



HAL
open science

Quantifying and modelling the impact of land consolidation and field borders on soil redistribution in agricultural landscapes (1954–2009)

Caroline Chartin, O. Evrard, Sébastien Salvador-Blanes, Florent Hinschberger, Kristof van Oost, Irène Lefèvre, Joël J. Daroussin, Jean-Jacques Macaire

► To cite this version:

Caroline Chartin, O. Evrard, Sébastien Salvador-Blanes, Florent Hinschberger, Kristof van Oost, et al.. Quantifying and modelling the impact of land consolidation and field borders on soil redistribution in agricultural landscapes (1954–2009). CATENA, 2013, 110, pp.184-195. <10.1016/j.catena.2013.06.006>. <hal-02308402>

HAL Id: hal-02308402

<https://hal.science/hal-02308402v1>

Submitted on 15 May 2020

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



HAL Authorization

1 **Quantifying and modelling the impact of land consolidation and field borders on soil**
2 **redistribution in agricultural landscapes (1954 – 2009)**

3 Caroline Chartin^{1,2}, Olivier Evrard^{2*}, Sébastien Salvador-Blanes¹, Florent Hinschberger¹,
4 Kristof Van Oost³, Irène Lefèvre², Joël Daroussin⁴, Jean-Jacques Macaire¹

5 ¹ EA 6293 GéHCo (Géo-Hydrosystèmes Continentaux), EA 6293, Université François-Rabelais de Tours,
6 Faculté des Sciences et Techniques, Parc de Grandmont, 37200 Tours (France)

7 ² LSCE (Laboratoire des Sciences du Climat et de l'Environnement), UMR 8212(CEA-CNRS-UVSQ)
8 Avenue de la Terrasse, 91198 Gif-sur-Yvette (France)

9 ³ TECLIM – Earth & Life Institute, Université catholique de Louvain, Place Louis Pasteur, 1348
10 Louvain-la-Neuve (Belgium)

11 ⁴ INRA – Unité de Science du Sol, 2163 avenue de la Pomme de Pin, CS 40001 Ardon, 45075 Orléans
12 Cedex 2, France

13

14 * **Corresponding author.** Tel.: +33 1 69 82 35 41; fax: +33 1 69 82 35 68.

15 E-mail address: caroline.chartin@lsce.ipsl.fr (C.Chartin)

16 Present address: LSCE (Laboratoire des Sciences du Climat et de l'Environnement), UMR 8212
17 (CEA-CNRS-UVSQ) Avenue de la Terrasse, 91198 Gif-sur-Yvette (France)

18

19 **Abstract**

20 Soil erosion rates in cultivated areas have intensified during the last decades leading to
21 both on and off-site problems for farmers and rural communities. Furthermore, soil
22 redistribution processes play an important role in sediment and carbon storage within, and
23 exports from, cultivated catchments. This study focuses on the impact of land consolidation
24 and changes in landscape structure on medium term soil erosion and landscape morphology
25 within a 3.7-ha field in France. The area was consolidated in 1967 and we used the ¹³⁷Cs-
26 technique to quantify soil erosion for the period (1954-2009). We measured the ¹³⁷Cs

27 inventories of 68 soil cores sampled along transects covering the entire area and especially
28 specific linear landforms located along both present and past field borders (i.e., lynchets and
29 undulations landforms, respectively). These results were then confronted with the outputs of a
30 spatially-distributed ^{137}Cs conversion model that simulates and discriminates soil
31 redistribution induced by water and tillage erosion processes. Our results showed that tillage
32 processes dominated the soil redistribution in our study area for the last 55 years and
33 generated about 95% (i.e., $4.50 \text{ Mg}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$) of the total gross erosion in the field.
34 Furthermore, we demonstrated that soil redistribution was largely affected by the presence of
35 current and also former field borders, where hotspots areas of erosion and deposition (> 20
36 $\text{Mg}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$) were concentrated. Land consolidation contributed to the acceleration of soil
37 erosion through the conversion of depositional areas into sediment generating areas. Although
38 the conversion model was able to reproduce the general tendencies observed in the patterns of
39 ^{137}Cs inventories, the model performance was relatively poor with a r^2 of 0.20. Discrepancies
40 were identified and associated with sampling points located along the current field borders.
41 Our data suggests that tillage erosion processes near field boundaries cannot be described as a
42 typical diffusive process. These processes near field boundaries should be characterised and
43 taken into account in a future version of the model to accurately simulate rates and patterns of
44 past soil redistribution in fragmented cultivated hillslopes. We also showed that the use of an
45 accurate DEM resulting from LIDAR data, based on present-day topography, leads to the
46 underestimation of soil redistribution rates by the model, especially in this landscape
47 submitted to recent and important morphological changes. Our results have important
48 implications for the simulation of tillage erosion processes and our understanding of soil
49 redistribution processes in complex cultivated areas. This is of particular interest to improve
50 our knowledge and prediction of patterns of soil physical parameters, such as carbon storage
51 or water content, particularly sensitive to surface erosion and landscape structuration.

52

53 **Keywords:** Soil erosion; Field border; Land consolidation; Cesium-137; Conversion model;

54 LIDAR

55

56 **1. Introduction**

57 During the last decades, soil erosion rates in cultivated areas of western Europe have

58 intensified and have become a problematic issue for farmers and rural communities. When it

59 is triggered by heavy storms, soil erosion and the associated muddy floods can have

60 disastrous and costly consequences (e.g. Pimentel et al., 1995; Evrard et al., 2007a).

61 Additional concerns about soil erosion are related to its subsequent negative impacts, such as

62 water pollution, decline in biodiversity and crop yields or reduction of soil water storage

63 capacity or organic carbon sequestration (e.g. Andraski and Lowery, 1992; Berger et al., 2006;

64 Boardman and Poesen, 2006; Papiernick et al., 2009). Because soil is a non-renewable

65 resource at human timescales, soil protection is crucial. Quantification of erosion and

66 deposition rates and the identification of their driving processes and their spatial variability

67 therefore constitute a prerequisite to develop and implement soil protection strategies.

68 Traditionally, soil redistribution processes observed on croplands in western Europe

69 were mainly attributed to water erosion processes. In that case, transport intensity is

70 controlled by topographical settings such as slope, drainage area and planform curvature

71 (Poesen, 1984; Foster, 1986; Chaplot and Le Bissonnais, 2003). However, research has shown

72 that tillage operations result in significant soil redistribution in intensively farmed cropland

73 (e.g. Lindstrom et al., 1992; Govers et al., 1994). Tillage erosion results from the net

74 downslope translocation of soil, controlled by slope gradient change, during farming

75 operations (Lindström et al., 1990; Govers et al., 1994; Montgomery et al., 1999; Van

76 Muysen et al., 1999). As shown by Govers et al. (1994), water and tillage-induced erosion

77 depend on different topographical parameters resulting in a specific spatial signature in the
78 landscape. Tillage erosion is the most intense on landscape positions where water erosion is
79 minimal (i.e. on convexities and in the proximity of upslope field boundaries), whereas areas
80 of tillage deposition often coincide with areas of maximal water erosion as hollows (Govers et
81 al., 1994; 1996; Van Oost et al., 2000).

82 The hydrological and sedimentological connectivity across cultivated hillslopes is to a
83 large extent controlled by the presence of field borders and associated linear elements, such as
84 hedges, roads, furrows and grass strips, which induce landscape fragmentation (Van Oost et
85 al., 2000; Follain et al., 2006; Szilassi et al., 2006). Vegetated borders (e.g., grass strips,
86 hedges and grassed waterways) can reinfiltrate surface runoff and trap sediment transported
87 by water (Van Dijk et al., 1996; Caubel et al., 2003; Evrard et al., 2008). In contrast, concave
88 anthropogenic features (e.g., furrows) provide preferential drainage pathways, thereby
89 increasing hydrological and sedimentological connectivity across the landscape. Linear
90 landscape elements with a compacted surface (e.g. roads, land tracks) have a limited
91 infiltration capacity and then enhance runoff and hydrological connectivity (Wemple et al.,
92 1996; Forman and Alexander, 1998). In tilled fields, all types of field borders act as lines of
93 zero-flux (Dabney et al., 1999; Van Oost et al., 2000). Consequently, tillage-induced
94 deposition and erosion preferentially occur upslope and downslope of field borders that are
95 oriented parallel to contour lines.

96 Field borders can therefore act as barriers to water and sediment fluxes generated by
97 both water and tillage erosion (Dabney et al., 1999; Govers et al., 1999; De Alba, 2003; Van
98 Dijk et al., 2005; Knapen et al., 2008). Interaction between erosion and deposition processes
99 at the vicinity of field borders leads to the development of anthropogenic linear landforms of
100 several metres width (e.g., ridges-and-furrows, headlands, and lynchets). These features are
101 common in the agricultural landscapes of western Europe (Callot, 1980; Hooke, 1988;

102 Zadora-Rio, 1991). These landforms are not conserved after the removal of the field border
103 but will instead keep evolving, and may finally lead to the formation of undulations (Houben,
104 2008; Chartin et al., 2011). Assessing the effect of field borders and their potential removal is
105 then essential to understand past, present and future spatial patterns of soil redistribution and
106 soil properties in the current global change context.

107 Agricultural policy and mechanisation led to the massive removal of field borders
108 through the implementation of numerous land consolidation schemes between 1960 and 1990
109 in western Europe (Baudry and Burel, 1984; Vitikainen, 2004), and is still ongoing in some
110 regions. The use of ¹³⁷Cs-technique can therefore offer a solution to evaluate soil
111 redistribution over these last decades (e.g., Rogowski and Tamura, 1965; Ritchie and
112 McHenry, 1990; Walling and Quine, 1992).

113 This study aims to quantify and improve our understanding of the effects of land
114 consolidation and field borders on mid-term soil erosion and on agricultural landscape
115 evolution. In order to achieve this objective, we analysed spatial patterns of ¹³⁷Cs inventories
116 for an agricultural hillslope that was subjected to land consolidation. The study area is
117 representative for field consolidation in intensively cultivated areas of the southwestern
118 Parisian basin (France). We used a spatially-distributed model to convert these observations
119 into soil redistribution rates. Emphasis will be put on the impact of small-scale topographical
120 features, especially lynchets and undulations landforms associated with local soil
121 accumulation along current and former field borders. Finally, we discuss the wider
122 implications of our findings in relation to agricultural landscape evolution and model
123 development.

124

125 **2. Materials and methods**

126 *2.1. Study area*

127 *2.1.1. Location and physiological settings*

128 The study was conducted on a 3.7 ha field located at the downslope part of a south-
129 east facing hillslope in the southwestern Parisian Basin, France (47°08.31'N, 0°10.97'E) (Fig.
130 1). The area is part of the Quincampoix watershed and is characterised by an undulating
131 topography commonly observed in terrains underlain by Cretaceous chalks in this region. In
132 the study field, the elevation ranges between 43 to 60m with slope between 0 to 8.8%. Two
133 types of linear anthropogenic landforms - lynchets and undulations – were also identified within
134 this field (see further).

135 Soils are calcareous Cambisols, leptosollic calcareous Cambisols and colluvic Cambisols with
136 clay and loam textures (Boutin et al., 1990; FAO, 1998). The mean annual precipitation
137 reaches ca. 600 mm and is evenly distributed throughout the year.

138 We reconstructed the changes in field boundaries using aerial photographs for 1945,
139 1959 and 2009. The study area is presently a unique field but it was divided into seven
140 individual fields before the last important campaign of land consolidation that occurred in
141 1967 (Fig. 2). Interviews with local farmers and aerial photographs have demonstrated that
142 this area has been cultivated with cereals and oilseed crops (maize, sunflower, wheat, barley
143 and rape) since at least 1945.

144

145 *2.1.2. Characteristics of the anthropogenic linear landforms*

146 We observed one lynchets (L1) and two undulations (U1, U2) in the study area.
147 Locations of the field borders associated with these linear landforms are presented in Figure 2.
148 The lynchets L1 and undulations U1 and U2 are oriented perpendicularly to the steepest slope
149 and separated by mostly regular hillslope sections in the study area (Chartin et al., 2011).

150 Lynchets landforms, also known as terraces, soil banks, or locally as “rideaux” in
151 northern France and Belgium, are predominantly shaped by the progressive accumulation of

152 soil material upslope of a field border (Bollinne, 1971; Papendick and Miller, 1977; Van Dijk
153 et al., 2005; Salvador-Blanes et al., 2006; Follain et al., 2007). A lynchet is defined by two
154 morphological components separated by a field border, i.e., the axis (Fig. 3a). Uphill,
155 progressive slope gentling from up- to downslope shapes a wide concave area (from 15 to
156 30m width in this region). Downhill, there is a break-in-slope that in this specific case, is 2 to
157 5 m-wide and reaches more than 2 m height creating a sharp discontinuity in the landscape.
158 The soil accumulation in a lynchet evolves as a pseudo right-angle triangle (Fig. 3c).

159 An undulation consists of a wide gentle central convexity gradually connected by
160 slight external concavities to the general hillslope morphology (Fig. 3b). The top of the
161 convexity - considered as its axis - coincides closely with a former field border (Houben,
162 2008; Chartin et al., 2011). Undulation landforms correspond to a more or less thickened soil
163 with a lenticular convex shape (Fig. 3d).

164

165 *2.2. Topographical data*

166 A 2 m resolution raster DEM was built from LIDAR data with the following method. Raw,
167 tiled LIDAR datasets for the study area were assembled. Only the datasets identified as
168 ground floor points were kept for this study (vegetation and infrastructure top points were not
169 considered). The 2 m cells covering the area contained from 0 to 247 LIDAR points with
170 different Z values. The median Z value was attributed to each cell centroid for cells with
171 points whereas centroids for cells without points were deleted. Only elevation points of each
172 cell belonging to the same landuse as the centroid were used to calculate this median value.
173 This prevents from an artificial smoothing of sharp topographic discontinuities such as
174 lynchet borders. A triangular irregular network (TIN) was then built from the remaining
175 centroids. The TIN was then interpolated to a 2 m resolution raster. The elevation raster was

176 finally filtered on a plot by plot basis depending on the land use.

177

178 2.3. ¹³⁷Cs analysis

179 2.3.1. Field sampling

180 Sixty-eight soil cores were sampled in the field in 2009 for ¹³⁷Cs activity analysis.

181 Thirteen cores were collected along each of the five transects parallel to the steepest slope and

182 referred to as I to V in Figure 4a to cover the entire range of topographic settings observed in

183 the area. Sample lines 1 and 2 are located in the concavity of lynchets L1; sample lines 5 and 9

184 are located along the axis of undulations U1 and U2, respectively, e.g. in their central

185 convexities; lines 4, 6, 8 and 10 are located in the external concavities of the latter undulations;

186 and, finally, sample lines 3, 7, 11, 12 and 13 are located in areas characterised by more or less

187 regular slopes. Three additional cores (IV-1a, IV-1b and IV-1c on Figure 4b) were sampled

188 along transect IV to detail the effect of the present field border on the recent soil redistribution

189 over a short distance in lynchets L1 (Fig. 4b).

190 Soil cores with 8 cm or 10 cm external diameter were collected with a percussion

191 drilling machine (Eijkelkamp) up to a soil depth of about 70 to 100 cm and immediately cut

192 into sections in the field. Depending on the local soil thickness, the first section corresponded

193 to the uppermost 20 to 40 cm of the core. Then, successive 10-cm sections were cut off until

194 the bedrock was reached. Two of the sixty-eight soil cores (sample points IV-1a and V-8

195 highlighted in Fig. 4) were cut into 5-cm sections to detail the vertical distribution of ¹³⁷Cs at

196 particular locations. The V-8 soil core was collected on the downslope external concavity of

197 undulation U2, e.g. just downslope of a former field border that was removed in 1967. Core

198 IV-1a was sampled on the gentle slope of L1 lynchets, 3 m upslope of the present lower field-

199 border. Each section of the 68 cores was oven-dried for 48 h at 40 °C, sieved to 8-mm. Soil in

200 the study area contains large quantities of coarser grains and chalk fragments. Attention was

201 paid to collect the fine particle fraction deposited on the surface of those coarser grains. The
202 <8mm fraction was ground to a fine powder. For each sample, a representative subsample of
203 the <8mm fraction (approx.. 70 g) was then collected to measure ^{137}Cs activities.

204

205 2.3.2. Measuring ^{137}Cs activities

206 ^{137}Cs in the soil cores was measured at 661 keV using low background Germanium
207 gamma-ray detectors (Germanium hyperpure – GeHP, N-type, coaxial model) for 24 to 48 h.
208 An initial qualitative assessment was performed on successive subsamples of each core to
209 determine the maximum depth of the ^{137}Cs signal. The ^{137}Cs activity (A_i in Bq.kg^{-1}) was then
210 derived for each core section. Finally, the ^{137}Cs total inventory (A_{surf} ; Bq.m^{-2}) of each core
211 was calculated according to Eq. (1) (Sutherland, 1992).

$$212 \quad A_{\text{surf}} = \sum_{i=1}^n \left(A_i \times \frac{M_i}{S} \right) \quad (1),$$

213 where A_i is the ^{137}Cs activity in the successive sections of the core (Bq.kg^{-1}); M_i is the mass
214 (kg) of the <8 mm soil fraction of the i^{th} sampled section; S is the surface area (m^2) of the soil
215 core cylinder, n the total number of sampled sections sections of the core.

216 To estimate whether soil erosion or deposition occurred in the investigated field since
217 the beginning of ^{137}Cs fallout (1954), ^{137}Cs inventories were compared to the local reference
218 inventory. This latter was the mean inventory obtained in four cores sampled in neighbouring
219 undisturbed sites such as orchards and pastures. Then, ^{137}Cs residuals were calculated
220 according to Eq. (2):

$$221 \quad C_{S_{\text{res},x}} = A_{\text{surf},x} - A_{\text{surf,ref}} \quad (2),$$

222 where $C_{S_{\text{res},x}}$ are the ^{137}Cs residuals at the x core location (Bq.m^{-2}), $A_{\text{surf},x}$ is the ^{137}Cs total
223 inventory at the the x core location (Bq.m^{-2}), and $A_{\text{surf,ref}}$ is the Cs reference inventory
224 (Bq.m^{-2}).

225 Negative residuals mean that the concerned location has underwent net soil erosion since
226 1954, whereas positive residuals indicate the occurrence of net soil deposition.

227

228 2.4 Converting ¹³⁷Cs activities into erosion-deposition rates

229 2.4.1. Conversion model description

230 We used a spatially explicit model to convert ¹³⁷Cs residuals into soil erosion and
231 deposition rates (Mg.ha⁻¹.yr⁻¹ or mm.yr⁻¹). The model consists in a combination of a punctual
232 mass-balance model and a spatially distributed and process-based model of water and erosion
233 tillage processes (Van Oost et al, 2003). The mass-balance model includes both the annual
234 fallouts and susceptible losses of ¹³⁷Cs due to runoff (before its incorporation within the tilled
235 layer) during the whole period of the radionuclide fallout (Quine, 1995). The conversion
236 model exploits the different patterns of water and tillage erosion in a spatial analysis of ¹³⁷Cs
237 inventories to assess the relative contribution of water and tillage erosion processes.

238 The water-induced processes of soil erosion (rill and interrill erosion) are defined as a
239 power function of slope gradient and contributing area, following Eqs. (3) and (4):

$$240 E_{rill} = k_1 \rho_b S^a A^b, \quad (3)$$

$$241 E_{irill} = c \rho_b S^d, \quad (4)$$

242 where E_{rill} and E_{irill} are rill and interrill potentials, respectively (kg.m⁻²), ρ_b is the dry bulk
243 density of the soil (kg.m⁻³), S is the slope (m.m⁻¹), A is the contributing area per unit contour
244 width (m².m⁻¹), and k_1 , a , b , c and d are coefficients (-).

245 The local rate of soil erosion is then calculated as the summation of both potentials for rill and
246 interrill erosion unless the local transport capacity is exceeded. The transport capacity on a
247 given slope segment is then considered as being proportional to the potential for rill erosion
248 (e.g., Desmet and Govers, 1995), Eq. (5):

$$249 T_c = k_2 E_{rill}, \quad (5)$$

250 where T_c is the transport capacity ($\text{kg}\cdot\text{m}^{-1}$) and k_2 is a coefficient (m).

251 When local sediment inflow exceeds the transport capacity T_c , deposition occurs. The amount
252 of soil translocated is then equal to T_c .

253 The net soil flux induced by tillage translocation on a hillslope of infinitesimal length
254 and unit width is considered as proportional to the local slope gradient (Govers et al., 1994;
255 Van Oost et al., 2000), Eq. (6):

$$256 \quad Q_t = k_3 S = -k_3 \frac{dh}{dx}, \quad (6)$$

257 where Q_t represents the net downslope flux due to tillage ($\text{kg}\cdot\text{m}^{-1}\cdot\text{a}^{-1}$), k_3 is the tillage transport
258 coefficient ($\text{kg}\cdot\text{m}^{-1}\cdot\text{a}^{-1}$), S is the local slope gradient ($\text{m}\cdot\text{m}^{-1}$), h is the height at a given point of
259 the hillslope (m), and x is the horizontal distance (m).

260 The local intensity of tillage-induced erosion (E_t in $\text{kg}\cdot\text{m}^{-2}$) is then modelled as a diffusive
261 process controlled by slope gradient changes, according to Eq. (7):

$$262 \quad E_t = \rho_b \frac{dh}{dt} = -\frac{dQ_t}{dx} = \frac{d^2h}{d^2t}, \quad (7)$$

263 where t is the time (s).

264 Finally, field borders were considered as lines of zero flux. This means that no soil material is
265 translocated from one field to another during tillage.

266

267 2.4.2. Conversion model application

268 The simulation process is iterative, and each iteration corresponds to one year. Annual
269 ^{137}Cs fallouts used in the model were based on the measured annual fallout for the northern
270 hemisphere (Cambrai et al., 1989). This value was rescaled to the local reference inventory
271 using the factor α (-), Eq. (8):

$$272 \quad \alpha = \frac{A_{surf,ref}}{A_{surf,NH}}, \quad (8)$$

273 where $A_{\text{surf,ref}}$ is the Cs reference inventory ($\text{Bq}\cdot\text{m}^{-2}$) for the study area and $A_{\text{surf,NH}}$ is the mean
274 Cs reference inventory ($\text{Bq}\cdot\text{m}^{-2}$) for the northern hemisphere.
275 ^{137}Cs fallouts associated with the Chernobyl accident were reported to be negligible in the
276 study area and were therefore not considered in Cs reference inventories of Eq. (8) (Fourmont,
277 2001).

278 The parameter values proposed by Quine (1997) were used for the punctual mass-
279 balance model. No a-priori assumptions were made about rates of water and tillage erosion. A
280 specific procedure developed by Van Oost et al. (2003) and based on the Generalized
281 Likelihood Uncertainty Estimation (Beven and Binley, 1992) was implemented to explore the
282 parameter space for which the model was in close agreement with the observed ^{137}Cs
283 inventories. Value ranges for parameters k_1 , k_2 and k_3 (Eqs. 2, 4 and 5) used in this procedure
284 are presented in Table 1. Coefficients a, b and d (Eqs. 2 and 3) were based on studies carried
285 out by Desmet and Govers (1995, 1997), Van Oost et al (2000) and Van Rompaey et al.
286 (2001).

287 The conversion model was applied to compare simulated and observed ^{137}Cs patterns
288 for 3000 randomly chosen parameter sets k_1 , k_2 and k_3 over the whole study area. The
289 observational dataset used in the evaluation procedure, called “total set”, contains 67
290 sampling points: the point IV-1b was excluded as it is located just 1 m from point IV-1a.
291 Likelihood values for each set of parameters were determined and associated with the
292 corresponding model output values (Van Oost et al., 2003). The cumulative likelihood
293 distribution of water and tillage erosion rates was then defined separately for the whole study
294 area. From these cumulative distributions, median (M), 5th (P5) and 95th (P95) percentile
295 values were calculated to provide a quantification of model uncertainty.

296

297 **3. Results and discussion**

298 *3.1. Recent soil redistribution patterns and relations with topographical settings*

299 The observed ^{137}Cs reference inventory was $1367 \pm 30 \text{ Bq.m}^{-2}$ in 2009 in Seully (Fig.
300 5a). About 40% and 65% of the total ^{137}Cs inventory was concentrated in the uppermost 5 cm
301 and 10 cm, respectively. As observed at many other undisturbed locations, the ^{137}Cs content
302 declined almost exponentially with soil depth in these profiles (Walling and Quine, 1992).

303 The ^{137}Cs residuals (Eq. 2) ranged from -1030 Bq.m^{-2} to 980 Bq.m^{-2} in the 68 analysed
304 cores. The largest variations were observed along the steepest slope direction (NNW-SSE)
305 and were strongly affected by anthropogenic undulations U1, U2, and lynchets L1 (Fig. 6).
306 About 50% of the ^{137}Cs contained in the soil at the time of sampling (2009) originates from
307 the period between 1962 and 1964. Consequently, currently observed patterns mostly reflected
308 the soil redistribution that occurred after the 1967 land consolidation, when field borders
309 associated with undulations U1 and U2 were removed (Fig. 2).

310 The ^{137}Cs residuals measured on undulation central convexities (sample lines 5 and 9)
311 ranged from -320 Bq.m^{-2} to 20 Bq.m^{-2} and were mostly negative, whereas residuals measured
312 on undulation external concavities (sample lines 4, 6, 8 and 10) ranged from 30 Bq.m^{-2} to
313 more than 730 Bq.m^{-2} . These results reflected the progressive levelling of the undulation
314 landforms since the last land consolidation. These patterns of ^{137}Cs residuals were then most
315 likely induced by redistribution through tillage practice such as it leads to soil erosion in
316 convexities and soil accumulation in concavities (Govers et al., 1994; 1996; De Alba et al.,
317 2004). The profile V-8 provided an example of ^{137}Cs vertical distribution in an undulation
318 external concavity, i.e. in a depositional context ($A_{\text{surf}} = 1786 \text{ Bq.m}^{-2}$; Fig. 5b). The ^{137}Cs
319 vertical distribution was homogeneous in the uppermost 30 cm and then declined rapidly in
320 the next five centimetres, reflecting the mixing induced by tillage operations (Kachanovski
321 and de Jong, 1984; Ritchie and McCarty, 2003). As undulation landforms initially correspond
322 to local soil accumulation induced by former field borders, their morphology in 2009

323 potentially derived from the levelling of two other types of anthropogenic landforms
324 consecutive to the field border removal: i) the undulations are former lynchets as suggested by
325 Bollinne (1971) and Houben (2008); ii) undulations are headlands created by an asymmetric
326 accumulation of soil due to tillage translocation on both sides of the borders (Callot, 1980;
327 Leturcq, 2008). In both cases, the morphology corresponding to current undulations in the
328 vicinity of the former field borders shows a strong evolution.

329 The ^{137}Cs residuals ranged from 420 to 560 $\text{Bq}\cdot\text{m}^{-2}$ 16 m upslope of the lynchet L1
330 field border (sample line 2). This area is characterised by a particularly gentle slope that is
331 clearly concave. In contrast, four of the five cores collected 2m upslope of same border
332 (sample line 1) showed negative residuals ranging from $-1000 \text{ Bq}\cdot\text{m}^{-2}$ to $-250 \text{ Bq}\cdot\text{m}^{-2}$ (Fig.6).
333 Fig. 7 shows that lynchet L1 (sample lines 1 and 2) was characterised by a large variability of
334 ^{137}Cs residuals revealing the occurrence of both erosion and deposition processes. It has
335 nevertheless mostly undergone soil accumulation since 1967. Indeed, ^{137}Cs residuals ranged
336 from $-426 \text{ Bq}\cdot\text{m}^{-2}$ to $946 \text{ Bq}\cdot\text{m}^{-2}$, with negative values exclusively concentrated within the
337 first 4m upslope the field border. Even though lynchets are typically developed by the
338 progressive accumulation of soil upslope of a field border, our results reflected that soil
339 erosion occurred along this downfield border during the period 1954-2009. This complex
340 behaviour could be due to specific tillage practices performed along the field border. Farmers
341 systematically end up their tillage operations by contouring the field, i.e. perpendicularly to
342 the main up- and downslope tillage direction in the case of the upslope and downslope field
343 borders. This operation with the mouldboard plough results in the translocation of soil to the
344 inside of the field. This process could explain the slight local convexity observed in the first
345 meters of the field along the lower field border (Fig. 7). Considering this short-distance
346 variability, sampling schemes have to be carefully designed to describe in an appropriate way

347 the major soil redistribution processes (erosion or deposition) occurring in landforms
348 associated with field borders.

349 A depositional context was also observed 10 m downslope of the current upslope field
350 border (^{137}Cs residuals varied from $475 \text{ Bq}\cdot\text{m}^{-2}$ to $800 \text{ Bq}\cdot\text{m}^{-2}$ along the sampling line 13; Fig.
351 5). Indeed, soil is thicker at this location than in surrounding areas with a depth locally up to
352 80 cm (Chartin, 2011). Moreover, the local slope is convex in the direction of the steepest
353 slope. Here again, tillage practices performed along this field border could explain the local
354 soil accumulation and the topographical convex settings. Unfortunately, sampling density was
355 not sufficient to check the relevance of this hypothesis in this specific study case.

356 Finally, spatial patterns of ^{137}Cs residuals in undifferentiated areas are rather complex
357 and do not seem to be directly influenced by slope gradient nor curvature (Fig. 6).

358

359 *3.2. Modelling erosion and deposition rates from 1954 to 2009*

360 *3.2.1. Conversion results*

361 The factor α used to determine mean annual ^{137}Cs fallouts in this area was 0.786
362 (Eq. 7). Fig. 8 presents the simulated optimal ^{137}Cs inventories, tillage and water erosion
363 simulated by the model over the whole study area.

364 The major observed patterns of ^{137}Cs inventories related to lynchets and undulations
365 were reproduced by the simulations. Convex landforms were characterised by soils with low
366 ^{137}Cs inventories when compared to the higher inventories simulated on concave landforms
367 (Fig. 8a). Tillage was found to be the dominant process controlling ^{137}Cs patterns since the
368 1967 land consolidation. Tillage erosion rates were often higher than $6 \text{ Mg}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$ and
369 reached locally up to $15 \text{ Mg}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$ in central convex parts of U1 and U2 (Fig. 8b). Soil
370 accumulation by tillage observed in external concave areas of undulations and over the whole
371 area of lynchet L1 seemed to be correctly reproduced with a maximum deposition rate

372 reaching 22 Mg.ha⁻¹.yr⁻¹. Water erosion output patterns were also greatly influenced by
373 undulation and lynchets landforms (Fig. 8c). U1 and U2 subdivided the study field in three
374 areas characterised by similar patterns of simulated water erosion. In each area, erosion of soil
375 material was simulated over most of the upslope part whereas deposition was simulated in the
376 concave depositional settings located downslope of the area. Maximum soil erosion and
377 deposition rates by water were simulated in the lower area, i.e. between U1 and L1, where the
378 general slope is the steepest. Here, erosion rates reached 0.6 Mg.ha⁻¹.yr⁻¹ within the U1
379 external concavity and net deposition reached 5 Mg.ha⁻¹.yr⁻¹ within L1 concavity.

380 Simulated tillage erosion was an order of magnitude higher than water erosion in both
381 erosional and depositional areas (e.g., the median water erosion rates was -0.20 Mg.ha⁻¹.yr⁻¹
382 whereas the median tillage erosion rate was -4.50 Mg.ha⁻¹.yr⁻¹; Tab. 2). The mean tillage
383 erosion rate over the whole study area was three to four times lower than the maximum
384 erosion rates simulated in undulations (Tab. 2; Fig. 8b). Considering the mean tillage
385 deposition rate over the whole study area, it was more than four times lower than maximum
386 deposition rates simulated within the lynchets L1 (Tab. 2; Fig. 8b). The uncertainty associated
387 with simulated water erosion and deposition was much higher than the one associated with
388 tillage simulation. This could be explained by the dominance of tillage erosion process (Tab.
389 2). Moreover, deposition rates and patterns of water erosion are largely controlled by k_2
390 whereas tillage process simulations are characterised by soil redistribution patterns that
391 remained stable for the entire range of the tested k_3 values (Van Oost et al., 2003).

392 The model runs confirmed our observations: soil redistribution by tillage is dominant
393 in the area since 1967. Tillage redistributes sediment in fields whereas water exports it from
394 fields. In this context, we estimated here that 98.5 % of the total eroded soil was deposited in
395 the study field, whereas only 1.5% was exported by water erosion. This result was in
396 agreement with previous findings obtained in the Parisian basin showing that land

397 consolidation generates a dramatic increase of soil redistribution within cultivated catchments,
398 and to a slight (Evrard et al., 2010; Delmas et al., 2012) or a large increase (Boardman et al.,
399 1994; Evrard et al., 2008) of sediment exports from the catchment, depending on the
400 catchment topography, land use characteristics and the implementation of soil conservation
401 measures. As soon as mechanization appeared in the 1950s, land consolidation campaigns
402 favoured its introduction across the world and, inversely, mechanization motivated the
403 implementation of land consolidation operations (Van Huylenbroeck et al., 1996; Crecente et
404 al., 2002; Niroula and Thapa, 2005). However, mechanized agriculture involved higher tillage
405 erosion rates when compared to previous non-mechanized tillage (Govers et al., 1996; Van
406 Oost et al., 2000, 2006). Land consolidation enhances hydrological and sedimentological
407 connectivity and leads to important increases of sediment exports in regions particularly
408 sensitive to water erosion (Evrard et al., 2007b). However, this increase is not observed when
409 tillage largely dominates soil redistribution. Moreover, soils developed on Cretaceous chalks
410 appear not to be particularly sensitive to water erosion, thereby limiting the hydrological and
411 sedimentological connectivity (Boutin et al., 1990).

412 Our results explicitly identified hotspot areas of soil erosion induced by land
413 consolidation, i.e., in the vicinity of removed field borders, and hotspot areas of soil
414 deposition, i.e. in the vicinity of present field borders and external concavities of undulations.
415 We thereby show that land consolidation led progressively to the general levelling of the
416 hillslope morphology. This was particularly true when considering the convex undulations.
417 From sinks for soil material before land consolidation, the corresponding areas progressively
418 became sources for soil material redistribution.

419

420 ***3.2.2. Analysis of the discrepancies***

421 Even though the conversion model reproduced the major trends of soil erosion and
422 deposition recorded in the study field, observed and simulated ^{137}Cs inventories fitted rather
423 poorly ($r^2 = 0.20$, $p < 0.05$; Fig. 9). Indeed, the model tended to systematically underestimate
424 inventories in depositional settings and to overestimate inventories in highly erosive areas.

425 Simulated ^{137}Cs inventories along the linear landforms were more or less
426 underestimated (from -150 to -750 Bq.m^{-2}) on observed depositional settings associated with
427 lynchets L1 and undulations U1 and U2, i.e. on concave parts (lines 2, 4, 6, 8 and 10; Fig. 10a).
428 However, most of these locations were simulated as being in a depositional context (Fig. 10b).
429 Similarly, central convexities located on undulations were simulated as eroded areas. The
430 largest under-estimations ($< -600 \text{ Bq.m}^{-2}$) were concentrated along the upslope field border
431 (Fig. 10a). In this case, observed depositional locations were simulated as eroded sites (Fig.
432 10b). Although deposition is simulated within a few-meter width area along this upslope
433 border (Fig. 8a), actual deposition occurring ten meters downslope of this border (along the
434 sample line 13) was not well reproduced by the model. The largest over-estimations were
435 concentrated along the downslope field-border (sample line 1 on lynchets L1) where
436 simulation errors reached up to 1000 Bq.m^{-2} . As mentioned before, we infer that specific
437 tillage operations performed along the upper and lower field borders could have induced
438 processes differing from the classical diffusive process associated with “infield” operations
439 and considered as the only tillage-induced process in the conversion model. The mechanisms
440 of those specific processes could therefore be implemented to improve the model efficiency.
441 Furthermore, sampling could be intensified in the vicinity of the current field borders in order
442 to describe more accurately their impact on local variations of soil redistribution.

443 We therefore ran the model with a dataset (subsequently referred to as the “infield set”)
444 excluding points sampled at the vicinity of upslope and downslope field borders, i.e. sampling
445 points IV-1a, IV-1b and those located along lines 1 and 13 ($n = 55$). Observed and simulated

446 inventories fitted much better when using the “infield set” ($r^2 = 0.42$; $p < 0.05$; Fig. 11) than
447 when using the “total set” ($r^2 = 0.20$), but discrepancies remained.

448 Both simulations outlined that tillage-induced processes were the driving factor
449 explaining more than 95 % of the total soil redistribution that occurred after the 1967 land
450 consolidation (Table 3). We demonstrated that tillage practices levelled the field morphology,
451 and we can then hypothesise that local curvatures derived from the DEM based on the 2009
452 LIDAR data were smoothed compared to those existing in 1967. Consequently, tillage
453 erosion and deposition rates simulated for the period 1954-2009 remained necessarily under-
454 estimated when considering curvatures as the morphological parameter controlling the
455 intensity of soil translocation by this diffusive process. The more the landscape morphology
456 would have evolved since ^{137}Cs fallouts, the less the conversion of ^{137}Cs inventories into soil
457 redistribution rates would be accurate. This should be taken into account when using the ^{137}Cs
458 method to validate the parameterization of erosion models dedicated to the prediction of
459 medium-term erosion (from decades to centuries).

460

461 **4. Conclusions**

462 This study focused on the impact of land consolidation and field borders on medium
463 term soil erosion (1954-2009) and landscape morphology within a 3.7-ha field consolidated in
464 1967. The spatial patterns of ^{137}Cs inventories were analyzed and a spatially-distributed
465 conversion model simulating the respective implication of water and tillage erosion was
466 applied. The model simulated tillage erosion as the most dominant process across the study
467 area, by generating 95% of soil redistribution movements (i.e., about $4.50 \text{ Mg}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$) and
468 deeply modifying the landscape morphology. Hence, soil redistribution was greatly affected
469 by the presence of current but also former field borders, where hotspots areas of erosion (on
470 undulations) and deposition (on lynchets; i.e., about $20 \text{ Mg}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$) are identified. Land

471 consolidation contributed to the acceleration of soil redistribution within the field through the
472 conversion of depositional areas into sediment delivering areas. The conversion model
473 reproduced the main patterns of ¹³⁷Cs inventories, but simulated inventories fitted rather
474 poorly with these latter ($r^2 = 0.20$). Discrepancies were identified and associated with
475 sampling points located along the current field borders where tillage is performed
476 perpendicularly to the main tillage direction in the field. This tillage operation is observed in
477 most cultivated plots and corresponds to a contouring of the field when finishing a tillage
478 operation. This particular tillage operation could be taken into account in a future version of
479 the model to accurately simulate rates and patterns of past soil redistribution in fragmented
480 cultivated hillslopes. An other outcome of this specific process is that ¹³⁷Cs sampling schemes
481 have to be carefully designed to describe in an appropriate way the major soil redistribution
482 processes occurring in landforms associated with field borders. We also suggest that the use
483 of an accurate DEM representing the actual topography in the model leads to the
484 underestimation of soil redistribution rates, especially in this landscape where morphology
485 was submitted to recent and significant changes. These results have important implications for
486 the modelling of tillage erosion and to better quantify and determine the spatial patterns of
487 soil redistribution processes across cultivated areas in a changing environment. This is of
488 particular interest to improve our knowledge and prediction of patterns of soil physical
489 parameters, as carbon storage or water content, particularly sensitive to surface erosion and
490 landscape structuration.

491

492 **Acknowledgements**

493 This project was funded by ANR (Agence Nationale de la Recherche) in the framework of the
494 LANDSOIL project (ANR-08-VULN-006). The authors would like to gratefully thank Jean-
495 Paul Bakyono and Isabel Pene-Galland for their role on field data collection and sample

496 preparation. This paper was much improved thanks to the comments of two anonymous
497 referees. This is LSCE contribution no. X.

498

499 **References**

500

501 Andraski, B.J. and Lowery, B., 1992. Erosion Effects on Soil Water Storage, Plant Water
502 Uptake, and Corn Growth. *Soil Science Society of America Journal* 56(6), 1911-1919.

503

504 Baudry, J., Burel, F., 1984. "Remembrement": Landscape consolidation in France. *Landscape*
505 *Planning* 11, 235-241.

506

507 Boardman, J., Poesen, J., 2006. Soil erosion in Europe: major processes, causes and
508 consequences. In: J. Boardman and J. Poesen (Editors), *Soil erosion in Europe*. Wiley,
509 Chichester, pp. 479-489.

510

511 Berger, G., Kaechele, H. and Pfeffer, H., 2006. The greening of the European common
512 agricultural policy by linking the European-wide obligation of set-aside with voluntary agri-
513 environmental measures on a regional scale. *Environmental Science & Policy* 9(6), 509-524.

514

515 Beven, K. and Binley, A., 1992. The Future Of Distributed Models – Model Calibration And
516 Uncertainty Prediction. *Hydrological Processes* 6(3), 279-298.

517

518 Boardman, J., Ligneau, L., de Roo, A., Vandaele, K., 1994. Flooding of property by runoff
519 from agricultural land in northwestern Europe. *Geomorphology* 10, 183-196.

520

521 Bollinne, A., 1971. Les rideaux en Hesbaye gembloutoise - Etude morphologique et
522 sédimentologique. *Bulletin de la Société géographique de Liège* 7, 61-67.

523

524 Boutin, D., Froger, D., Rassineux, J., 1990. Feuille Loudun (1724-1624), Carte des sols du
525 Département de la Vienne et de la région Centre au 1:50000, Chambre d'Agriculture de la
526 Vienne - IGN - INRA.

527

528 Callot, H.J., 1980. La plaine d'Alsace. Modelé agraire et parcellaire. Université de Nancy II,
529 France.

530

531 Cambrai, R.S., Playford, K., Carpenter, R.C., 1989. Radioactive fallout in air and rain: results
532 to the end of 1988. UK Atomic Energy Authority Report AERE-R 10155, HMSO.

533

534 Caubel, V., Grimaldi, C., Merot, P., Grimaldi, M., 2003. Influence of a hedge surrounding
535 bottomland on seasonal soil-water movement. *Hydrological Processes* 17, 1811-1821.

536

537 Chaplot, V., Le Bissonnais, Y., 2003. Runoff features for interrill erosion at different rainfall
538 intensities, slope lengths, and gradients in agricultural loessial hillslope. *Soil Science Society*
539 *of America Journal* 67(3), 844-851.

540

541 Chartin, C., 2011. Effet de l'évolution du parcellaire agricole sur la redistribution des sols et
542 la morphologie des versants cultivés – exemple du Bassin parisien. Université de Tours,
543 France, 322 pp.
544

545 Crecente, R., Alvarez, C., Fra, U. 2002. Economic, social and environmental impact of land
546 consolidation in Galicia. *Land Use Policy* (19), 135-147.
547

548 Chartin, C., Bourennane H., Salvador-Blanes, S., Hirschberger, F., Macaire, J.-J., 2011.
549 Classification and mapping of anthropogenic landforms on cultivated hillslopes using DEMs
550 and soil thickness data — Example from the SW Parisian Basin, France. *Geomorphology* 135,
551 8-20.
552

553 Dabney, S.M., Liu, Z., Lane, M., Douglas, J., Zhu, J., Flanagan, D.C., 1999. Landscape
554 benching from tillage erosion between grass hedges. *Soil & Tillage Research* 51, 219-231.
555

556 De Alba, S., 2003. Simulating long-term soil redistribution generated by different patterns of
557 mouldboard ploughing in landscapes of complex topography. *Soil and Tillage Research* 71,
558 71–86.
559

560 De Alba, S., Lindstrom, M.J., Schumacher, T.E., Malo, D.D., 2004. Soil landscape evolution
561 due to soil redistribution by tillage: new model of soil catena evolution in agricultural
562 landscapes. *Catena* 58, 77-100.
563

564 Delmas, M., Pak, L.T., Cerdan, O., Souchère, V., Le Bissonnais, Y., Couturier, A, Sore, L.,
565 2012. Erosion and sediment budget across scale: A case study in a catchment of the European
566 loess belt. *Journal of Hydrology* 420, 255-263.
567

568 Desmet, P.J.J., Govers, G., 1995. GIS-based simulation of erosion and deposition patterns in
569 an agricultural landscape: a comparison of model results with soil map information. *Catena* 25,
570 389-401.
571

572 Desmet, P.J.J., Govers, G., 1997. Two-dimensional modelling of the within-field variation in
573 rill and gully geometry and location related to topography. *Catena* 29, 283-306.
574

575 Evrard, O., Bielders, C.L., Vandaele, K., Van Wesemael, B., 2007a. Spatial and temporal
576 variation of muddy floods in central Belgium, off-site impacts and potential control measures.
577 *Catena* 70, 443-454.
578

579 Evrard, O., Persoons, E., Vandaele, K., van Wesemael, B., 2007b. Effectiveness of erosion
580 mitigation measures to prevent muddy floods: A case study in the Belgian loam belt.
581 *Agriculture, Ecosystems & Environment* 118, 149-158.
582

583 Evrard, O., Vandaele, K., van Wesemael, B., Bielders, C.L, 2008. A grassed waterway and
584 earthen dams to control muddy floods from a cultivated catchment of the Belgian loess belt.
585 *Geomorphology* 100, 419-428.
586

587 Evrard, O., Nord, G., Cerdan, O., Souchère, V., Le Bissonnais, Y., Bonté, P., 2010. Modelling
588 the impact of land use change and rainfall seasonality on sediment export from an agricultural
589 catchment of the northwestern European loess belt. *Agriculture, ecosystems and environment*
590 138, 83-94.

591
592 FAO, 1998. World reference base for soil resources. Food and Agriculture Organization of
593 the United Nations. World Soil Resources Report No 84, FAO, Rome.
594
595 Follain, S., Minasny, B., McBratney, A.B., Walter, C., 2006. Simulation of soil thickness
596 evolution in a complex agricultural landscape at fine spatial and temporal scales. *Geoderma*
597 133, 71-86.
598
599 Forman, R.T.T., Alexander, L.E., 1998. Roads and major ecological effects. *Annual Review*
600 *of Ecology and Systematics* 29, 207-231.
601
602 Foster, G.R., 1986. Understanding ephemeral gully erosion. In: B.i.A. National Research
603 Council (Editor), *Soil conservation: Assesing the national research inventory*. National
604 Academy Press, Washington, pp. 90-118.
605
606 Fourmont, A., 2001. Analyse de l'évolution subactuelle des banquettes colluviales
607 anthropiques par la méthode du Césium-137. Influence sur le bilan sédimentaire du bassin du
608 Quincampoix (Sud-ouest du Bassin Parisien, France), Rapport de stage de DEA, Université
609 de Tours, France, pp. 40.
610
611 Govers, G., Lobb, D.A., Quine, T.A., 1999. Tillage erosion and translocation: emergence of a
612 new paradigm in soil erosion research. *Soil & Tillage Research* 51, 167-174.
613
614 Govers, G., Quine, T.A., Desmet, P.J.J., Walling, D.E., 1996. The relative contribution of soil
615 tillage and overland flow erosion to soil redistribution on agricultural land. *Earth Surface*
616 *Processes and Landforms* 21, 929-946.
617
618 Govers, G., Vandaele, K., Desmet, P.J.J., Poesen, J., Bunte, K., 1994. The role of tillage in
619 soil redistribution on hillslopes. *European Journal of Soil Science* 45, 469-478.
620
621 Hooke, D., 1988. Cosmogenic nuclides, topography, and the spatial variation of soil depth.
622 *Geografiska Annaler* 70 B(1), 123-131.
623
624 Houben, P., 2008. Scale linkage and contingency effects of field-scale and hillslope-scale
625 controls of long-term soil erosion: anthropogeomorphic sediment flux in agricultural loess
626 watersheds of Southern Germany. *Geomorphology* 101, 172-191.
627
628 Kachanovski, R. G., de Jong, E., 1984. Predicting the temporal relationship between soil
629 Cesium-137 and erosion rate. *Journal of Environmental Quality* 13(2), 301-304.
630
631 Knapen, A., Poesen, J., Govers, G., De Baets, S., 2008. The effect of conservation tillage on
632 runoff erosivity and soil erodibility during concentrated flow. *Hydrological Processes* 22,
633 1497-1508.
634
635 Leturcq, S., 2008. Fonction et devenir d'un réseau invisible: les crêtes de labour dans les
636 terroirs beaucerons (XIVe-XXe siècles), COST du Mans. Marqueurs des paysages et
637 systèmes socio-économiques. R.Compatangelo-Soussignan, J.R.Bertrand, J.Chapman, P.Y.
638 Laffont, Rennes (France), pp. 163-174.
639

640 Lindstrom, M.J., Nelson, W.W., Schumacher, T.E., 1992. Quantifying tillage erosion rates
641 due to moldboard plowing. *Soil & Tillage Research* 24, 243-255.
642
643 Lindstrom, M.J., Nelson, W.W., Schumacher, T.E., Lemme, G.D., 1990. Soil movement by
644 tillage as affected by slope. *Soil & Tillage Research* 17, 255-264.
645
646 Montgomery, J.A., McCool, D.K., Busacca, A.J., Frazier, B.E., 1999. Quantifying tillage
647 translocation and deposition rates due to moldboard plowing in the Palouse region of the
648 Pacific Northwest, USA. *Soil & Tillage Research* 51, 175-187.
649
650 Niroula, G.S., Thapa, G.B. 2005. Impacts and causes of land fragmentation, and lessons
651 learned from land consolidation in South Asia. *Land use Policy* 22, 358-372.
652
653 Papendick, R.I., Miller, D.E., 1977. Conservation tillage in Pacific Northwest. *Journal of Soil
654 and Water Conservation* 32, 49-56.
655
656 Papiernick, S.K., Schumacher, T.E., Lobb, D.A., Lindstrom, M.J., Lieser, M.L., Eynard, A.,
657 Schumacher, J.A., 2009. Soil properties and productivity as affected by topsoil movement
658 within an eroded landform. *Soil & Tillage Research* 102, 67-77.
659
660 Pimentel, D., Harvey, C., Resosudarmo, P., Sinclair, K., Kurz, D., McNair, M., Crist, S.,
661 Shpritz, L., Fitton, L., Saffouri, R., Blair, R. 1995. Environmental and economic costs of soil
662 erosion and conservation benefits. *Science* 267(5201), 1117-1123.
663
664 Poesen, J., 1984. The influence of slope gradient on infiltration rate and Hortonian overland
665 flow volume. *Z. Geomorphol., N.F. Suppl.-Bd.* 49, 117-131.
666
667 Quine, T.A., 1995. Estimation of erosion rates from caesium-137 data: the calibration
668 question. In: I.D.L. Webster, A.M. Gurnell and B.W. Webb (Editors), *Sediment and Water
669 Quality in River Catchments*. John Wiley & Sons, Chicester, pp. 307-329.
670
671 Quine, T.A., Govers, G., Walling, D.E., Zhang, X., Desmet, P., Zhang, Y., Vandaele, K.,
672 1997. Erosion processes and landform evolution on agricultural land - new perspectives from
673 caesium-137 measurements and topographic-based erosion modelling. *Earth Surface
674 Processes and Landforms* 22, 799-816.
675
676 Ritchie, J.C., McCarty, G.W., 2003. Using ¹³⁷Cesium to understand soil carbon redistribution
677 on agricultural watersheds. *Soil and tillage Research* 69, 45-51.
678
679 Ritchie, J.C., McHenry, J.R., 1990. Application of radioactive fallout Cesium-137 for
680 measuring soil erosion and sediment accumulation rates and patterns: a review. *Journal of
681 Environmental Quality* 19, 215-233.
682
683 Rogowski, A.S., Tamura, T., 1965. Movement of ¹³⁷Cs by runoff, erosion and infiltration on
684 the alluvial Captina silt loam. *Health Physics* 11(12), 1333-1340.
685
686 Salvador-Blanes, S., Cornu, S., Couturier, A., King, D., Macaire, J.-J., 2006. Morphological
687 and geochemical properties of soil accumulated in hedge-induced terraces in the Massif
688 Central, France. *Soil and Tillage Research* 85, 62-77.
689

690 Sutherland, R.A., 1992. Caesium-137 estimates of erosion in agricultural areas. *Hydrological*
691 *Processes* 6, 215-225.
692

693 Szilassi, P., Jordan, G., Van Rompaey, A., Csillag, G., 2006. Impacts of historical land use
694 changes on erosion and agricultural soil properties in the Kali Basin at the Lake Balaton,
695 Hungary. *Catena* 68, 96-108.
696

697 Van Dijk, P.M., Auzet, A.-V., Lemmel, M., 2005. Rapid assessment of field erosion and
698 sediment transport pathways in cultivated catchments after heavy rainfall events. *Earth*
699 *Surface Processes and Landforms* 30(2), 169-182.
700

701 Van Dijk, P.M., Kwaad, F.J.P.M., Klapwijk, M., 1996. Retention of water and sediment by
702 grass strips. *Hydrological Processes* 10, 1069-1080.
703

704 Van Huylenbroeck, G., Castro Coelho, J., Pinto, P.A. 1996. Evaluation of Land Consolidation
705 Projects (LCPs): A Multidisciplinary Approach. *Journal of Rural Studies* 12(3), 297-310.
706

707 Van Muysen, W., Govers, G., Bergkamp, G., Roxo, M., Poesen, J., 1999. Measurement and
708 modelling of the effects of initial soil conditions and slope gradient on soil translocation by
709 tillage. *Soil & Tillage Research* 51, 303-316.
710

711 Van Oost, K., Govers, G., De Alba, S., Quine, T.A. 2006. Tillage erosion: a review of
712 controlling factors and implications for soil quality. *Progress in Physical geography* 30(4),
713 443-466.
714

715 Van Oost, K., Govers, G., Desmet, P.J.J., 2000. Evaluating the effects of changes in landscape
716 structure on soil erosion by water and tillage. *Landscape Ecology* 15, 577-589.
717

718 Van Oost, K., Govers, G., Van Muysen, W., 2003. A process-based model for Caesium-137
719 derived erosion rates on agricultural land: an integrated spatial approach. *Earth Surface*
720 *Processes and Landforms* 28, 187-207.
721

722 Van Rompaey, A.J.J., Verstraeten, G., Van Oost, K., Govers, G., Poesen, J., 2001. Modelling
723 mean annual sediment yield using a distributed approach. *Earth Surface Processes and*
724 *Landforms* 26(11), 1221-1236.
725

726 Vitikainen, A., 2004. An overview of land consolidation in Europe. *Nordic Journal of*
727 *Surveying and Real Estate Research* 1, 25-44.
728

729 Walling, D.E., Quine, T.A., 1992. The use of Caesium-137 measurements in soil erosion
730 surveys, Erosion and sediment transport monitoring programmes in river basins. IAHS, Oslo,
731 pp. 143-152.
732

733 Wemple, B.C., Jones, J.A., Grant, G.E., 1996. Channel network extension by logging roads in
734 two basins, Western Cascades, Oregon. *Water Resources Bulletin* 32, 1195-1207.
735

736 Zadora-Rio, E., 1991. Les terroirs médiévaux dans le Nord-Ouest de l'Europe, Pour une
737 Archéologie agraire. J. Guilaine, Paris, pp. 165-192.

Table 1. Values of parameters and coefficients input in the model application.

Parameter / coefficient	Related to Equation	Values	
a (-)	(3)	1.45	
b (-)	(3)	0.75	
d (-)	(4)	0.8	
		Minimum	Maximum
k_1 (-)	(3)	0	0.40
k_2 (m)	(5)	20	220
k_3 (Mg.m ⁻¹ .yr ⁻¹)	(6)	300	1000

Table 2. Simulated soil redistribution rates for the whole study area for the period 1954-2009. P5 and P95 are the 5th and 95th percentile simulation limits, respectively, and M the median.

	Mean erosion (Mg.ha ⁻¹ .yr ⁻¹)			Mean deposition (Mg.ha ⁻¹ .yr ⁻¹)		
	P5	M	P95	P5	M	P95
Water	-0.69	-0.20	-0.13	0.07	0.13	0.24
Tillage	-4.55	-4.50	-4.46	4.47	4.50	4.55

Table 3. Results of the conversion model applications to “Total” and “Infield” datasets.

Dataset	Elevation inputs	R ²	Mean erosion (Mg.ha ⁻¹ .yr ⁻¹)	Mean deposition (Mg.ha ⁻¹ .yr ⁻¹)	Implication of Tillage (%)
Total	LIDAR	0.20	-4.70	4.63	~ 98
Infield		0.42	-5.82	5.77	~ 98

Fig. 1. Location of the study area.

Fig. 2. Reconstruction of the field borders in 1945, 1959 and 2009.

Fig. 3. Geometrical characteristics of the two types of anthropogenic landforms, and the associated soils: (a) and (c) provide a picture and a cross-section of a lynchet; (b) and (d) provide a picture and a cross-section of an undulation.

Fig. 4. ^{137}Cs sampling schemes. (a) Sampling in the whole study area. (b) Zoom on samples to give details on lynchet L1.

Fig. 5. Vertical distribution of ^{137}Cs in: (a) mean reference profile of Seuilly, (b) profile V-8 and (c) profile IV-1a.

Fig. 6. ^{137}Cs residuals measured in the study area with slope gradient contours.

Fig. 7. ^{137}Cs residuals measured along a topographic cross-section within lynchet L1 (transect IV).

Fig. 8. Model outputs overlaid on an isometric projection of the study area topography: (a) simulated ^{137}Cs inventories, (b) simulated soil redistribution rates by tillage erosion, and (c) simulated soil redistribution rates by water erosion.

Fig. 9. Median simulated ^{137}Cs inventories plotted against observed ^{137}Cs inventories. Black line is the 1:1 line and grey lines correspond to the ^{137}Cs reference inventory (i.e., 1367 Bq.m⁻²).

Fig. 10. Spatial distribution of a) simulation errors and b) simulated ^{137}Cs residuals in the study field.

Fig. 11. Median simulated ^{137}Cs inventories, based on the “infield dataset”, plotted against observed ^{137}Cs inventories. Black line is the 1:1 line and grey lines correspond to the ^{137}Cs reference inventory (i.e., 1367 Bq.m⁻²).

Figure
[Click here to download high resolution image](#)

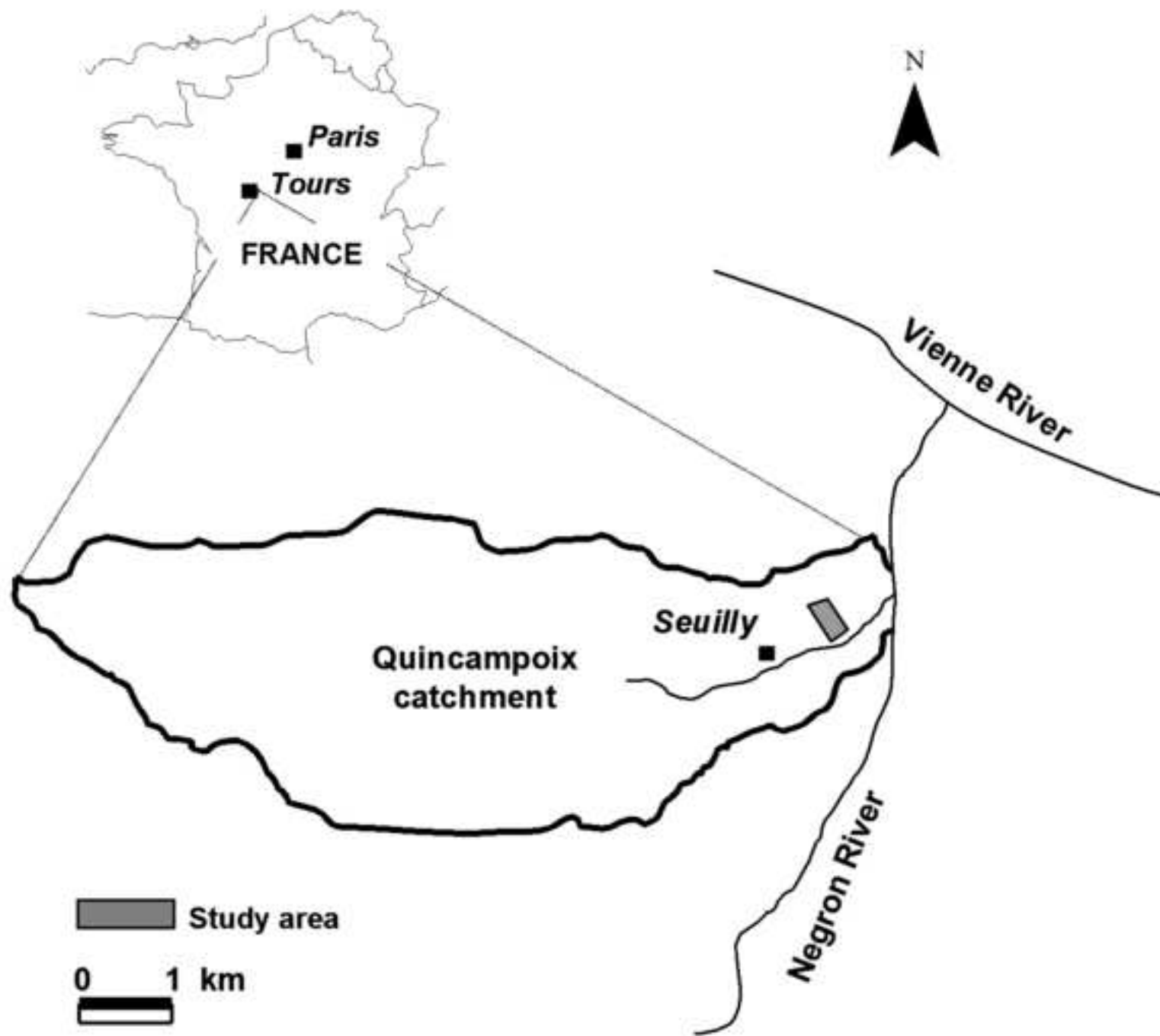
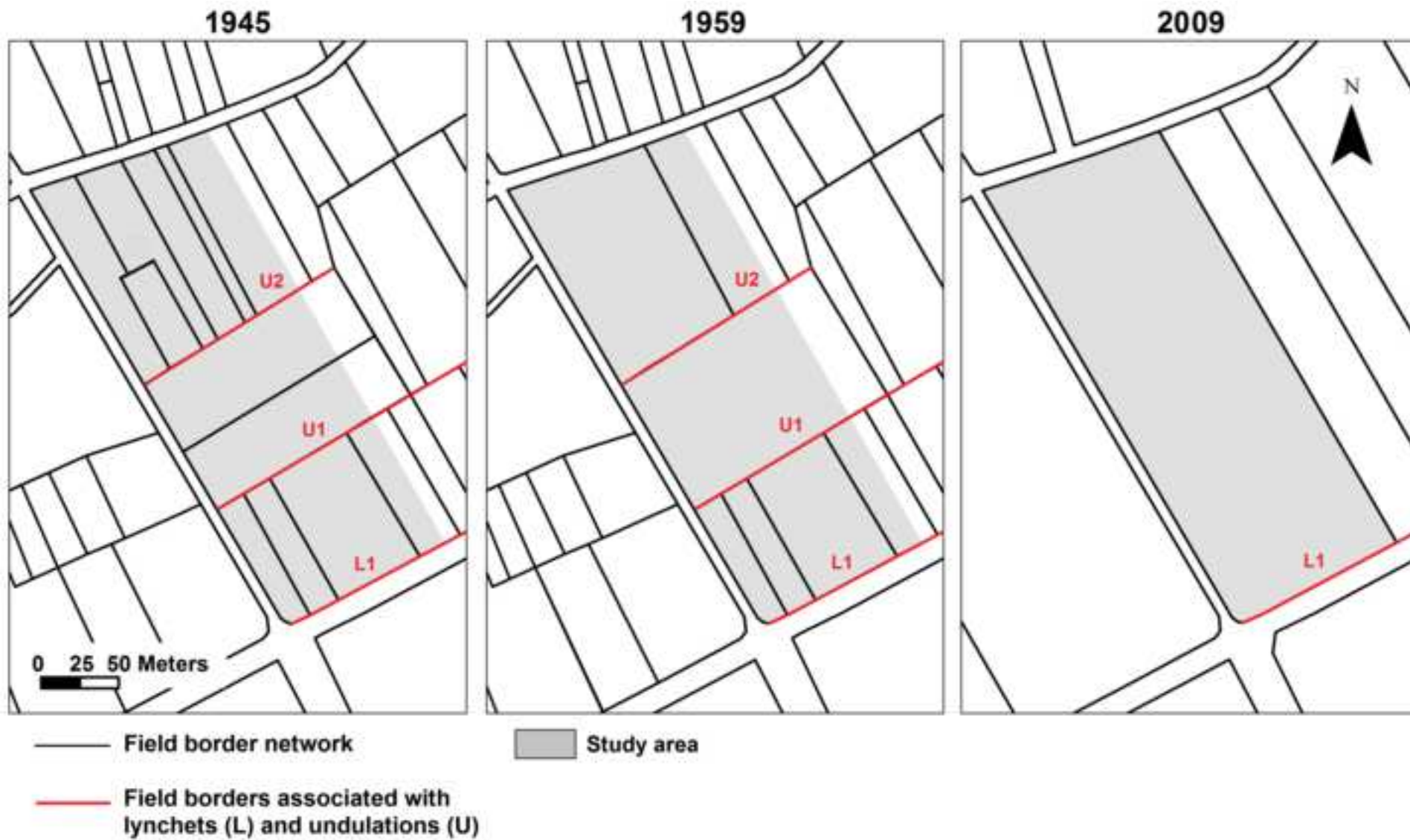


Figure
[Click here to download high resolution image](#)



Figure

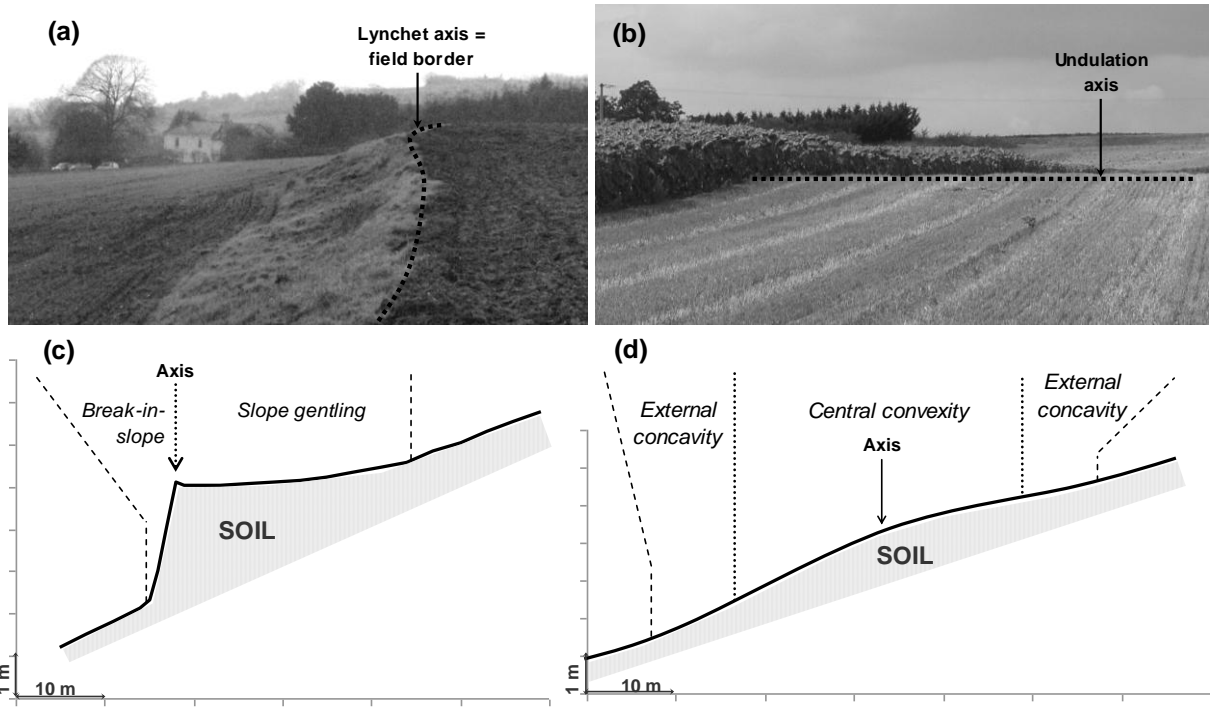
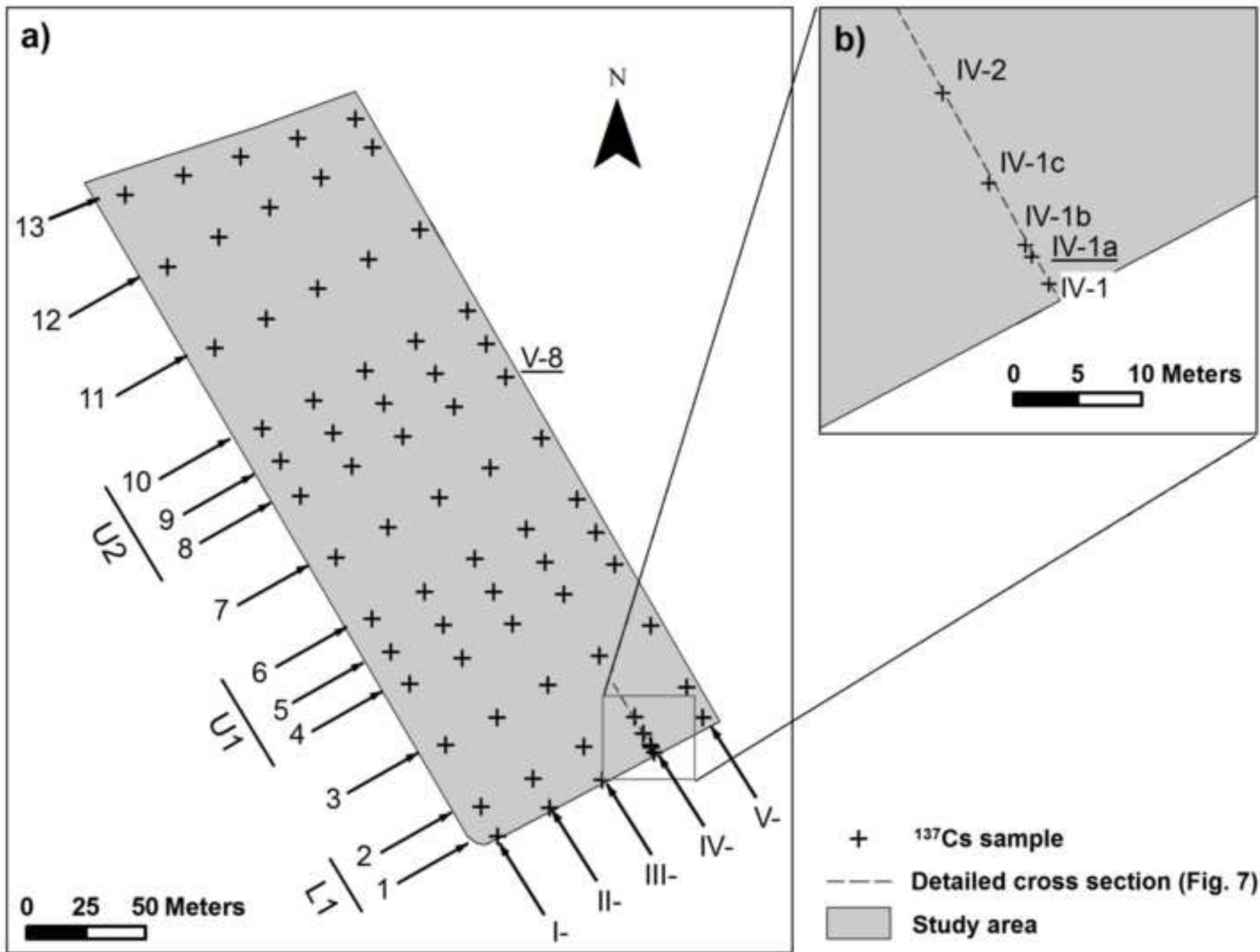
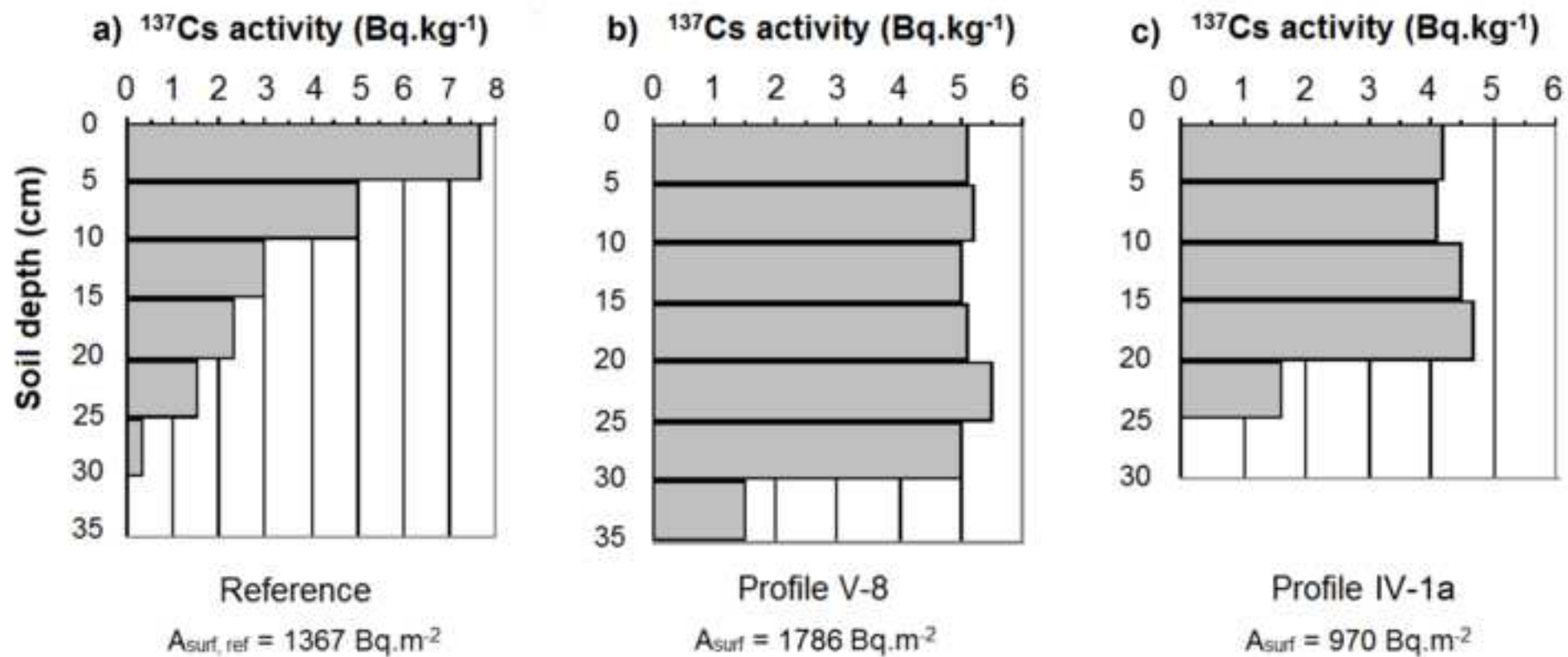


Figure
[Click here to download high resolution image](#)





Figure

[Click here to download high resolution image](#)

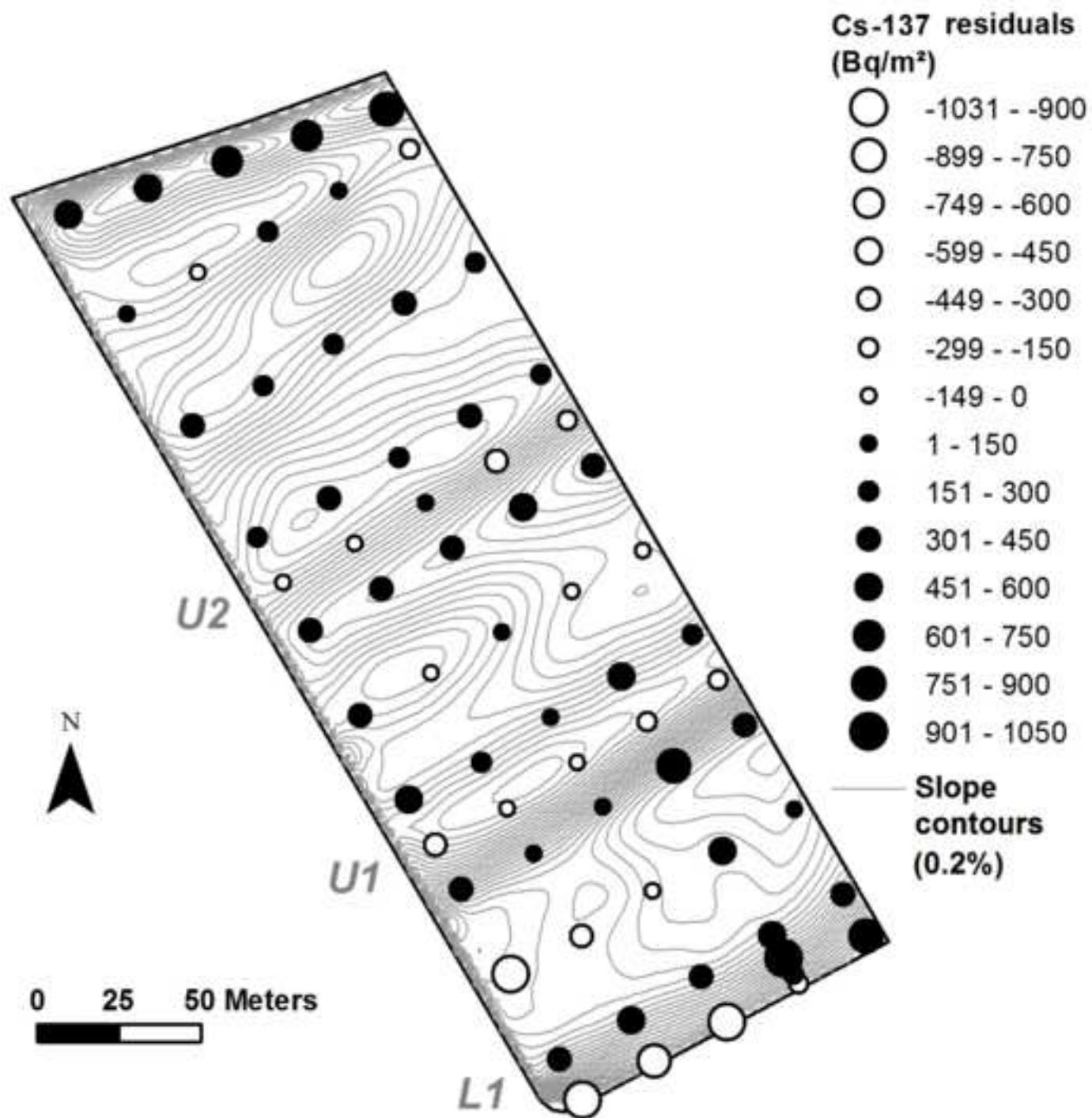
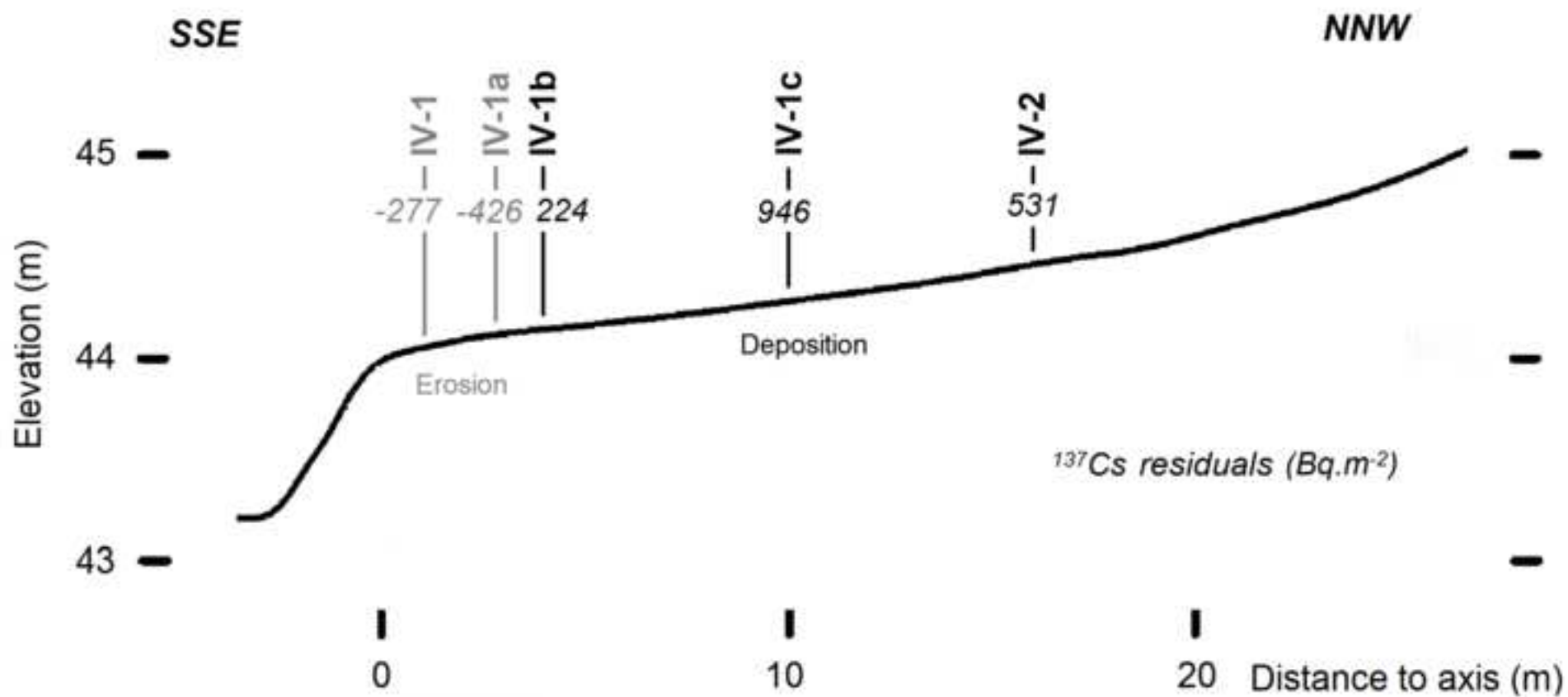


Figure
[Click here to download high resolution image](#)



Figure

[Click here to download high resolution image](#)

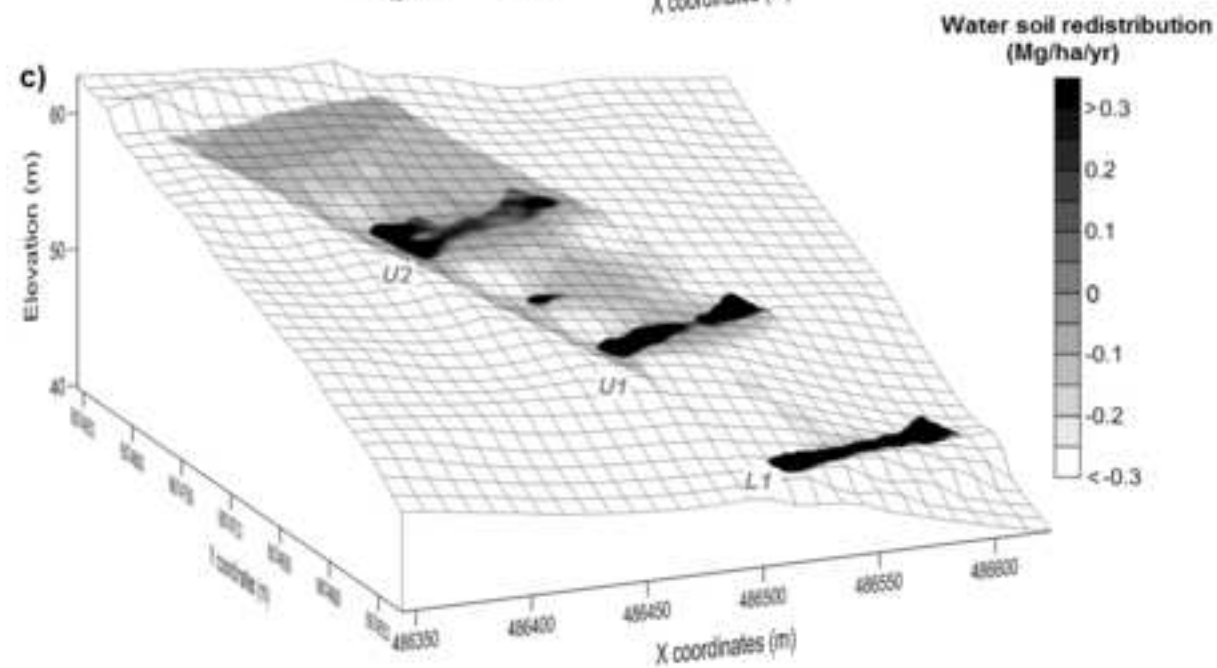
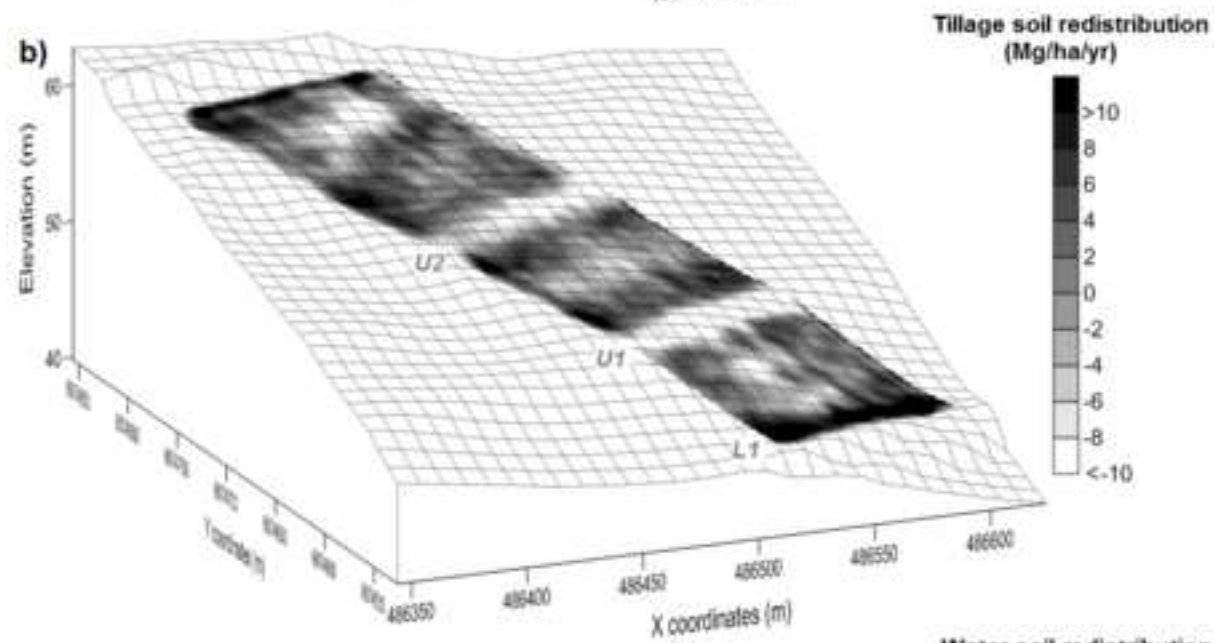
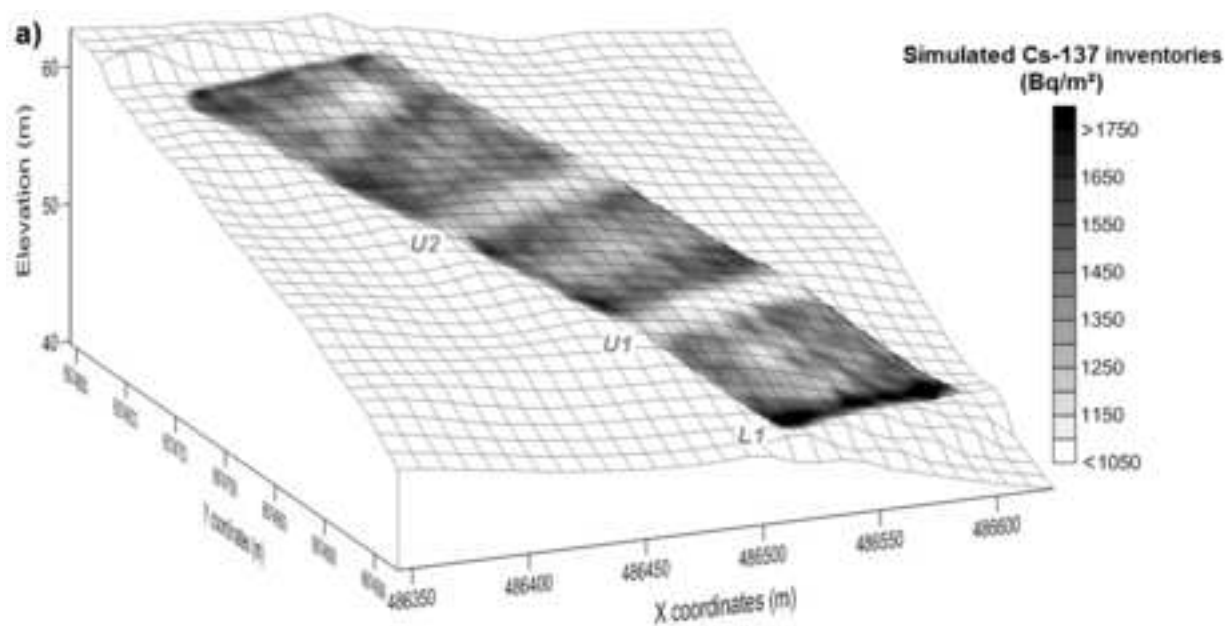


Figure
[Click here to download high resolution image](#)

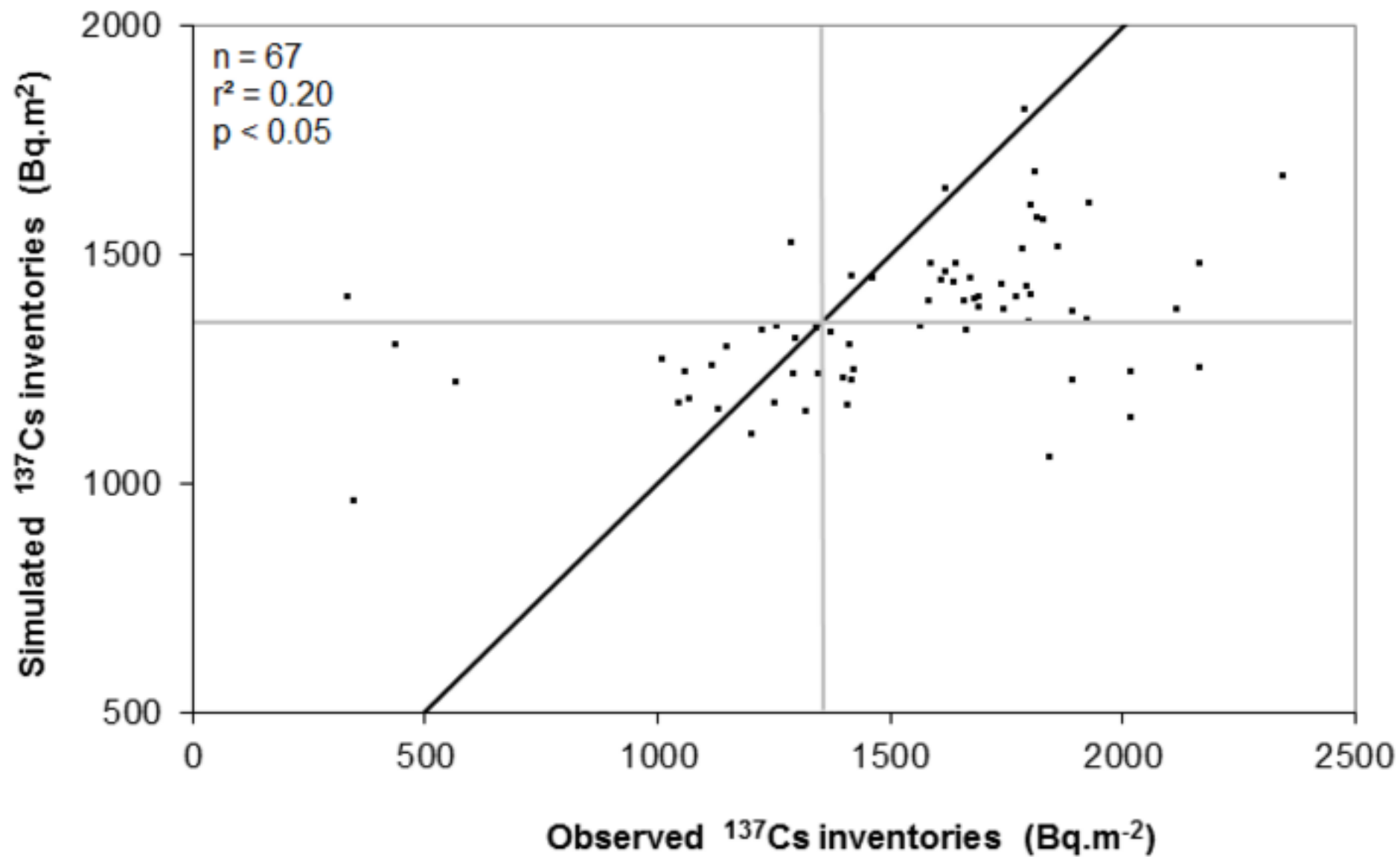


Figure
[Click here to download high resolution image](#)

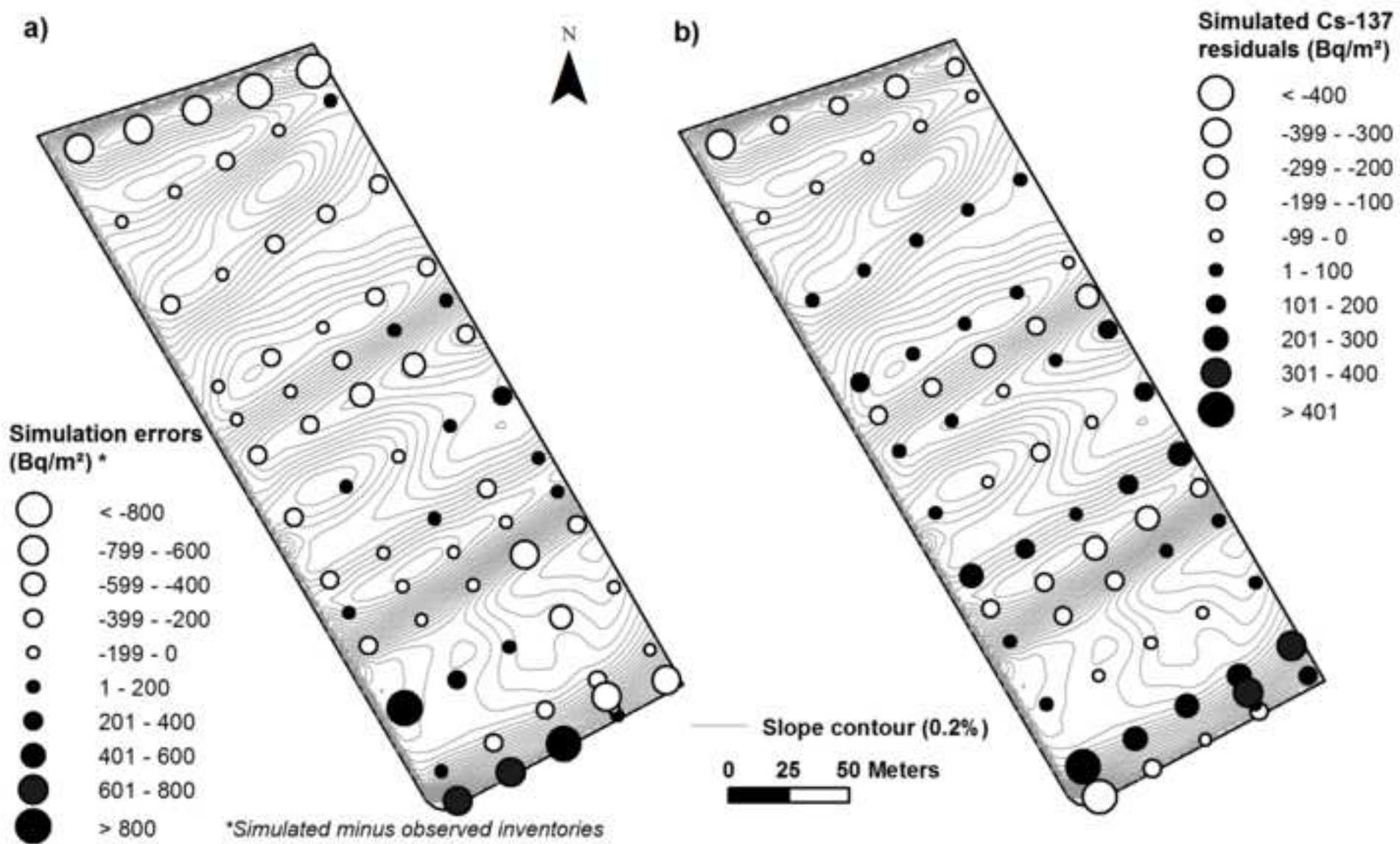


Figure
[Click here to download high resolution image](#)

