0.1 - 2.0
- 2.1 - 4.0

DEM

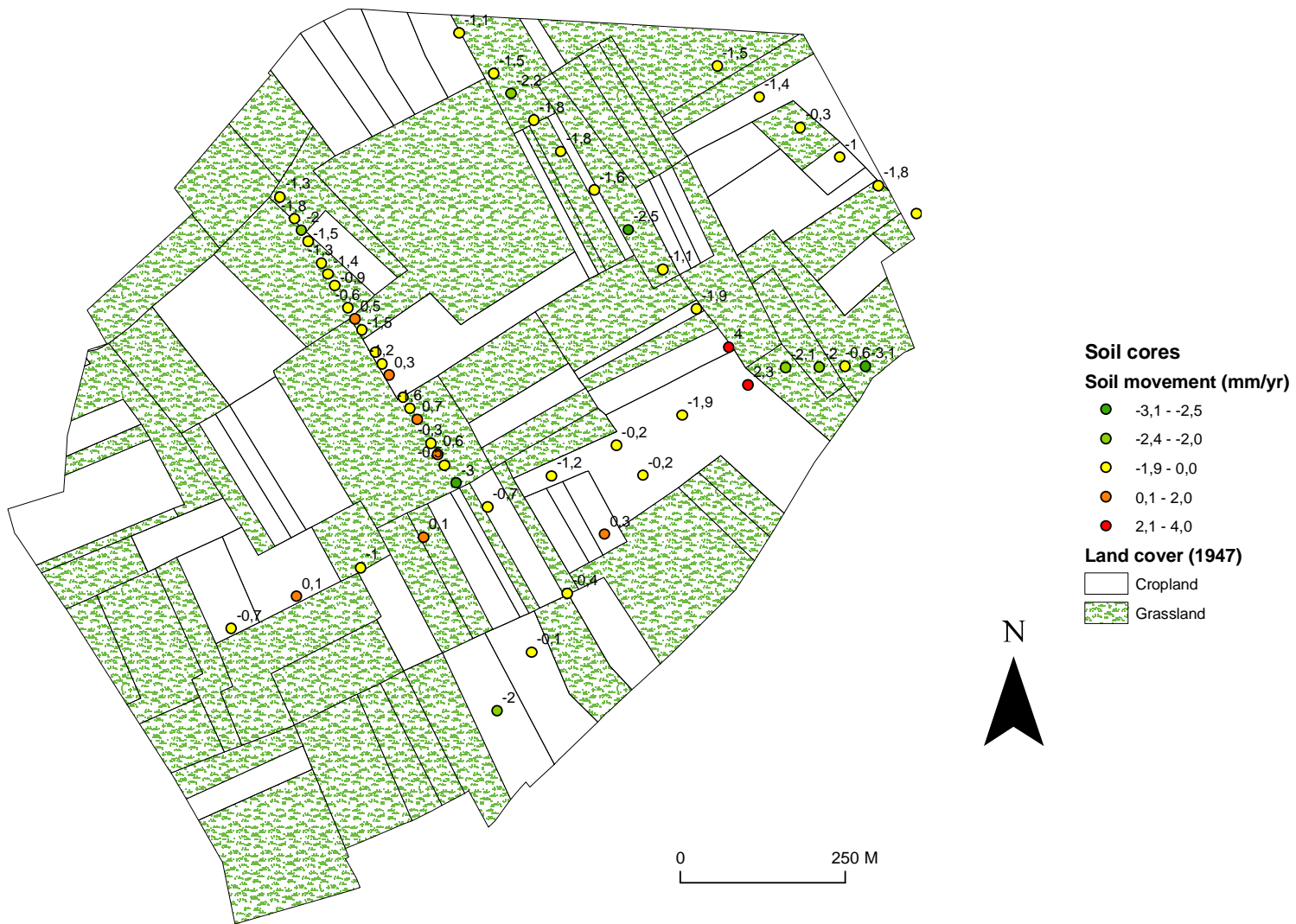
Altitude (m)

- High : 82
- Low : 53



0 250 M

(a)



(b)