

24 land uses since the soil remained unsaturated during this period as a consequence of low
25 rainfall intensities and soil surface roughness. Monthly values for total detachment were
26 highest in barley fields, reaching a maximum of 17.2 and 16.9 Mg ha⁻¹ in September and
27 October. The mean annual detachment rates for barley, pastures and recently and old
28 abandoned fields were 81.1, 0.8, 61.8 and 22.3 Mg ha⁻¹, respectively. The splash and runoff
29 detachment rates of the RMMF model appeared to be sensitive to land cover factors, rainfall
30 intensity and soil micro-topography, thus it is a better model for assessing soil detachment for
31 various land uses. The comparison of erosion rates between the ¹³⁷Cs and the MMF and
32 RMMF models shows that the models predict lower erosion rates due to the low estimated
33 rates of the runoff transport capacity. However, the estimated and measured rates are in close
34 agreement and are under the limit of the tolerable soil loss for soils under Mediterranean
35 conditions.

36

37 Keywords: Splash Detachment; Runoff Detachment; Rainfed crop; MMF model; RMMF
38 model; Soil erosion; Spanish Pyrenees.

39

40 **1. Introduction**

41 The detachment of soil particles from the impact of raindrops is the first stage in the erosion
42 process and is the primary cause of erosion on short, steep slopes (Wu et al., 1996).
43 Understanding the factors involved in splash and runoff detachment is needed to gain a
44 greater understanding of the onset of soil erosion.

45 Intense convective storms with high rainfall intensities (rainfall rates > 50 mm h⁻¹) are
46 frequent during the summer in the south-central Pyrenees (Sánchez et al., 2003). In Spain,
47 Ayala-Carcedo and Iglesias (2000) showed that an increase in the number of heavy storms
48 changed the temporal pattern of sediment load in streams. Thus storms and rainfall promote

49 the detachment of soil particles and thus more information on this process, which affects soil
50 productivity and sustainability, is urgently required. Moreover, Nearing et al. (2004) predict
51 that global warming will lead to a higher frequency of extreme weather conditions.

52 Soil degradation, caused by intensive agriculture, deforestation and land abandonment have
53 led to increased runoff and soil erosion in the Central Pyrenees (Navas et al., 2007). Rainfed
54 crops, such as cereals, cover important areas in the drier parts of Mediterranean countries and
55 occupy mountainous areas. Aggressive rainfalls on these slopping landscapes contribute to
56 erosion of cultivated lands. Furthermore, agriculture in semiarid areas suffers from strong
57 annual variations in crop yields that directly depend on rainfall volume and distribution and
58 soil quality during the growing season.

59 In northeastern areas of Spain, agriculture has been intensively developed over the last
60 centuries through severe deforestation. Important socio-economic changes in the middle of
61 the 20th Century led to the rapid abandonment of land. Deforestation in exchange for long-
62 term cultivation has led to the deterioration of soil quality in many diverse environments
63 worldwide (Lu et al., 2002). In addition, the agrarian policy of the European Union has
64 encouraged the abandonment of marginal, unproductive and degraded lands. During the peak
65 period of land abandonment, rivers and other waterways had high amounts of sediment and
66 this coincided with higher flood discharges (Valero-Garcés et al., 1999). In this region, severe
67 soil losses have been reported in abandoned lands (Navas et al., 2005) and, as a consequence,
68 the upper soil horizons have been completely eroded. This has contributed to changes in the
69 surrounding environment and increased the vulnerability of agrosystems because of
70 progressive soil loss (Sanchez-Marañón et al., 2002).

71 In general, soil degradation in areas of changing land use is relatively well studied (Machín
72 and Navas, 1995). Studies have described the processes that occur in abandoned fields and
73 their effects on infiltration, runoff, and erosion (Lasanta et al., 1995, Navas et al., 1997).

74 However, no information is available on the monthly splash and runoff detachment of soil
75 particles in agricultural fields in the Pyrenees. Conservation of soil and improved
76 management practices can be achieved with a detailed study of the risk factors involved in
77 water erosion.

78 In this study, two empirical models were used to estimate monthly detachment rates from
79 fields with different land uses in order to identify the land use that is more prone to soil
80 detachment. The Morgan, Morgan and Finney (MMF) empirical model estimates soil particle
81 detachment caused by raindrop impact. The more complex Revised Morgan, Morgan and
82 Finney (RMMF) model estimates soil particle detachment caused by both raindrop impact and
83 runoff. These models were modified to account for soil infiltration properties and surface
84 micro-topography. A comparison of each model might identify the most accurate approach
85 for revealing land uses which are most susceptible to erosion. These results may contribute to
86 the development of guidelines for soil conservation in these rapidly changing agro-systems.

87

88 **2. Materials and methods**

89 2.1 Study area

90 In this study, 41 fields under four different land uses were chosen as representatives of the
91 rainfed agro-systems in the south-central Pyrenees, Spain. The fields were located between
92 690 and 830 m above sea level in the “Lagos de Estaña” area of Huesca (Fig. 1a). The area
93 has a Mediterranean continental climate that includes two periods of intensive rainfall, one in
94 spring (April and May) and a second in autumn (September and October). Mean annual
95 rainfall is 595 mm (estimated from the period 1993-2006) with an interannual oscillation of
96 404 mm in 2004 and 876 mm in 1996. The mean annual temperature is 12.8 °C with the
97 coldest month being January (mean 4.2 °C) and the hottest month being July (mean 21.6 °C).
98 López-Vicente et al. (2005) calculated monthly rainfall and temperature using data from the

99 Benabarre and Camporrélls weather stations for the period 1993-2004; weather data from
100 2005 and 2006 were also included in this study.

101 From the 41 fields, twelve were old abandoned fields (6.1 ha; more than 50 years ago), nine
102 were more recently abandoned fields (5.7 ha; less than 20 years ago), 10 were cultivated with
103 winter barley (12.8 ha), and ten were used for pasture (4.3 ha) (Fig. 1b). The old abandoned
104 fields were covered with mature shrubs, especially *Buxus sempervirens*, and young evergreen
105 oaks (*Quercus rotundifolia*), deciduous oaks (*Quercus faginea*) and kermes oaks (*Quercus*
106 *coccifera*). Recently abandoned fields were sparsely covered with shrubs of *Buxus*
107 *sempervirens*, *Juniperus oxicedrus* and sub-Mediterranean plants.

108 Soils were identified as Calcisols, Leptosols, haplic Regosols, gypsic Regosols, Gleysols and
109 Gypsisols (Machín, personal communication, 2007). López-Vicente et al. (2005) measured
110 the saturated hydraulic conductivity and matrix flux potential for each type of soil (Table 1).

111

112 2.2 The MMF and RMMF empirical erosion models

113 The MMF soil erosion model, which was proposed as a simple empirical model for predicting
114 annual soil loss (Morgan et al., 1984), has the advantage of being easy to understand and data
115 are readily available. The MMF model has been used in different areas of the world and has
116 been the basis for other models such as the SEMMED model (Soil Erosion Model for
117 Mediterranean Areas) proposed by De Jong et al. (1999) and used in southern France and
118 Italy. The RMMF model of Morgan (2001) was validated using erosion plot data from 16
119 countries (Vigiak et al., 2006). Table 2 describes the input parameters of the MMF and
120 RMMF models for assessing the splash and runoff detachment rates.

121

122 *Estimation of rainfall energy and runoff*

123 The energy of the rainfall in the MMF model (E ; J m^{-2}) is based upon the kinetic energy (KE ;
124 $\text{J m}^{-2} \text{mm}^{-1}$) and the amount of the annual rainfall (R ; mm) given by:

$$125 \quad E = R KE \quad (1)$$

126 In the RMMF model the procedure for calculating rainfall energy was revised to take into
127 account rainfall partitioning during interception and the energy of the leaf drainage. The
128 effective rainfall (ER ; mm) is computed from the annual total rainfall and the proportion
129 (between 0 and 1) of the rainfall which reaches the ground after allowing for rainfall
130 interception (A).

$$131 \quad ER = R A \quad (2)$$

132 The effective rainfall ER is then separated into rainfall reaching the ground surface as direct
133 throughfall (DT ; mm) and as leaf drainage (LD ; mm). This separation is a direct function of
134 the percentage canopy cover (CC):

$$135 \quad DT = ER - LD \quad (3)$$

$$136 \quad LD = ER CC \quad (4)$$

137 The energy of the direct throughfall [$E(DT)$, J m^{-2}] is determined as a function of rainfall
138 intensity (I , mm h^{-1}) using a typical value for the erosive rainfall of the region. Although the
139 original version of the MMF model used the relationship of Wischmeier and Smith (1978),
140 the enhanced version of the model proposes alternative equations based on local rainfall
141 energy–intensity relationships. In this paper the equation developed by Coutinho and Tomás
142 (1995) in southern Portugal has been selected for calculating the kinetic energy in the MMF
143 and the RMMF models:

$$144 \quad KE = 35.9[1 - 0.56 \exp(-0.034I)] \quad (5)$$

$$145 \quad E(DT) = DT KE \quad (6)$$

146 The energy of the leaf drainage [$E(LD)$; J m^{-2}] is a function of the height of the plant canopy
147 (PH ; m) as proposed by Brandt (1990):

148
$$E(LD) = (15.8 PH^{0.5}) - 5.87 \quad (7)$$

149 The total energy of the effective rainfall (EE ; $J m^{-2}$) is obtained from:

150
$$EE = E(DT) + E(LD) \quad (8)$$

151 The procedure for estimating the runoff per raster cell (Q_i ; mm) is the same for the two
 152 models based on the method proposed by Kirkby (1976) which assumes that runoff occurs
 153 when the daily rainfall exceeds the soil moisture storage capacity (R_C ; mm). The monthly
 154 runoff Q_m is obtained from:

155
$$Q_m = R_m \exp(-R_C/R_0) \quad (9)$$

156
$$R_0 = R/R_n \quad (10)$$

157 where R_0 is the mean rainfall per erosive rain day (mm) and R_n is the annual number of days
 158 with erosive rainfall. Soil moisture storage capacity is estimated as:

159
$$R_C = 1000 MS BD EHD (E_t / E_0)^{0.5} \quad (11)$$

160 where MS is soil moisture content at field capacity (% on weight basis), BD is the bulk
 161 density of the soil ($Mg m^{-3}$), EHD is the effective hydrological depth of the soil (m) and $E_t /$
 162 E_0 is the ratio between actual and potential evapotranspiration. EHD indicates the depth of the
 163 soil within which moisture storage capacity controls the generation of runoff and is a function
 164 of soil type and plant cover which influence the depth and density of roots.

165 The estimated runoff volume in Eq. (9) was modified by accounting for the amount of rainfall
 166 that is necessary to pond the soil (Rp_i , mm) and the maximum surface storage capacity (SS_{max} ,
 167 mm). Hogarth et al. (1991) proposed that time to ponding (Tp , s) has a minimum and a
 168 maximum time and state that the average value can be calculated as:

169
$$\frac{1}{2} \frac{S_m^2}{K_{fs}} \ln \left(\frac{I_m}{I_m - K_{fs}} \right) \leq Tp_m \leq \frac{1}{2} \frac{S_m^2}{I_m - K_{fs}} \quad (12)$$

170
$$S_m = \sqrt{2(\Delta\theta_m)\phi} \quad (13)$$

171
$$\Delta\theta_m = \theta_s - \theta_{0m} \quad (14)$$

172 where S_m ($\text{mm s}^{-0.5}$) is the monthly soil sorptivity, K_{fs} (mm s^{-1}) is the saturated hydraulic
 173 conductivity, I_m (mm s^{-1}) is the monthly rainfall intensity, ϕ is the matrix flux potential (mm^2
 174 s^{-1}) of each soil type and θ_s and θ_{0m} is the volumetric water content at saturation and initial
 175 conditions. The monthly rainfall volume to ponding (Rp_m , mm) was calculated by multiplying
 176 I_m by Tp :

177
$$Rp_m = Tp_m I_m \quad (15)$$

178 The maximum monthly surface storage capacity (SS_{max-m} , mm) was calculated according to
 179 Driessen (1986). This includes surface roughness (RG_m ; mm), slope steepness (S ; degree) and
 180 the surface furrow and ridge angle determined by tillage marks and micro-topography (SIG ;
 181 degree). The effective volume of monthly runoff (Q_{m-eff} , mm) was calculated after the
 182 subtraction of Rp_m and SS_{max-m} from the initial value of monthly runoff per raster cell (Q_m):

183
$$SS_{max-m} = 0.5 RG_m \frac{\sin^2(SIG - S) \cot(SIG + S) + \cot(SIG - S)}{\sin(SIG) 2 \cos(SIG) \cos(S)} \quad (16)$$

184
$$Q_{m-eff} = (Q_m - Rp_m EE_m - SS_{max-m} EE_m) \quad (17)$$

185 where EE_m is the number of erosive events per month m , and takes into account the effect of
 186 the monthly distribution of erosive events along the year. A SIG value of 30° was considered
 187 valid for the study area based on Terzoudi et al. (2007). Surface roughness is the
 188 configuration of the soil caused by the randomly orientated arrangement of soil clods. Tillage
 189 tools can produce random roughness and orientated roughness. In this work the roughness
 190 values for forest areas (random roughness, $RG = 20.3$ mm) and cultivated fields with plough
 191 ($RG = 48.3$ mm) and field cultivator ($RG = 17.8$ mm) were taken from Renard et al. (1997).

192

193 *Splash and runoff detachment rates*

194 The splash detachment rate (F ; kg m^{-2}) in the MMF model is calculated as:

195
$$F = K [E \exp(-aA)]^b 10^{-3} \quad (18)$$

196 where K is the soil detachability index (g J^{-1}), a is a coefficient ($a = 0.05$) and b is an exponent
 197 ($b = 1.0$). The values of a and b in Eq. (18) correspond to those proposed by Quansah (1981)
 198 and used by De Jong et al. (1999). K depends on the particle size distribution of the soil and is
 199 adopted from the MMF model guide (Morgan, 2001; Table 3). In the RMMF model, soil
 200 particle detachment by raindrop impact (F ; Kg m^{-2}) is defined as:

201
$$F = K E E 10^{-3} \quad (19)$$

202 The RMMF model includes a component to assess the effect of runoff on soil detachment (H ;
 203 kg m^{-2}) as a function of soil resistance (Z , kPa^{-1}), runoff (Q_i ; mm) and slope steepness (S ;
 204 radian). Soil detachment from runoff was estimated using the equation proposed by Quansah
 205 (1982) and modified by Morgan (2001):

206
$$H = Z Q_{m-eff}^{1.5} \sin(S)(1 - GC)10^{-3} \quad (20)$$

207
$$Z = \frac{1}{0.5 COH} \quad (21)$$

208 where GC is the amount of ground cover (%) and COH is the cohesion of the soil (kPa). The
 209 GC factor includes crop residue, rocks and other non-erodible material that is in direct contact
 210 with the soil surface. The COH is an important component of the soil's resistance to erosion
 211 based upon soil texture (Table 3).

212 Finally, the soil particle detachment rates by splash and runoff are summed to produce a total
 213 detachment rate. For the fields with the highest detachment rates, a method to validate the
 214 reliability of the predictions was made through an estimation of the transport capacity of the
 215 runoff (TC ; kg m^{-2}) using the following equation:

216
$$TC = C P Q_{m-eff}^d \sin(S)10^{-3} \quad (22)$$

217 where C (–) and P (–) are the cover-management and the support practice factors,
218 respectively, of the Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1997), and
219 d is an exponent equal to 2 (Morgan, 2001).

220 Final soil loss predictions are computed on the basis of the conceptual model of Meyer and
221 Wischmeier (1969) by comparing the rates of total detachment and runoff transport capacity.
222 The lower of the two values per raster cell is assigned as the annual soil loss rate:

$$223 \quad \text{Mean Annual Soil Loss} = \min\{(F + H), TC\} \quad (23)$$

224

225 2.3 Data collection

226 Monthly rainfall values were calculated using daily precipitation values from the Benabarre
227 and Camporrélls weather stations. Intensity of erosive rain was obtained from rainfall data
228 recorded every 15 min at the Canelles Weather Station for the period 1993 – 2006. These
229 weather stations are 10.1, 7.5 and 11 km northwest, south and southeast from the study area,
230 respectively. Erosive storms were distinguished from other events by comparing the amount
231 and intensity of rainfall to thresholds proposed by Renard et al. (1997) in the RUSLE soil
232 erosion guide. Data defined as erosive storms was used to calculate the typical value of the
233 intensity of erosive events (I in Eq. 5) and the mean rainfall per erosive rainday (R_θ in Eq. 9
234 and 10).

235 A total of 54 soil samples were collected from the 41 fields. To determine the textural class of
236 each sample, laser equipment was used and the corresponding values of K (Eqs 18 and 19)
237 and COH (Eq. 21) were estimated based on the model guide (Morgan, 2001). The bulk
238 density, BD (Eq. 11), and soil moisture content at field capacity, MS (Eq. 11), was measured
239 for each sample using a porous ceramic plate in a closed chamber. The volumetric content of
240 water at saturation was calculated for each soil sample and initial conditions were measured in
241 June, August, December and February as representatives of seasonal variations.

242 The values of effective hydrological depth, EHD (Eq. 11), for each land use were calculated
243 using the data of López-Vicente et al. (2005) for each soil type (Table 4). These authors
244 calculated the ratio between actual and potential evapotranspiration (E_t / E_0 in Eq. 11) using
245 the Penman-Monteith and Priestley-Taylor equations for the different land uses (Table 4).

246 The slope steepness parameter (S in Eqs 16, 20 and 22) for each land use (Table 4) was
247 calculated using the slope map derived from an enhanced digital elevation model of the study
248 area (López-Vicente and Navas, 2005) at high spatial resolution (cell size: 5 x 5 m).

249 Rodríguez and Schnabel (1998) cited an average rainfall interception value of 22.5 % for a
250 Mediterranean forest of *Quercus ilex* in the Castanya experimental basin (Montseny, province
251 of Barcelona, NE Spain). Belmonte and Romero (1998) estimated the net rainfall interception
252 at 30.8 % in scrublands of southeastern Spain. These data were adopted for the old and more
253 recently abandoned fields, respectively (Table 4). Reliable data to parameterize pasture
254 species and crops were difficult to find. Eberbach and Pala (2005) obtained a rainfall
255 interception of 14 % for barley fields in northern Syria with a mean annual rainfall of 330 mm
256 during March, April, May and June. Alternatively, a rainfall interception of 3 % for crop
257 residues was estimated by Cook et al. (2006) during the months of July and August. It was
258 assumed that the months of September and October have a value of 0 due to plowing and
259 values for the months of November, December, January and February increase gradually from
260 0 to maximum 14 % until the month of March. Ashby (1999) measured a rainfall interception
261 of 8.33 % in pastures with a mean plant height (PH in Eq. 7) of 0.28 m (Table 4). The height
262 of the plant canopy for barley fields ranged from a minimum of 0 to a maximum of 0.46 m
263 with a mean value of 0.1 m (Renard et al., 1997) (Table 4). The PH parameter of the old and
264 recent abandoned fields (Table 4) was estimated using data from southern France (Rambal et
265 al., 2003).

266 Rodríguez-Calcerrada et al. (2007) measured the percentage of canopy cover at 80.7 % for the
267 Mediterranean forest at Montejo de la Sierra in the Iberian Peninsula, whereas Carreiras et al.
268 (2006) obtained a value of 27.5 % for the open Mediterranean forest and shrubs in a region of
269 southern Portugal. These values were assigned to the old and recently abandoned fields,
270 respectively. The canopy cover for barley fields was 30.42 % (Renard et al., 1997) whereas
271 the value for pastures was 100 % due to the total soil coverage by this type of vegetation. The
272 ground cover values for each land use were obtained from the percentage of coarse fragments
273 calculated by López-Vicente et al. (2006) and percentage of soil surface covered by crop
274 residues (Table 4).

275 The *C-RUSLE* factor, included in the crop cover parameter (*C* in Eq. 22), was calculated by
276 López-Vicente et al. (2005) with the assistance of the *CropSyst 4.04.14* cropping simulator.
277 Corresponding values were very low for the abandoned fields and moderate for cultivated
278 fields (Table 4). The *P-RUSLE* factor, in absence of detailed data, was set to 1.

279

280 **3. Results and discussion**

281 **3.1 Rainfall energy and runoff volume**

282 A total of 74 storm events were recorded with 12 erosive storms (17 %) per year. The mean
283 annual rainfall intensity calculated for the period 1993 – 2006 was 15.1 mm h⁻¹, with
284 September having the highest average at 26.9 mm h⁻¹ (Fig. 2a), and a maximum value of 69.8
285 mm h⁻¹ for one single storm event. Usón and Ramos (2001) observed a mean rainfall intensity
286 of less than 10 mm h⁻¹ in northeastern Spain with a maximum of 103 mm h⁻¹ for one single
287 storm event.

288 The erosive storm events in September and October represented 53.5 % of the total (Fig. 2b).
289 Rainfall intensity also varied seasonally. The most erosive storm events occurred from May to
290 October with a mean intensity of 19.9 mm h⁻¹, whereas the mean value from November to

291 April was 7.4 mm h^{-1} . The mean annual rainfall per erosive rain day (R_0 in Eq. 9) was 47.2
292 mm.

293 After accounting for the effect of the rainfall interception and canopy cover parameters, the
294 volume of direct throughfall rainfall (DT in Eq. 3) was highest for barley fields, except in
295 May and June when the canopy cover parameter for this crop was very high. Moreover, the
296 volume of direct throughfall decreased with the age of abandonment of the fields. Old
297 abandoned fields had higher rainfall interception, canopy cover and plant height, without
298 seasonal variations. Pastures presented a minimum DT of zero, due to total soil coverage of
299 the canopy.

300 In the MMF model, a single monthly value of the rainfall energy for each land use was
301 calculated, whereas in the RMMF model, an individual temporal pattern for the total energy
302 of each land use was determined. The rainfall energy of leaf drainage represented 15.3, 1.7,
303 0.1 and 100 % of the total rainfall energy for old and recently abandoned fields, barley fields
304 and pastures, respectively. Barley fields exhibited the highest energy for direct throughfall
305 and total energy of the effective rainfall, and the lowest energy of leaf drainage. Total rainfall
306 energy decreased with increasing age of abandonment. Pastures gave the minimum value and
307 were more than 300 times lower than the annual value of barley fields. These results are
308 consistent with land uses that have greater canopy cover, percentage of interception, and
309 height of the plant canopy. The MMF model generated an annual value of kinetic energy that
310 was 1.5 times higher than the value generated by the RMMF model for barley fields.

311 The critical value of soil moisture storage (R_C in Eq. 11) was higher in the soils of barley
312 fields (34 mm) compared to old abandoned fields (24 mm). The effective hydrological depth
313 is the most important parameter to control soil moisture storage, however, variability was
314 very high in the soil samples collected in old abandoned fields. The results obtained by
315 Belmonte et al. (1999) in Murcia, Spain, in abandoned fields also agree with the results of the

316 present study. Old abandoned fields had the highest and barley fields the lowest monthly
317 runoff per raster cell (Q_m in Eq. 9). The temporal pattern of monthly runoff (Fig. 3a) was
318 correlated with monthly rainfall (Fig. 2a).

319 The estimated mean volumetric water content at saturation was 48.4 % and the mean
320 volumetric water content at initial conditions in June, August, December and February were
321 15.6, 10.6, 17.7, and 13.1 %, respectively. The values of time to ponding showed that soil did
322 not achieve saturation from December to March regardless of land use because the recorded
323 rainfall intensities were lower than the saturated hydraulic conductivity, in spite of similar
324 values of precipitation for the periods January to March and June to August (Fig. 2a).

325 Due to different K_{fs} values for the different land uses, runoff only took place from May to
326 October in the old abandoned fields, from July to September in the recently abandoned fields,
327 from April to November in barley fields, and from June to October in pastures. However, in
328 the months when rainfall intensity was higher than K_{fs} , the estimated time to ponding was
329 very short. Mean values were 4.5, 8.5, 8.2, and 13.1 s for old and recently abandoned fields,
330 barley fields and pastures, respectively. In the months when I_m is higher than K_{fs} , the
331 calculated rainfall volume to ponding, Rp_i , decreased by 0.1, 0.2, 0.1 and 0.4 % from the
332 initial runoff volume for the old and recently abandoned fields, barley fields and pastures,
333 respectively.

334 The maximum surface storage capacity, SS_{max} , varied with monthly rainfall and the amount of
335 water that remained on the soil surface was 12, 13, 22, and 12 % of the initial runoff volume
336 for old and recently abandoned fields, barley fields and pastures, respectively. The annual
337 volume of effective runoff was only 48, 21, 56, and 37 % of the initial annual runoff for old
338 and recently abandoned fields, barley fields and pastures, respectively. Hence, the combined
339 effect of infiltration properties and soil microtopography significantly reduced the amount of
340 runoff (Fig. 3b).

341

342 3.2 Soil detachment

343 The mean soil detachability index (K in Eqs 18 and 19) and cohesion (COH in Eq. 21) for
344 each land use are quite similar because all soils were silt loam (Fig. 4). Among the different
345 land uses, the MMF model predicted the highest monthly splash detachment rates for barley
346 fields with a total annual rate of $93.8 \text{ Mg ha}^{-1} \text{ y}^{-1}$ and a maximum of 18.1 and 17.8 Mg ha^{-1} in
347 September and October, respectively. The highest splash detachment rates for the period
348 February to June were associated with recently abandoned fields (Fig. 5a). The annual splash
349 detachment was quite similar for recently abandoned fields and pastures with 79.0 and 78.4
350 $\text{Mg ha}^{-1} \text{ y}^{-1}$, respectively. The lowest rates were in February with 1.7 Mg ha^{-1} in the old
351 abandoned fields and 2.7 Mg ha^{-1} in the recently abandoned fields and pastures. Based on the
352 RMMF model, monthly splash detachment rates were highest in barley fields with maximum
353 rates of 17.2 and 16.8 Mg ha^{-1} in September and October, respectively (Fig. 5b). The annual
354 splash detachment rates for barley fields, old and recently abandoned fields and pastures were
355 80.8 , 21.5 , 61.6 and $0.3 \text{ Mg ha}^{-1} \text{ y}^{-1}$, respectively. These values were lower than the annual
356 rate predicted with the MMF model, especially in pastures. In both models, splash detachment
357 rates were negatively correlated with abandonment. The highest splash detachment rates
358 occurred in September and October which were the months with the highest intensity and
359 volume of erosive rain and the lowest soil protection by canopy.

360 Barley and recently abandoned fields had the lowest monthly soil detachment by runoff (H in
361 Eq. 20) with annual rates of 0.23 and $0.28 \text{ Mg ha}^{-1} \text{ y}^{-1}$, respectively. Higher annual
362 detachment rates occurred in pastures and old abandoned fields despite higher values of
363 ground cover with 0.84 and $0.56 \text{ Mg ha}^{-1} \text{ y}^{-1}$, respectively (Fig. 5c). These results may be
364 explained by the higher soil cohesion and saturated hydraulic conductivity and the lower

365 slope steepness in barley fields. Therefore, slope steepness factor, rainfall intensity and
366 infiltration properties are the most important parameters controlling runoff detachment rate.
367 As seen in Fig. 5d, values of total monthly detachment in old and recently abandoned fields
368 and in barley fields are similar to splash detachment rates because of a low percentage of
369 runoff detachment (3.8, 0.5 and 0.3 %, respectively). However, runoff detachment rates
370 represented 68.7 % of total detachment rate in pasture despite this land use showing the
371 lowest total detachment rate with an annual value of $0.8 \text{ Mg ha}^{-1} \text{ y}^{-1}$. The maximum
372 detachment rate occurred in barley fields. Maximum values were 17.2 and 16.9 Mg ha^{-1} in
373 September and October and a total detachment rate was $81.1 \text{ Mg ha}^{-1} \text{ y}^{-1}$. Annual detachment
374 rates in old and recently abandoned fields were 22.3 and $61.8 \text{ Mg ha}^{-1} \text{ y}^{-1}$, respectively.
375 Total detachment rates predicted with the RMMF model are lower than those predicted with
376 the MMF model, especially in pastures. However, both models predicted the same temporal
377 pattern of detachment for the different land uses (Fig. 5a and d). The RMMF model predicted
378 maximum rates in September and October with 28, 29, 42, and 51 % of the annual rates in old
379 and recently abandoned fields, barley fields and pasture, respectively. Both models also
380 predicted lower detachment rates with increasing age of abandonment. Research by Navas et
381 al. (2005) in old abandoned fields revealed that detachment rates were highest in soils on
382 sunny orientated slopes with a low vegetative cover and high slope steepness. These results
383 correspond with the predicted rates for the abandoned fields in the current study. Moreover,
384 the decrease in detachment rates observed from recently to old abandoned fields in the south-
385 central Pyrenees are similar to those observed in Almeria, Spain (Govers et al., 2006). In that
386 study, land abandonment led to an exponential decrease in water erosion rates and sediment
387 transport over 50-70 years. Navas et al. (1997) found higher soil displacement in cultivated
388 and recently abandoned fields. Moreover, the negative effects of cultivation on erosion were

389 also observed in semiarid areas located in the same region of the study area (Quine et al.,
390 1994).

391 Temporal patterns observed in the current study were similar to that reported by Regüés and
392 Gallart (2004) at Vallcebre, southeast Pyrenees. In that study, sediment concentrations in
393 runoff samples were higher in spring and autumn than in winter and summer, and sediment
394 detachability by splash was higher in spring and autumn than in winter and summer.

395

396 3.3 Soil erosion and validation

397 To assess the reliability of the MMF and the RMMF model in estimating annual detachment
398 rates in barley fields, transport capacity by runoff was estimated (TC in Eq. 22) and the annual
399 soil loss rates were calculated (Eq. 23). These results were then compared with the erosion
400 rates measured by using fallout ^{137}Cs in eight soil samples that are included on an ongoing
401 research in the study area (Navas et al., personal communication, 2007). The mean values of
402 predicted and measured soil loss were 0.46 and $5.38 \text{ Mg ha}^{-1} \text{ y}^{-1}$, respectively. Predicted soil
403 erosion rates were the same for both models and similar to values obtained by Morgan (2001)
404 in other Mediterranean agrosystems such as Italy ($0.2 \text{ Mg ha}^{-1} \text{ y}^{-1}$), Spain ($0.49 \text{ Mg ha}^{-1} \text{ y}^{-1}$)
405 and Greece ($< 0.01 \text{ Mg ha}^{-1} \text{ y}^{-1}$). Morgan (2001) also found low rates for measured soil losses.
406 The low value of predicted soil erosion is explained by the low rate of runoff transport
407 capacity calculated with the RMMF model (Table 5). This is a limiting factor for estimating
408 annual erosion rate according to Eq. (23). Moreover, the estimated values of effective runoff
409 do not account for the erosive events from October to June when rainfall intensity is higher
410 than the saturated hydraulic conductivity because time to ponding was calculated with mean
411 values of I_m . Hence, the equations used to estimate the effective volume of runoff are
412 underestimating the actual volume of runoff and transport capacity, and thus, soil erosion
413 rates.

414 Tolerable soil loss (T) is defined as the maximum rate of annual soil erosion that will
415 economically sustain a high level of crop productivity over the long-term. Boellstorff and
416 Benito (2005) proposed a value of T between 1 and 13 Mg ha⁻¹ y⁻¹ for the majority of soils,
417 whereas Renard et al. (1997) established a range between 2.2 and 11.2 Mg ha⁻¹ y⁻¹ for North
418 American soils. In central Spain, De la Horra (1992) calculated a T value of 6 Mg ha⁻¹ y⁻¹ for
419 the province of Toledo. The predicted soil erosion rate in barley fields with the RMMF model
420 was lower than the T value proposed by De la Horra, whereas the measured rate with ¹³⁷Cs
421 was almost equal to the maximum tolerable erosion rate.

422

423 **4. Conclusion**

424 Despite considerable variation in land cover factors, the temporal pattern of splash
425 detachment rates with the MMF and the RMMF models are similar for the different land uses
426 examined in this study. However, the predicted splash and total detachment rates were lower
427 with the RMMF model than with the MMF approach, especially in pastures. The more
428 complex approach of the RMMF model assessed the monthly detachment rate by raindrop
429 impact using more accurate values, including temporal variability triggered by the different
430 phases of tillage. Maximum surface storage capacity, time to soil ponding and rainfall to soil
431 ponding play a key role in controlling runoff origin and volume and may explain the lack of
432 runoff observed from December to March for the four types of land use.

433 The highest rates of runoff detachment occurred in old abandoned fields due to higher runoff
434 volume, steeper slopes and lower soil resistance. Splash and total detachment rates were
435 highest in barley fields and lowest in pastures although pastures and abandoned fields were
436 located on steep hillsides. Moreover, old abandoned fields had lower splash and total
437 detachment rates compared to recently abandoned fields. These results demonstrate that the
438 more complex approach of the RMMF model provided a more accurate representation of the

439 erosive processes and is more sensitive to the detachment rates by raindrop impact and by
440 runoff than did the simple approach of the MMF model. Hence, we conclude that land cover
441 and intensity of erosive rainfall are more important in assessing splash and runoff detachment
442 rates than mean monthly rainfall.

443 The average annual erosion rates obtained for barley fields with the two models were equal to
444 and lower than the T value for soils under Mediterranean conditions due to an underestimation
445 of the effective runoff volume. Further research is required to calculate the effective runoff
446 volume at event scale for a more accurate assessment of runoff detachment and transport
447 capacity. These results have implications for land conservation considering that current
448 predictions of climate change will increase the frequency of extreme storm events, especially
449 in Mediterranean areas. The high detachment rates that occurred in barley fields, with the
450 maximum occurring between July and November, should be considered when designing and
451 promoting better management practices aimed at preserving soil and water resources.

452

453 **Acknowledgements**

454 CICYT Projects REN2002-02702/GLO and CGL2005-02009/BTE funded this study.

455

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595 Table 1. Saturated hydraulic conductivity (K_{fs}) and matrix flux potential (ϕ) for each soil type.

Soil type	K_{fs}	ϕ
	cm s ⁻¹	cm ² s ⁻¹
Calcisol	0.0010	0.0182
Gleysol	0.0007	0.0009
Gypsic Regosol	0.0003	0.0006
Gypsisol	4.6E-5	0.0002
Haplic Regosol	0.0003	0.0033
Leptosol	0.0016	0.0011

596

597

598 Table 2. Input parameters for assessing soil detachment and transport capacity rates in the south-central Pyrenees
 599 for the MMF and the RMMF erosion models.

Factor	Parameter	Model	Definition
Rainfall	R	MMF & RMMF	Rainfall (mm)
	I	MMF & RMMF	Typical value for intensity of erosive rain (mm h^{-1})
	R_0	MMF & RMMF	Mean rain per erosive rain day (mm)
Soil	K	MMF & RMMF	Soil detachability index (g J^{-1})
	COH	RMMF	Cohesion of the surface soil (kPa)
	MS	MMF & RMMF	Soil moisture content at field capacity (% w w ⁻¹)
	BD	MMF & RMMF	Bulk density of the top layer soil (Mg m^{-3})
	EHD	MMF & RMMF	Effective hydrological depth of the soil (m)
Landform	S	MMF & RMMF	Slope steepness (radian)
Land cover	A	MMF & RMMF	Rainfall intercepted by the vegetation and crop residue (%)
	E_t/E_0	MMF & RMMF	Ratio of actual (E_t) to potential (E_0) evapotranspiration
	CC	RMMF	Percentage canopy cover (%)
	GC	RMMF	Percentage ground cover (%)
	PH	RMMF	Plant height (m)
	C	MMF & RMMF	Cover – management factor in the RUSLE model (–)
Land use	P	MMF & RMMF	Support practice factor in the RUSLE model (–)

600

601 Table 3. Guide values of the soil parameters.

Soil texture	K	COH
	g J ⁻¹	kPa
Sand	1.2	2
Loamy sand	0.3	2
Sandy loam	0.7	2
Loam	0.8	3
Silt	1.0	-
Silt loam	0.9	3
Sandy clay loam	0.1	3
Clay loam	0.7	10
Silty clay loam	0.8	9
Sandy clay	0.3	-
Silty clay	0.5	10
Clay	0.05	12

602

603 Table 4. Values of soil, landform and land cover parameters for the various land uses (see Table 2).

Land use	MS	BD	EHD	K	COH	E _v /E ₀	A	CC	PH	GC	C	S
	% w w ⁻¹	Mg m ⁻³	m	g J ⁻¹	kPa	ratio	%	%	m	%	-	%
Old aband. field	0.352	1.34	0.087	0.874	3.31	0.32	22.5	80.7	5.5	0.36	0.004	21.8
Recently aband. field	0.309	1.23	0.119	0.873	3.44	0.33	30.8	27.5	1.0	0.36	0.022	19.9
Barley field	0.318	1.27	0.156	0.881	3.51	0.28	0–14	5–100	0–0.5	0.27	0.188	6.9
Pasture	0.332	1.18	0.138	0.869	3.58	0.33	8.3	100	0.3	0.30	0.123	24.5

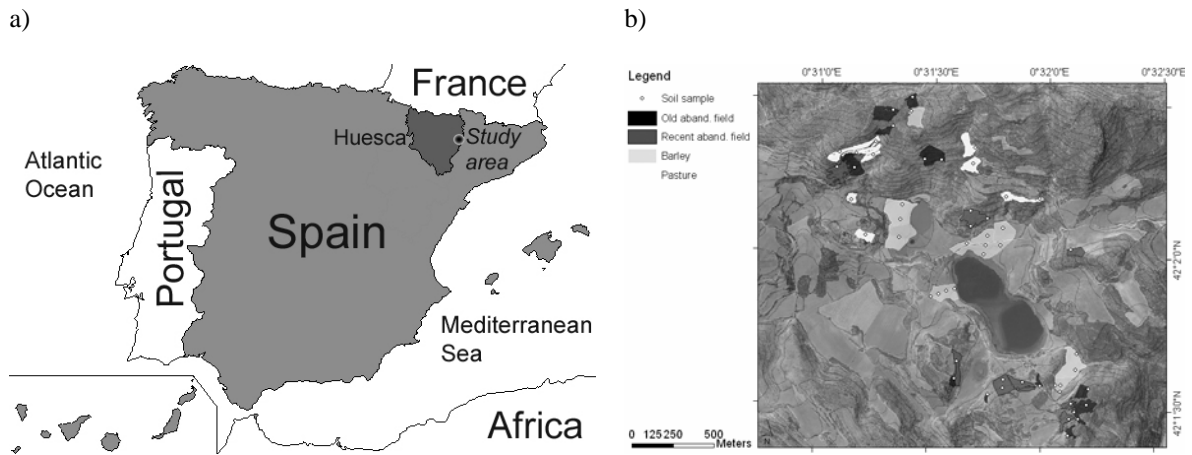
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605 Table 5 Mean monthly runoff transport capacity (*TC*; Mg ha⁻¹ month⁻¹) for the various land uses estimated with
606 the MMF and RMMF models.

Land use	Jr	Fb	Mr	Ap	My	Jn	Jl	Ag	Sp	Oc	Nv	Dc	Annual
Old aband. field	0	0	0	0	0.012	0.003	0.002	0.005	0.014	0.016	0	0	0.052
Recently aband. field	0	0	0	0	0	0	0.010	0.019	0.053	0	0	0	0.081
Barley field	0	0	0	0.073	0.079	0.018	0.018	0.034	0.090	0.100	0.050	0	0.462
Pasture	0	0	0	0	0	0.011	0.011	0.021	0.059	0.067	0	0	0.169

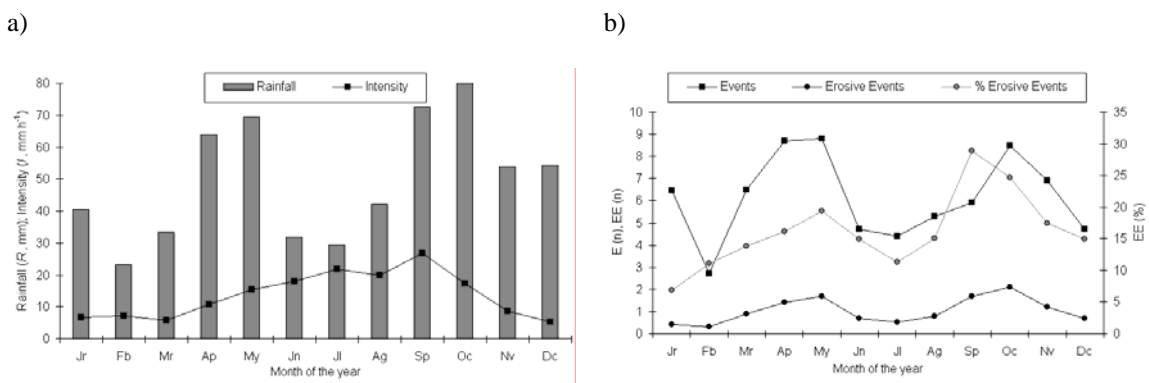
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608 Fig. 1. Location of the study area in the Huesca province, Spain (a), and location of the fields on the orthophoto
 609 of the “Lagos de Estaña” area (b).



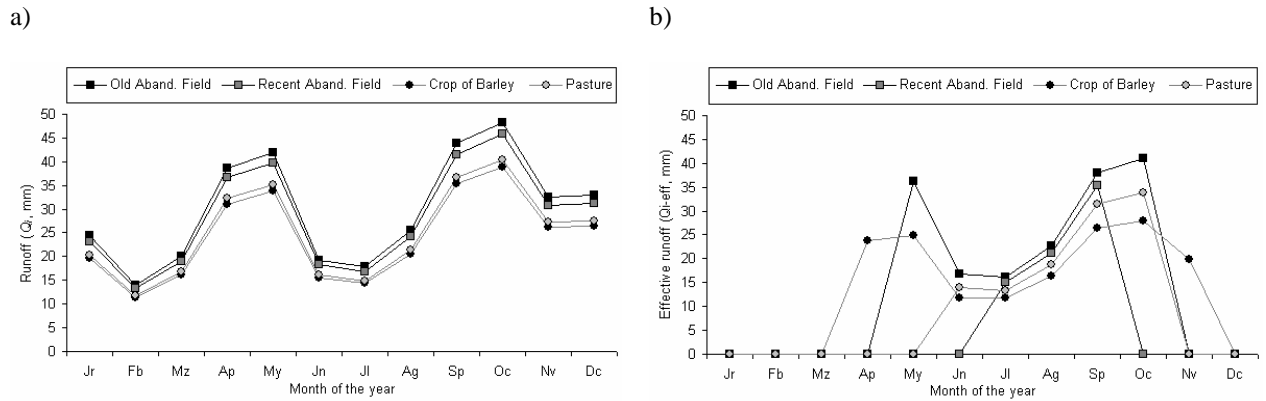
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Fig. 2. Average monthly rainfall and typical intensities of erosive rainfall (a), and mean monthly number of
 storm and erosive storm events, and percentage of erosive storm events (b) between 1993 and 2006 in the study
 area, based on data from the Canelles Weather Station, Spain.

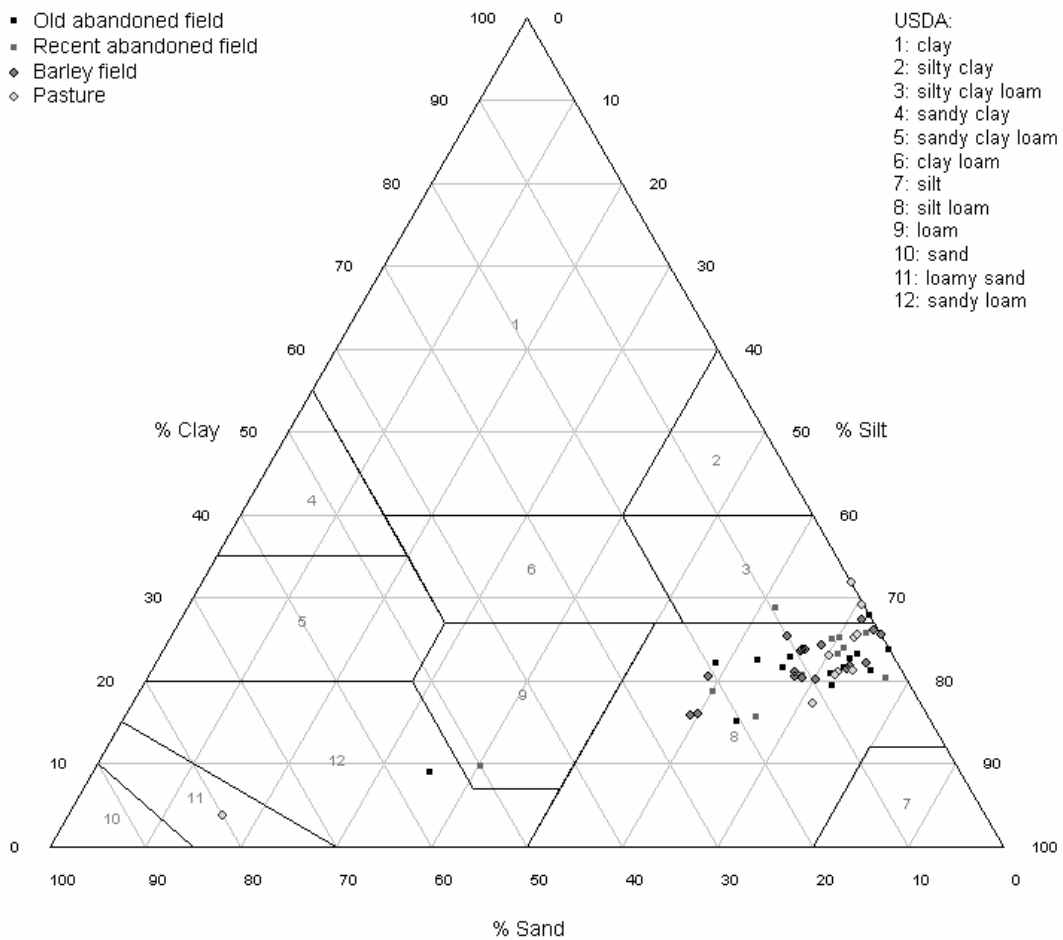


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617 Fig. 3. Minimum, maximum, and mean monthly runoff, Q_m (a) and effective runoff, Q_{m-eff} , (b) for four types of
 618 fields in the south-central Pyrenees, Spain based on the RMMF erosion model.



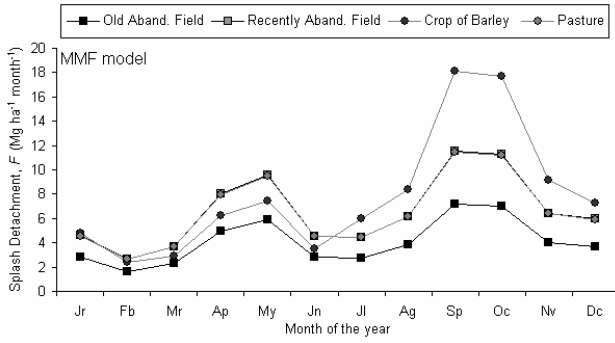
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 620 Fig. 4. Textural classification of the soil samples from four types of fields in the south-central Pyrenees, Spain.



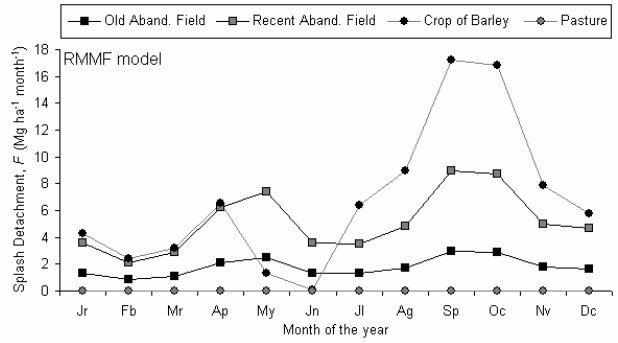
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624 Fig. 5. Monthly splash detachment rates (F) calculated with the MMF erosion model (a) and with the RMMF
 625 erosion model (b), and monthly detachment by runoff (H) (c) and total detachment (d) for each of the four field
 626 types in the south-central Pyrenees, Spain.

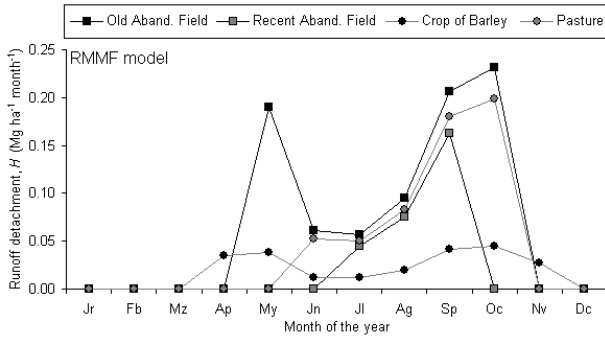
a)



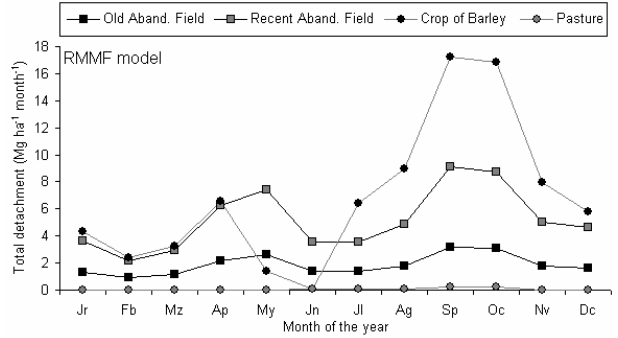
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d)



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