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Short Title: Target for catchment land degradation neutral management in Mediterranean

Long title: Landscaping compromises for land degradation neutrality: the case of soil erosion in a Mediterranean agricultural landscape

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1 Abstract

2 Soil erosion is the primary process driving land degradation. Using multiple scales of
3 management to minimize soil erosion is crucial to achieve land degradation neutrality targets
4 within the Sustainable Development Goals agenda. Land management (LM) influences both on-
5 site and off-site erosion on the event-scale and over the long-term. However, each LM differs in
6 effectiveness depending on the temporal scale considered. In order to understand how LM
7 effects internal and external catchment dynamics, we apply LandSoil, a physically based
8 landscape evolution model, to evaluate 7 LM scenarios over long- (30 years) and short-terms
9 (event scale). LM scenarios included changes in land use and/or landscape structure. Under
10 current LM, mean surface soil erosion was $\sim 0.69 \pm 39 \cdot 10^{-3}$ m over 30 years. In contrast, a
11 single extreme event (435 mm/24h) in January resulted in $\sim 0.62 \pm 3 \cdot 10^{-3}$ m loss and $\sim 0.04 \pm$
12 $2 \cdot 10^{-3}$ m if it occurred in October. Heterogeneous patterns of erosion and deposition developed
13 after 30 years, whereas extreme events dominantly showed soil loss and high catchment
14 connectivity. Effectiveness of LM in erosion mitigation and sediment trapping differed according
15 to temporal and spatial scales for each scenario. We concluded that multiple temporal and
16 spatial scales must be incorporated in order to adaptively manage land degradation and meet
17 neutrality targets.

18

19 Key words:

20 Land degradation, Degradation neutrality, Soil erosion, Landscaping, Mitigation strategy

21

22 1. Introduction

23

24 Land degradation neutrality targets of the Sustainable Development Goals (SDG 15.3) contain
25 time-specific measures to avoid, reduce and reverse land degradation at both national and
26 subnational levels (The Global Mechanism of UNCCD, 2016). Soil erosion by water is a major
27 land degradation process (Orr et al, 2017). Therefore, land management seeking to minimize
28 soil erosion is crucial for maintaining food and water security, climate regulation, soil ecosystem
29 services (Dominati et al., 2010; Koch et al., 2013; Lal, 2004; McBratney et al., 2014;

30 Montanarella et al., 2016; and achieving of multiple SDGs (Keesstra et al., 2016; Orr et al.,
31 2017).

32

33 It is expected, that soil erosion and suspended sediment yield in rivers will increase beginning in
34 the mid-21st century due to climate change (Raclot et al., 2018; Routschek et al., 2014a, 2014b,
35 Bussi et al., 2016; Rodríguez-Blanco et al., 2016). The majority of soil loss occurs during high-
36 magnitude events of low frequency/recurrence, especially in Mediterranean environments where
37 3-10 of the largest daily events can account for over 50% of total soil loss (González-Hidalogo
38 et al., 2007, 2010). Due to climate change, the frequency of high-magnitude rainfall events
39 increases (e.g., Serpa et al., 2015). Therefore, considering seasonal patterns of soil loss
40 (Smetanová et al., 2018) alongside water and sediment connectivity, and evaluating economic
41 effects of on- and off-site effects of land management are all essential for preventing land
42 degradation (García-Ruiz et al, 2017; Raclot et al., 2018).

43

44 Land use influences both soil erosion (sediment production) and sediment connectivity, while
45 landscape structure can influence sediment transport and connectivity (Ciampalini et al., 2012;
46 Coulthard & Van De Wiel, 2017; David et al, 2014; Follain et al., 2006; Fryirs, 2013). Modelling
47 studies shown, that proper management can reduce the future effects of climate change on mid-
48 and long-term soil erosion rates (Parroissien et al.2015; Rodriguez-Lloveras et al., 2016;
49 Routschek et al., 2014a, 2014b). Modelling approaches successfully tested the effects of crop
50 allocation, sediment trapping, and ditch optimisation techniques under mean or extreme rainfall
51 events (David et al, 2014; Furlan et al., 2012; Gumiere et al., 2014; Levavasseur et al, 2016;
52 Mullan et al., 2016; Nunes et al., 2013; Ronfort et al., 2011).

53

54 However, in order to meet land degradation neutrality targets, it is crucial to focus land
55 management simultaneously on the relevant spatial and temporal scales for erosional
56 processes (Larson et al., 1997; Stroosnijder, 2005) and stakeholders' scales of practice
57 (Smetanová, et al, 2018). This requires providing of multi-foci, multi-scale solution. For example,
58 a management reducing sheet and gully erosion during high-magnitude events of low

59 frequency/recurrence, and in long-term. Simultaneously, an effective management should
60 reflect differing priorities of stakeholders operating in the same region. For example, the spatial
61 scale of interests and mind-sets of a vineyards farmer and watershed manager might likely differ
62 between understanding internal catchment dynamics on individual field scales (farmer) versus
63 external catchment dynamics (e.g., sediment export to reservoirs). Furthermore, farmers
64 establishing vineyards are interested in soil productivity over timescales that plants achieve
65 highest productivity (10-30 years), while watershed managers might focus on reducing or
66 preventing flash floods (single events). Understanding how land management effects on soil
67 erosion contrast on temporal and spatial scales can help define targets for land management
68 decisions aimed at reducing land degradation.

69

70 The objective of this study is to compare the internal and external catchment soil erosion
71 dynamics for different land management scenarios over short-term (event scale) and long-term
72 (30 years) scales, in order to answer the question: "Should management strategies for land
73 degradation be tailored for specific spatial and temporal scales to achieve land degradation
74 neutral management?"

75

76 2. Materials and Methods

77 2.1 Study site

78

79 The Roujan catchment (0.91 km²), located in south France (43°30'N, 3°19'E) has been
80 monitored for rainfall in the three meteorological stations equipped with tipping bucket rain
81 gauges, and for continuous runoff and sediment concentration at parcel, mid- and whole
82 catchment since 1992. It was described comprehensively by David et al. (2014). It belongs to a
83 sub-humid Mediterranean climate (Peel et al., 2017) with mean annual rainfall 634 mm and a
84 dry summer period, with maximum runoff and sediment yield from October to February.
85 Elevation ranges 50m and slopes are 2–20% (David et al., 2014). Miocene marine and
86 lacustrine sedimentary rocks with calcaric Regosols and Calcisols cover most of the catchment.
87 Land use is dominated by vineyards (62%) followed by cereal and alfalfa production, and

88 scrubland (Guix-Hébrard et al., 2007). Chemical weeding in vineyards is performed using
89 herbicide application alongside mechanical weeding by shallow (0.05–0.10 m) tillage with a
90 duck foot cultivator in spring and autumn (Biarnès and Colin, 2006; Coulouma et al., 2006).
91 Wheat and barley are rotated in the fields with annual crops. Fields are treated biannually in the
92 post-harvest period (summer–autumn) with a disc-and-chisel plough down to depths of 7 to 12
93 cm. Landscape structure is characterised by 140 fields (0.6 ± 0.5 ha) with grass, bare soil or
94 vegetated compacted soil strips along field borders, and an 11-km network of ditches (David et
95 al. 2014). Current land use and landscape structures represent baseline land use scenario
96 (Figure 1).

97

98 2.3. LandSoil model

99 LandSoil model was previously developed and calibrated in Roujan catchment (Ciampalini et al.
100 2012), and since then applied in variety of environments (e.g., Ciampalini et al.2011; Chartin et
101 al, 2011; Lacoste et al., 2016). LandSoil is a spatial raster-based model for simulating water and
102 tillage soil erosion as well as evolution of topography at plot to catchment scale. After modelling
103 each event, LandSoil recalculates the elevation raster. Soil surface properties control water
104 infiltration, runoff, and sediment concentration for each grid-cell and rainfall event (David et al.,
105 2014; Leonard and Andrieux, 1998). Runoff in each grid cell is combination of input from
106 upstream/upslope cells and runoff generated within the cell. Runoff flows in the flow line
107 direction, or, if flow lines are interrupted, along liner landscape elements (roads, ditches, field
108 boundaries, and tillage rows). The model uses a modified single-flow runoff model (Jenson and
109 Domingue, 1988; Souchère et al., 1998) under eight possible flow directions. Both contour and
110 downslope tillage were modelled in different fields with tillage transport coefficients spanning
111 $111\text{--}139 \text{ kg m}^{-1}$ (David et al., 2014).

112

113 2.4. Numerical experiment scheme

114

115 We considered two temporal dynamics (Figure 2):

116 (i) Long-term - 30 years. This period refers to long-term erosion rates over the timescale

117 that a new vineyard will reach peak productivity.

118 (ii) Single extreme rainfall event – maximum measured daily rainfall event. Events were
119 modelled for January and October in order to consider variability in soil surface
120 properties (David et al., 2014) that arise during periods when large erosion events
121 usually occur (Smetanová et al., 2018).

122 We considered two spatial dynamics:

123 (i) Internal catchment dynamics – represented by fine spatial resolution modelling (1-meter
124 grid) to simulate erosion and deposition patterns over the entire catchment. It related to
125 spatial scale of farmers.

126 (ii) External catchment dynamics – represented by sediment export at the catchment outlet.
127 It related to sediment input to river system, and management scale of watershed
128 managers and policy makers.

129 We applied seven predictive land use scenarios that combine narrative and modelling methods
130 developed by David et al. (2014). Three narratives were (i) stationary production (B - “baseline”,
131 corresponding to current land mangement), (ii) more intensive production (I - “intensified”), and
132 (iii) less intensive production (E - “extensified”) than stationary production. These narratives
133 were transformed into seven scenarios (BLUS, ILU; ILS; ILUS; ELU, ELS, ELUS) by modifying
134 the baseline land use and / or landscape structure by allocation rules for of land use (LU) and
135 landscape structure (LS) as described in Figure 3.

136

137 2.5. Model inputs

138

139 ***Elevation and soil surface topography***

140 LIDAR-based digital elevation model derived at 2-m resolution (David et al., 2014) represented
141 initial input topography for all scenarios. Elevation was recalculated after every/each event by
142 subtracting the depth of eroded soil or adding the height of deposited sediment in each raster
143 cell. Soil erosion rates and sediment export (in Mg·km⁻², where 1 Mg·km⁻² corresponds to 0.01
144 tonnes per hectare) at the catchment outlet were recalculated at the end of each simulation
145 period based on equations provided by David et al. (2014).

146

147 ***Rainfall dataset***

148 Long-term rainfall series were based on 10-years extension of empirical rainfall event
149 measurements in the Roujan catchment between 1992-2012 (David et al., 2014; Figure 4). The
150 total rainfall depth (mm), maximum intensity over 6 min (mm h^{-1}) and rainfall duration (h) were
151 considered for each event, separated by at least a 6-hour dry period.

152 An event with return period >100 years was represented by extreme event measured in
153 Perpignan (120km from Roujan) on 26 October, 1915 (Cosadney and Robison, 2000; Meteo
154 France, 2018). Rainfall depth was 435 mm over 24 hours, but no measurement of rainfall
155 intensity was available. Rainfall intensity was estimated using the Montana law, with results
156 suggest that the Montana coefficient value exceeded the maximum intensity class for the
157 LandSoil model. Therefore, the maximum rainfall intensity class ($>40 \text{ mm h}^{-1}$) was applied
158 based on calibration from Ciampalini et al. (2012). Model parameters and soil conditions are
159 described in additional detail by David et al. (2014).

160

161 ***Tillage Dataset***

162 Modelled tillage events occurred in fields with annual crops and in vineyards with mechanical
163 weeding. We simulated tillage twice a year in April or May and October. The exact day of a
164 tillage simulation was determined by cumulative rainfall depth (40 mm) since the last tillage
165 event.

166

167 **3. Results**

168 **3.1 Temporal dynamics: Long-term vs. extreme event soil erosion**

169

170 Under current land use and landscape structure conditions (BLUS), mean soil loss was $0.69 \pm$
171 $38.97 \cdot 10^{-3} \text{ m}$ across the catchment over the 30-year simulation period (Table 1). Mean soil loss
172 here is the mean of all raster-cell values after 30 years of simulation. Each raster-cell value
173 represented cumulative elevation change after 30 years of simulation. Soil export at the outlet
174 (i.e., external catchment dynamics) under BLUS scenario was $9.02 \cdot 10^{-2} \text{ Mg} \cdot \text{km}^{-2}$. Soil export at

175 catchment outlet varied from 4.74 (ELUS) to $119.20 \cdot 10^{-2}$ Mg·km⁻² (ILUS).
176 Erosional responses to single extreme rainfall events differed from long-term (30 years)
177 cumulative soil loss and were different for January and October. Mean soil loss in single
178 extreme rainfall event was $0.60 \pm 2.72 \cdot 10^{-3}$ m in January, and $0.00 \pm 1.55 \cdot 10^{-3}$ m in October
179 under BLUS scenario. Sediment export (external dynamics) was 16.4x higher in January than in
180 October. Similar patterns were observed in other scenarios, where mean soil loss for extreme
181 events were 1.3x (ILU) to 20x (ELS) higher in January relative to October.
182 Comparing mean soil loss of long-term and extreme events (Table 1) under BLUS scenario
183 showed that 8.3±14-times more soil was eroded after thirty years than by a single extreme
184 event in January.
185 Sediment exported by a single event in January or October is only reached as the cumulative
186 effect of many erosion events under normal rainfall conditions. This comparison could be called
187 'equal erosion delivery', which refers to the duration required for continuous "normal" erosion to
188 match the quantity of sediment delivered by an extreme event. In BLUS, sediment exported in
189 January was reached after ~27 years, while sediment exported during October was matched
190 after ~2 years. Sediment exported in all January extreme events was reached in ~21-26 years
191 under extensified land use scenarios, but dropped drastically to ~2-4 years if October extreme
192 events were considered. Under ILU and ILUS, soil loss by both extreme events were more
193 similar than by all remaining scenarios. Under long-term rainfall conditions, an equivalent
194 amount of sediment export was reached in 6-7 years.

195

196 3.2 Internal catchment dynamics

197

198 Long-term rainfall conditions under current land use and landscape structure (BLUS) led to soil
199 redistribution within the catchment (Figure 5B). Soil loss ranged from 0.01 to 0.3 m in vineyards
200 with chemical weeding, with less than 0.01 m loss in scrubland and no tillage annual crop fields.
201 In vineyards with mechanical weeding and in fields with tilled annual crops, erosion ranged from
202 0.01 to 0.3 m and deposition >0.01 m occurred. Rills created in parcels with no tillage and
203 scrubland were infilled by shallow deposition (<0.01 m). Zero net erosion or deposition (<10⁻¹²m)

204 was observed on or along linear landscape structures (e.g., roads, field borders).

205

206 In contrast to previous results, during an extreme event in January (Figure 5C), net soil loss was
207 0.01 to 0.3 m in all land uses excluding scrubland, where a series of long rills with depths <
208 0.01 m, were created. Rills deeper than 0.3 m were formed along some recent and/or historical
209 linear landscape structures. Deposition > 0.1 m only took place on some of the vegetated strips.
210 During an extreme event in October, mean soil loss was lower than that from extreme events in
211 January (Table 1). Furthermore, the rill network within scrubland and along field borders was
212 less dense and generally, shorter rills infilled with less than 0.01 m sediment (Figure 5D). "Equal
213 erosion delivery" duration was ~27-years for an extreme event in January. However, soil
214 redistribution patterns were completely different (Figure 5E). Sediment exported during an
215 extreme rainfall event in October was reached after ~2 years of long-term rainfall conditions
216 (Figure 5F), but contrary to extreme rainfall in October (Figure 5D) nearly zero erosion or
217 deposition occurred within most of the parcels under normal rainfall conditions.

218

219 For other scenarios, the relation between long-term and extreme event internal catchment
220 dynamics was similar to those in BLUS (Supplementary Info 1). Normal rainfall simulations led
221 to heterogeneous soil redistribution patterns with areas of both erosion and deposition after 30
222 years, while nearly zero net soil erosion over the majority of the catchment during extreme
223 events.

224 Differences in internal catchment dynamics for each temporal scale are shown using an
225 example of upper (terraced) slopes divided to two parcels (Figure 6). The upper parcel was
226 divided to one (ILS) or more (BLUS, ELS) fields with mechanical weeding. Chemical weeding
227 was applied in ILU and ILUS scenarios, while scrubland covered the parcel in ELU and ELUS
228 (Figure 6A). The lower parcel was covered by scrubland in all scenarios, but the field border
229 cover varied (Figure 6A). Under scenarios of intensified land use (ILU and ILUS), 0.01-0.3 m of
230 soil was removed from surface in vineyards with mechanical weeding. Furthermore, deep rills
231 (0.01-0.3 m) in scrublands were infilled with transported material after 30 years (Figure 6B).
232 During extreme events in January (Figure 6C), the scrubland rill network was much less dense

233 compared to long-term simulations. However, during extreme event in January some of the
234 partly infilled rills cut into adjacent field borders and continued eroding. Additionally, exclusively
235 soil erosion occurred downhill of the scrubland field border during extreme events in January.
236 Substituting vegetated pathways with bare soil (Figure 6A-ILS) increased connectivity between
237 parcels and concentration of overland flow from upper parcel in lower parcels under long-term
238 rainfall conditions (Figure 6B-ILS). During extreme events (Figure 6C, 6D –ILS) erosion <0.01 m
239 occurred along some rills in scrubland. Under ILS, equal erosion delivery was attained after 17
240 years in comparison to January extreme event. Soil redistribution after 17 and 30-years under
241 ILS was similar. For ILU and ILUS, equal erosion delivery was 7 and 6 years. Again the soil
242 erosion pattern of equal soil erosion delivery was similar to long-term soil redistribution pattern
243 (Figure 6E –ILU and ILUS).

244 Under ELU overland flow generated in upper parcel (scrubland, Figure 6A-ELU) caused less
245 intensive erosion on-site than vineyards parcels in stationary and more intensive production
246 scenarios in 30 years (Figure 6B). Furthermore, scrubland led to rill formation and their infilling
247 in lower parcel after 30 years (Figure 6B-ELU). In ELUS, combined land use and landscape
248 structure changes helped protect rill incision (Figure 6B ELUS), but as Figure 6B ELS shows,
249 change of landscape structure alone was not sufficient to prevent rill erosion. Under extreme
250 events, erosion was low along scrubland field borders, and downslope rills emerged only under
251 ELS. During the year when sediment export from long-term rainfall conditions equalled extreme
252 events, soil redistribution patterns was more related to long-term precipitation patterns (Figure
253 6, Supplementary Info 1).

254

255 3.3 External catchment dynamics

256 Sediment export is referred to external catchment dynamics, and is reported in section 3.1,
257 Table 1. In scenarios with intensified land use (ILU, ILUS), total sediment export over long-term
258 conditions was over 10-fold higher than BLUS, over 4-fold higher than ILS. Total sediment
259 export under extreme event in January was in ILU and ILUS over 2.6-fold higher than BLUS,
260 and over 1.6-fold higher than ILS. For scenarios with less intensive production than BLUS, long-
261 term sediment export at catchment outlet by 10% (ELU), 40% (ELS) and 50% (ELUS) in

262 comparison with BLUS sediment export.

263

264 Sediment export under all scenarios was increasingly stable over the first four years of model
265 simulations, followed by sudden increases in the fifth year triggered by rainfall (Figure 7). The
266 sediment export response to natural rainfall conditions differed between the modelled scenarios.
267 Intensified scenarios responded with higher sediment production (i.e., erosion) and transport.
268 Soil export in ILUS more than doubled, and increased ~1.5-fold in ILU and ILS (Figure 7B). On
269 the contrary, ELU exhibited increased sediment export than ELS. Threshold behaviours with
270 different magnitudes of sediment response existed for all scenarios in several years (e.g., year
271 16, year 24).

272 Figure 7B compares sediment export by extreme events in January with long-term sediment
273 export. Intensified scenarios reached the sediment export of BLUS within first 4 to 10 years (for
274 ILUS and ILS, respectively).

275

276 4. Discussion

277

278 4.1 Land management optimisation: understanding the impact on differing temporal scales

279

280 Comparing scenarios over different time scales showed that both external and internal
281 catchment dynamics differed for long-term and extreme-event rainfall conditions. Mean and
282 variability of soil loss were greater after long-term rainfall events than extreme rainfall
283 conditions. However, sediment export at the catchment outlet from a single extreme event (in
284 January) accounted for 89% (BLUS) of long-term sediment export. Within-catchment and within-
285 parcels erosional hotspots formed over the 30 year simulations. Hotspots' spatial distribution
286 differed for each land use scenario, while landscape structure influenced within-catchment (dis-)
287 connectivity. Soil redistribution within parcels was strongly influenced by erosion from tillage
288 (David et al, 2014), which temporarily influences soil properties and micro-landforms (e.g.,
289 infilling rills, creating tillage rows) and thus, hydrology and associated sediment connectivity
290 along hillslopes.

291 During extreme events, most of the catchment was connected. Soil erosion removed up to 0.01-
292 m from almost the entire catchment independent of land use or landscape structure (except for
293 scrubland and some of the filed borders, grass strips, pathways). Land uses or landscape
294 structures sometimes acted as barriers or buffers under normal rainfall conditions, but were less
295 effective in damping overland flow and sediment trapping. Yet, effects of single extreme rainfall
296 events differed for October and January depending on soil-vegetation properties in the
297 respective month. In October, transport-limited deposition took place in some pathways,
298 whereas only transport and zero net erosion or deposition took place in January. Antecedent
299 conditions such as previous rainfall or tillage influenced sensitivity of sediment response to
300 seasonal changes in soil hydrological properties, demonstrated previously by monitoring studies
301 (e.g., Biddocu et al., 2017; Inoubli et al., 2017; Raclot et al., 2009, Smetanova et al., under
302 revision).

303

304 4.2 Land management optimisation: understanding effects of management measures under
305 different scenarios

306

307 We discuss the effect of land management on land-degradation based on area-specific
308 sediment budgets for both long-term and extreme events (Figure 8).
309 Chemical weeding led to erosion when applied on vineyards in all scenarios and timescales.
310 Mechanical weeding, was also a net source of sediment under extreme rainfall conditions in
311 January, but over 30 years, had nearly neutral sediment budget. According to David et al.
312 (2014), mechanical weeding caused three-times less sediment erosion compared to chemical
313 weeding over 100 years. However, extensive mechanical weeding in ELU without using
314 extensive landscape structures (such as in ELS) increased sediment export more than both
315 current land use and extensive landscape structure in ELS (Table 1). This confirms that land
316 use and landscape structure management must be used in combination to effectively decrease
317 both sediment production (i.e., erosion) from farmers' fields and sediment exported from the
318 catchment to river system.

319 Grass strips and vegetated strips were the most effective management strategies for trapping

320 sediment at both temporal scales (and in 100 years as in David et al., 2014), but the sediment
321 trapped was highest for extreme events. Total area and spatial distribution of vegetated strips
322 was identical under BLUS; ILU and ILUS, but sediment trapping in vegetated strips decreased
323 with decreasing sediment production. Sediment trapping efficiency of vegetated strips differed
324 with (i) amount of sediment produced, (ii) spatial redistribution of landscape elements and land
325 uses, and (iii) single (process) versus cumulative events (long-term processes). Trapping
326 efficiency was directly linked to sediment connectivity during extreme events and over the long-
327 term. This confirm previous findings that both sediment connectivity and sediment trapping
328 efficiency are dependent on spatial distribution of management (Collin et al., 2012; Gumiere et
329 al., 2011; Mekonnen et al., 2015; Ramos et al., 2010). Using a raster-based approach allowed
330 us to assess sediment production and transport at individual parcel scale at both temporal
331 scales (example in Figure 6). However, we did not calculate soil loss and effectiveness of
332 measures for each farmer at different time scales, which is possible and recommended for
333 supporting decision-making schemes (Souchère et al., 2010). At the catchment scale, soil
334 surface properties drove sediment export regardless of land use (David et al., 2014). Therefore,
335 management techniques aimed at the soil surface can reduce soil erosion. Such approaches
336 include straw mulch or intercropping, and are known to decrease soil erosion under long-term
337 and extreme rainfall conditions (Biddocu et al., 2014, 2016, 2017; Blavet et al., 2009; Cerdà et
338 al., 2016; Gómez et al., 2009, 2014; Kosmas et al., 1997; Prosdocimi et al., 2016; Raclot et al.,
339 2009; Ramos et al., 2007; Rodrigo-Comino et al., 2016; Ruiz-Colmenro et al., 2011).

340 Management strategies can be either (i) permanently incorporated in land use scenarios, or (ii)
341 used in conjunction with others (e.g., geotextiles, mobile sediment trapping barriers) as ad-hoc
342 measures during extreme events (Sherrif et al., 2016).

343

344 4.3 Pathways for applicable optimisation for land-degradation neutral management

345

346 Our results suggest that using multiple temporal, spatial and management scales to evaluate
347 soil erosion and connectivity can significantly improve existing modelling approaches (Bussi et
348 al., 2016; Collin et al., 2012; David et al., 2014; Gumiere et al., 2014; Mullan et al., 2016; Nunes

349 et al., 2013; Paroissien et al, 2015; Ramos et al., 2015; Rodriguez-Lloveras et al., 2016; Ronfort
350 et al., 2011; Routschek et al., 2014). Our approach includes temporally- and spatially-adjusted
351 measures that are applicable for meeting soil erosion and land degradation neutrality targets
352 (The Global Mechanism of UNCCD, 2016). We demonstrate that proposing land degradation
353 neutrality measures in agricultural catchments is extremely complex due to (i) natural variability
354 of catchment responses to normal rainfall conditions and extreme events, and (ii) variability in
355 cumulative response depending on the spatial distribution of selected measures. Furthermore,
356 we showed that (iii) the same sediment export (sediment yield) values represented different
357 patterns of soil erosion and deposition within a catchment. The complexity of applying measures
358 to reduce land degradation is reinforced by differing interests and management aims of each
359 stakeholder (e.g., farmer or watershed manager; Smetanová et al., 2018). Therefore, modelling
360 approaches applied on differing spatial and temporal scales are valuable aid for participative
361 decision making on best practice management (Hewett et al., 2018, Keesstra et al., 2018).

362

363 5. CONCLUSION

364

365 Our research proved, that tailoring specific management strategies for specific spatial and
366 temporal scales might be suitable in order to achieve land degradation neutral management.

367 Our research contributions included the following in regards to attaining land degradation
368 neutrality goals:

- 369 1. Managing changes to land use or cover won't appropriately serve land degradation
370 neutrality targets at the catchment scale (sub-national level). It is essential to include
371 landscape structure change and connectivity management into land use scenarios.
- 372 2. Internal and external catchment dynamics differ for long-term and extreme events, and
373 therefore multiple temporal, spatial, and management scales must be compared and
374 incorporated in to planning adaptive management for land degradation. Optimally, this
375 will span from farm- to catchment-scales, as well as sub-national levels.
- 376 3. Modelling approaches such as LandSoil enable comparison of management efficiency
377 for both long- and extreme event-scales. Additionally, the model improves selection of

378 timely and adaptive management scenarios best serving land degradation neutrality
379 targets (SDGs 15.3)

380

381 We suggest that holistic land degradation neutrality management can be selected by using
382 multi-scale consideration based on models incorporated in participative decision making. Using
383 such inputs will bring multiple co-benefits fostering life on land, including avoiding, reducing and
384 reversing land degradation processes.

385

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392

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Figure description:

Figure 1. Study area (A), land use (B), and landscape structures (C)

Figure 2: Flowchart of numerical experiment in LandSoil. Model inputs were digital elevation model, dynamic soil properties, seven land management scenarios, and rainfall. Two temporal (long-term, single event) and two spatial dynamics (internal and external) were considered. Red triangle indicates management priorities of a farmer, inverted red triangle priorities of a watershed manager. Outputs related to internal (v) and external (inverted v) catchment dynamics were produced for each scenario.

Figure 3. Land management allocation matrix.

Figure 4. The full 30 years of precipitation data plotted over time. First 20 years (red frame) are empirically measured rainfall events in Roujan (1992-2012), while the last 10 years are extension of the empirical dataset. The red star represents the amount of rainfall during the extreme event (435 mm/24h) measured in Perpignan in 1915.

Figure 5. Internal catchment dynamics under current land use and landscape structure (BLUS)

A: Land use and landscape structure, B-F: Erosion and deposition: (B) after 30 years of normal rainfall conditions, (C) after an extreme event in January, (D) after an extreme event in October. (E) internal catchment dynamics in year (indicated by number) when sediment export by the long-term rainfall series matches that of an extreme event in January, and (F) same as E, but for an extreme event in October. An elevation change legend (bottom right) shows deposition as positive, erosion as negative, and anything $<10^{-12}\text{m}$ and $> -10^{-12}\text{m}$ as "no erosion, no deposition".

Figure 6. Internal catchment dynamics in one selected catchment segment

Land use and landscape structure(A), and erosion and deposition on different time scales (B-F) under different scenarios (indicated by rows) are shown in the selected catchment segment (locator figure, left bottom). Time scales: (B) 30 years under normal rainfall conditions, (C) an extreme event in January, and (D) an extreme event in October. In columns E and F, internal catchment dynamics are shown for the year when catchment outlet sediment export under long-term rainfall series met that of

an extreme event (E) in January and (F) in October.

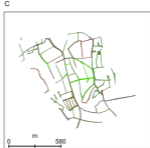
Baseline scenario (B) represents steady production under current land use (LU) and landscape structure (S). More intensive (I) production than steady production is represented by ILU, ILS, ILUS scenario, less intensive (E) production by ELU, ELS, ELUS.

An elevation change legend (bottom right) shows deposition as positive, erosion as negative, and anything $<10^{-12}\text{m}$ and $> -10^{-12}\text{m}$ as “no erosion, no deposition”.

Figure 7. External catchment dynamics

(A) Area specific sediment yield at the catchment outlet ($10^{-2} \text{ Mg}\cdot\text{km}^{-2}$) over 30 years. (B) Comparison between sediment delivery over long-term (30 years) and extreme events in January (arrow). Baseline scenario (B) represents steady production under current land use (LU) and landscape structure (S). More intensive (I) production than steady production is represented by ILU, ILS, ILUS scenario, less intensive € production by ELU, ELS, ELUS.

Figure 8. Land management effect on land degradation under different scenarios and temporal scales. Area-specific sediment budget within landscape management ($10^{-2} \text{ Mg}\cdot\text{km}^{-2}$) is plotted for long-term (30 years, x-axis), and an extreme event in January (y-axis). Erosion is plotted in red and orange, deposition in green and blue.



Baseline scenario: (A) land use and (B) landscape structure

- | | |
|--------------------------------|---------------------------|
| vineyards - mechanical weeding | fruit trees |
| vineyards - chemical weeding | scrubland |
| annual crops - tillage | annual crops - no tillage |

- | | |
|--------------------------|------------|
| pathway - bare soil | building |
| pathway - vegetated soil | paved road |
| grass strip | |

Management		Narrative		
		Stationary production (B)	More intensive production (I)	Less intensive production (E)
Landuse (LU)	Area: vineyards and crop	—	↑	↓
	Area: chemical weeding	—	↑	↓
	Area: no tillage	—	↓	↑
Landscape structure (LS)	Field unit surface	—	↑	↓
	Linear structure density	—	↓	↑
	Downslope tillage direction	—	↑	↑
	Area: grass strips	—	↓	↑

Scenarios were build according to three narratives: (B) – stationary production (representing current conditions), (I) more intensive production and (E) less intensive production than current conditions. Land use (LU) and/or landscape structure (LS) management was modified by increase (↑) or decrease (↓) in total area, and change in spatial allocation of LU and/or LD management in comparison with stationary production (-). The abbreviations of resulting seven scenarios (BLUS, ILU, ILS, ILUS, ELU, ELS, ELUS) indicate the narrative (B, I, S) and management (LU, LS, or LUS- both LU and LS). Detailed rules on allocation are in David et al. (2014). Spatial allocation of BLUS is plotted in Figure 5A (BLUS), and remaining scenarios in Supplementary Info 1.1A-1.6A.

Digital Elevation Model

Dynamic soil surface properties

Land Management

Narrative

Stationary production (B)

More intensive production (I)

Less intensive production (E)

Modified

Land Use (LU)

Landscape structure (LS)

LU & LS

Land Use (LU)

Landscape structure (LS)

LU & LS

Scenarios:

BLUS

ILU

ILS

ILUS

ELU

ELS

ELUS

INPUTS

Temporal dynamics:

Rainfall

Long-term (30 years)

Event occurring in

January

October



OUTPUTS

Spatial dynamics



Internal catchment dynamics (v)
(Spatial distribution of soil loss)

v ^

v ^

v ^

v ^

v ^

v ^

v ^

v ^

v ^

v ^

v ^

v ^

v ^

v ^

v ^

v ^

v ^

v ^

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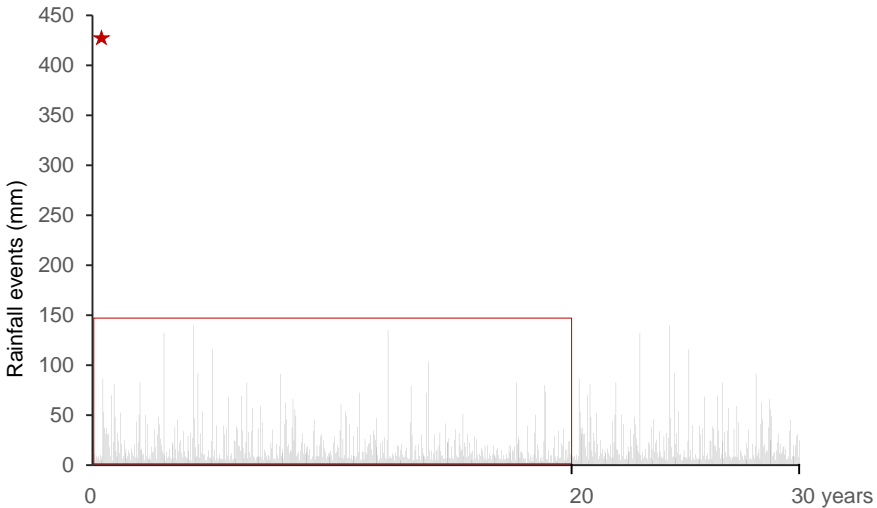
v ^

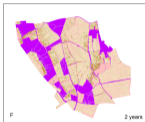
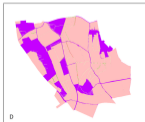
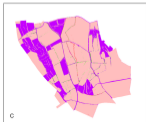
v ^

External catchment dynamics (λ)
(Sediment export at catchment outlet)



LANDSOIL





Land use and landscape structure

- vineyards - mechanical weeding
- vineyards - chemical weeding
- annual crops - no tillage
- annual crops - tillage
- fruit trees
- scrubland
- pathway - bare soil
- pathway - vegetated soil

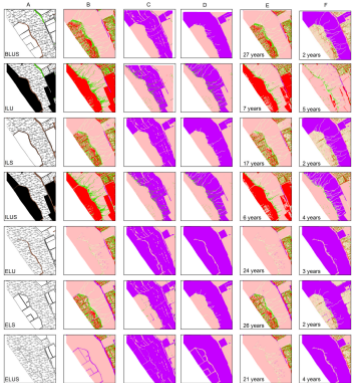
Erosion

- < 0.3 m
- 0.01 to 0.3 m
- 0 to 0.01 m
- no erosion, no deposition

Accumulation

- 0 to 0.01 m
- 0.01 to 0.3 m
- > 0.3 m

- grass strip
- building
- paved roads



Selected area

Land use and landscape structure

- vineyards - mechanical weeding
- vineyards - chemical weeding
- annual crops - tillage
- fruit trees
- scrubland
- annual crops - no tillage
- pathway - bare soil
- pathway - vegetated soil

- grass strip
- building
- paved road

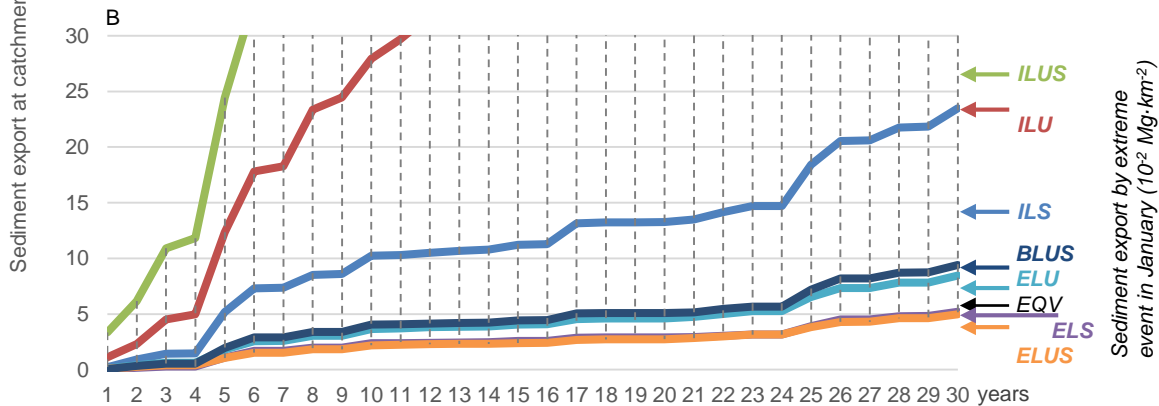
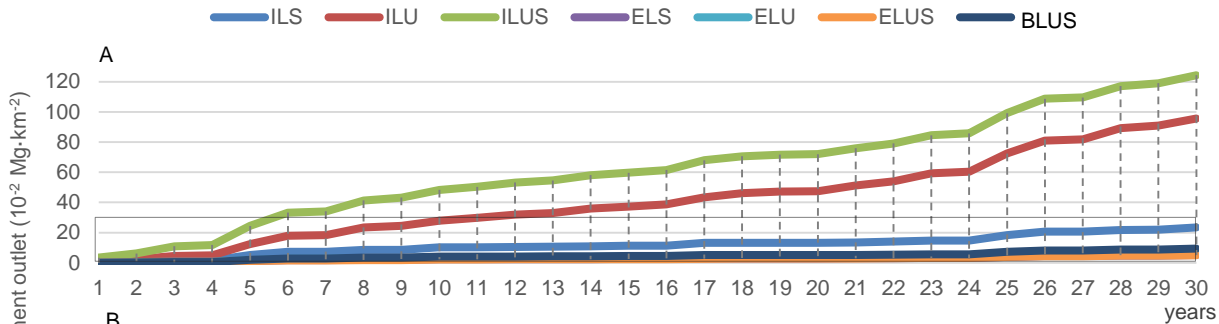
0 75 150 300

Erosion

- = 0.3 m
- 0.01 to 0.3 m
- 0 to 0.01 m
- no erosion, no deposition

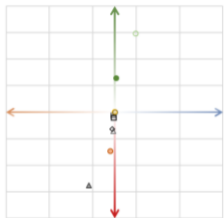
Accumulation

- 0 to 0.01 m
- 0.01 to 0.3 m
- = 0.3 m

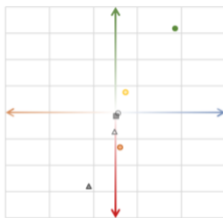


Extreme event (January)

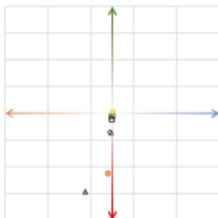
BLUS



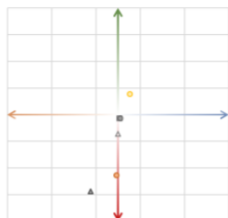
ILU



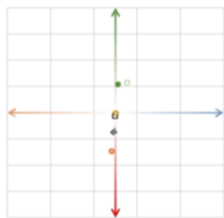
ILS



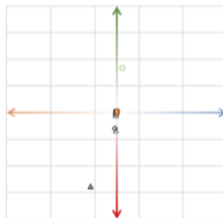
ILUS



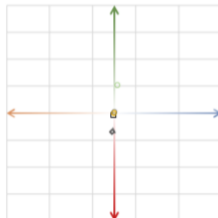
ELU



ELS



ELUS



Long-term

vineyard: weeding:

■ mechanical ▲ chemical

crop:

■ tillage □ no tillage

soil strip:

● vegetated ● unvegetated

● scrubland ● grass strip

◇ fruit tree ○ road

Table 1. Mean soil loss for the catchment and soil export at catchment outlet under each scenario

	Long-term erosion			Extreme event in							
				January				October			
	Mean soil loss*	Soil export at outlet		Mean soil loss*	Soil export at outlet		Equal **	Mean soil loss*	Soil export at outlet		Equal **
10 ⁻³ m	Mg	10 ⁻² Mg·km ⁻²	10 ⁻³ m	Mg	10 ⁻² Mg·km ⁻²	years	10 ⁻³ m	Mg	10 ⁻² Mg·km ⁻²	years	
BLUS	0.69±38.97	856.11	9.02	0.62±2.71	762.10	8.03	26.7	0.04±1.55	46.16	0.49	1.6
ILU	7.05±80.47	8700.59	91.70	1.62±4.39	1996.81	21.05	6.9	1.18±4.38	1456.43	15.35	5.0
ILS	1.73±35.69	2135.83	22.51	0.99±2.16	1216.83	12.82	17.1	0.09±0.74	112.82	1.19	1.6
ILUS	9.17±52.68	11309.58	119.20	1.89±3.44	2334.57	24.60	6.2	1.17±3.26	1445.42	15.23	3.8
ELU	0.62±25.16	769.80	8.11	0.50±2.01	614.55	6.48	23.9	0.07±1.16	88.06	0.93	3.4
ELS	0.38±35.01	469.59	4.95	0.33±3.10	412.83	4.35	26.4	0.03±1.38	36.87	0.39	2.4
ELUS	0.36±19.43	449.81	4.74	0.26±2.47	318.81	3.36	21.3	0.05±1.35	57.60	0.61	3.8

*- mean calculated based on raster cells, ± indicates standard deviation. Mean soil loss is also referred to as internal catchment dynamics in the text. Soil export is also referred to as external catchment dynamics in the text. **- number of years in which catchment outlet sediment export over long-term rainfall matched that of extreme events; BLUS-steady production - baseline land use and landscape structure. I-more intensive production than B. E-less intensive production than B; 10⁻² Mg·km⁻² equals t/ha