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A Multidimensional statistical framework to explore seasonal profile, severity and land-use preferences of wildfires in a Mediterranean country

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Assessing Latent Relationships between Land Degradation Drivers and Candidate Responses to Desertification: A Data Mining Approach

Abstract

This study investigates the relationship between fine resolution, local-scale biophysical and socioeconomic contexts within which land degradation occurs, and the human responses to it. The research draws on experimental data collected under different territorial and socioeconomic conditions at 586 field sites in 5 Mediterranean countries (Spain, Greece, Turkey, Tunisia and Morocco). We assess the level of desertification risk under various land management practices (terracing, grazing control, prevention of wildland fires, soil erosion control, soil water conservation, sustainable farming, protected areas and financial subsidies to farms) taken as possible responses to land degradation. A data mining approach incorporating principal component analysis, non-parametric correlations, multiple regression and canonical analysis, was developed to identify spatial relationships between land management conditions, local background (assessed using 40 biophysical and socioeconomic indicators) and desertification risk. Our analysis identified distinct relationships between the level of desertification experienced and the underlying socioeconomic context, suggesting that the effectiveness of responses to land degradation is strictly dependent on the local biophysical and socioeconomic context. Assessing the latent relationship between land management practices and the biophysical/socioeconomic attributes characterizing areas exposed to different levels of desertification risk proved to be an indirect measure of the effectiveness of field actions contrasting land degradation.

Key words: Multivariate statistics, Human pressure, Indicators, Response assemblage, Mediterranean region.

64 **1. Introduction**

65

66 Land Degradation is a complex phenomenon occurring when specific biophysical, economic,
67 social, cultural and institutional factors act synergistically to produce and entrench
68 desertification over the long term (Reynolds et al., 2011). Unsustainable use of natural
69 resources, weak economic development and policy inaction are relevant drivers of land
70 degradation and reflect the complex relationship between local ecological conditions,
71 socioeconomic dynamics and policy action (Bisaro et al., 2013). Desertification results in a
72 progressive decline of land productivity and ecosystem functions, and is a key issue on the
73 global policy agenda (Stringer and Harris, 2014). Desertification has negative impacts on food
74 security, biodiversity and quality of life (Glenn et al., 1998). Abuse or misuse of land, drives to
75 regional disparities in the availability of natural resources and results in a spatially unbalanced
76 development (Johnson and Lewis, 2007).

77 In the last decades, desertification risk has increased in many parts of the world, with land
78 degradation now becoming severe in both emerging and developed countries (Thomas et al.,
79 2012; Izzo et al., 2013; Yang et al., 2013). In the Mediterranean basin, Land Degradation (LD)
80 is the result of the interplay between natural and socioeconomic systems (Wilson and Juntti,
81 2005). This process involves a number of biophysical attributes of the landscape (topography,
82 climate, soil, vegetation) and conditions deriving from human activity (e.g. land-use
83 transformations, agricultural intensification, land abandonment, population density, settlement
84 distribution, industry and tourism development).

85 A large part of the Mediterranean region is vulnerable to LD (Hill et al., 2008). While desert
86 land is relatively scarce, areas with semi-arid climate and socioeconomic conditions which
87 negatively impact soil fertility, biodiversity and ecosystem services are rather common. In such
88 contexts, landscapes have lost part of their ecological and economic potential (Basso et al.,
89 2010). LD processes in the Mediterranean basin are highly variable in time and space, closely
90 influenced by the different speeds of change in environmental and socioeconomic conditions
91 (Ibanez et al., 2008).

92 Studies that have addressed the most important causes and consequences of LD from a socio-
93 environmental perspective have identified some of the core proximate drivers and underlying
94 factors of change which lead to desertification risk (Zdruli, 2013). Salvati et al. (2015) have
95 proposed an approach to assess the multiple relationships between biophysical factors and
96 socioeconomic attributes in a representative sample of Mediterranean sites, identifying
97 diverging spatial patterns for biophysical and human drivers of LD, with higher variability

98 observed for economic and social indicators. Gaps in knowledge on the role of system
99 complexity in shaping land vulnerability to desertification, however, have often been
100 underestimated (Briassoulis, 2015). Research often focused on single - albeit important - factors
101 such as soil degradation, whilst diachronic approaches which draw on data at a national or
102 regional scale with an adequate spatial resolution are relatively scarce (Kosmas et al., 2015).
103 Indicator-based approaches have been developed mainly for permanent monitoring of
104 biophysical conditions characterizing LD processes (Ferrara et al., 2012). Whilst development
105 of proper indicators and decision support systems to inform mitigation policies is a research
106 priority (Glenn et al., 1998), further investigation is required to identify a comparative
107 framework for assessing the impact of regional-scale drivers, and enable the importance of
108 biophysical and socioeconomic factors to be ranked (Salvati et al., 2015).

109 Based on the issues discussed above, rethinking a non-reductionist approach to LD in relation
110 to the characteristic territorial dimensions and the most suitable policy responses is imperative
111 (Sabbi and Salvati, 2014). Emphasis should be given to the social, demographic, economic,
112 political and cultural processes that shape LD in any given area, and to the responses that
113 society, in that specific local context, is able to implement (Iosifides and Politidis, 2005).
114 According to Briassoulis (2015), "human response to land degradation can be considered any
115 planned (formal) or unplanned (informal) actions that purport to directly and explicitly tackle
116 it and/or address other individual and collective socioeconomic goals in affected socio-
117 ecological systems". Depending on the prevailing socioeconomic conditions, stakeholders and
118 other actors may have no option but to continue with business as usual (no remedial action), or
119 to engage in resource-intensive activities (negative responses). Conversely, in some local
120 contexts, stakeholders may be able to undertake actions to mitigate soil and land degradation
121 (positive responses). Positive responses contribute to sustainable development of the local
122 system preserving critical ecological functions and relevant socioeconomic attributes (Kelly et
123 al., 2015).

124 Three key issues should be considered when effective responses to LD are proposed. First, a
125 policy response or the implementation of a policy instrument does not always result in the
126 intended impact in every context. Second, responses may have multiple impacts on the target
127 environment and third, a holistic approach (as opposed to a target-specific or process-specific
128 approach) is required in order to cope with a complex and multifaceted phenomenon such as
129 LD (Salvati et al., 2015). The non-linear, highly-diversified nature of LD processes justifies the
130 implementation of responsive and locally-adaptable policy instruments that are suitable to
131 address place-specific environmental patterns (Wilson and Juntti, 2005). Previous studies have

132 also suggested that the lack of relevant policy, due to *laissez-faire* practices or weak decision-
133 making processes can be considered as tangible policy implementation, although inaction costs
134 have been insufficiently acknowledged and investigated (Ferrara et al., 2012). As a
135 consequence, policy implementation is a relatively fuzzy decision-making spectrum of (more
136 or less) integrated measures, instead of a clear process of well-informed and locally-specific
137 decision-making (Briassoulis, 2005).

138 In fact, to be effective on the ground, responses have take account of diverse components which
139 are operating at various spatial scales and temporal speeds, and their effectiveness will therefore
140 depend on their ability to respond to the relationships amongst these components. An integrative
141 approach based on the concept of ‘response assemblage’ was recently proposed with the aim of
142 identifying various types of interventions to combat LD (Briassoulis, 2015). Response
143 assemblages reflect the need for humans to use natural resources sustainably to satisfy societal
144 needs and are intended as "geographically and historically unique, provisional, open, territorial
145 wholes, complex compositions emerging from processes of assembling biophysical and human
146 components" (Briassoulis, 2015). A response assemblage operates at multiple spatial scales and
147 is characterized by specific environmental attributes, land-use regimes and socioeconomic
148 profiles.

149 Apart from the contribution mentioned above, frameworks identifying responses to LD are still
150 relatively scarce (Thomas et al., 2012; Zdruli, 2013). Understanding place-specific LD
151 processes, and identifying the spatial relationship between drivers of LD at different
152 geographical scales, have allowed designing more effective mitigation strategies (MacDonald
153 et al., 2000; Gellrich et al., 2007; Koulouri and Giourga, 2007; Corbelle Rico et al., 2012).
154 Since place-specific factors and socioeconomic changes at multiple spatial and temporal scales
155 have major impacts on LD responses (Sluiter and De Jong, 2007; Weissteiner et al., 2011; Kairis
156 et al., 2014), stakeholder participation in the design of mitigation responses is crucial in the
157 fight against desertification (Briassoulis, 2005). Iosifides and Politidis (2005) investigated the
158 local context and its impact on individual stakeholder decision-making, and highlighted the
159 importance of an integrated analysis of biophysical and socioeconomic drivers of change in
160 order to identify and understand responses to LD. An in-depth knowledge of the latent
161 relationship between LD drivers and components of the specific local human-biophysical
162 system is an essential baseline when implementing Sustainable Land Management (SLM)
163 strategies (Zdruli, 2013). Salvati et al. (2015) introduced a comprehensive approach to the
164 analysis of the spatial relationship between biophysical and socioeconomic components of a
165 socio-ecological system based on data mining techniques. This framework was applied to a

166 number of rural districts in southern Europe exposed to different levels of desertification risk
167 and allows us to quantify the main environmental and socioeconomic impacts on land. Based
168 on this information, mitigation policies and adaptation strategies for locally-based LD processes
169 have been proposed (Kosmas et al., 2015).

170 The study reported in this paper contributes to this research frame by illustrating an exploratory
171 framework based on data mining techniques applied to a number of indicators that assesses
172 biophysical and socioeconomic conditions at 586 Mediterranean field sites exposed to variable
173 levels of desertification risk, and where different responses to LD have been implemented.
174 Responses to LD form a set of actions targeting specific environmental problems or coping with
175 undesirable conditions (Bakker et al., 2005; Strijker, 2005; Sluiter and De Jong, 2007).
176 Environmental legislation, economic incentives, customary rules and SLM practices were
177 frequently considered as candidate responses to LD (Thomas et al., 2012; Zdruli, 2013; Kelly
178 et al., 2015). In this study, 8 practical actions covering the abovementioned issues (terracing,
179 grazing control, wildland fire prevention, soil erosion control, soil water conservation,
180 sustainable farming, protected areas, financial subsidies to farms) were selected as relevant
181 examples of candidate responses to LD in the studied areas (Kosmas et al., 2015) and were
182 correlated with the local context profiled using 40 biophysical and socioeconomic indicators
183 (Salvati et al., 2015).

184 The aims of this study were (i) to investigate spatial occurrence and intensity of candidate
185 responses to LD identifying possible 'response assemblages' at the field scale, (ii) to correlate
186 the occurrence and intensity of candidate responses to LD with the level of desertification risk
187 and (iii) to identify spatial relationships between candidate responses to LD and
188 biophysical/socioeconomic contexts at each field site. The study contributes to the
189 identification of practical actions and policy measures against LD using a statistical procedure
190 which is robust, simple and adaptable to different environmental and socioeconomic conditions.
191 The proposed approach is flexible to changes in background and response indicators. An
192 enriched set of indicators can be used covering relevant candidate responses to LD under
193 different territorial contexts. Data mining is a promising tool for ascertaining the spatial
194 configuration of factors shaping desertification risk (Ferrara et al., 2016) and allows for an
195 indirect evaluation of the effectiveness of land management actions in LD mitigation.

196

197 **2. Materials and methods**

198

199 *2.1. Study area*

200

201 A total of 586 field sites were selected in 5 Mediterranean regions. Two areas are situated in
202 European Union (EU) member states (Greece and Spain) and the remaining three areas are in
203 countries which are not part of the EU (Turkey, Tunisia, Morocco). Specifically, the study sites
204 are: (i) Crete island, southern Greece, (ii) Guadalentin basin, south-eastern Spain, (iii) Eskisehir
205 plain, Turkey, (iv) Zeuss Koutine, Tunisia and (v) Mamora Sehoul, Morocco. Each study site
206 covers a surface area ranging between 100 km² and 150 km² and includes a number of
207 individual field sites.

208 Field sites were representative of a variety of biophysical and socioeconomic conditions typical
209 of Mediterranean rural landscapes. Data were collected as a part of the extensive fieldwork
210 carried out through the DESIRE research project, financed by European Commission (see
211 Kosmas et al., 2015 and references therein). The field sites are located in areas affected by
212 variable degrees of land degradation, due to their differing levels of soil erosion, salinization,
213 compaction, sealing, contamination, water stress, overgrazing, wildfires and anthropogenic
214 pressures (population growth, tourism development, industrialization, depopulation, land
215 abandonment). In 80% of the study sites, climatic conditions are semi-arid or dry with rainfall
216 ranging between 200 and 600 mm. Reference evapotranspiration > 800 mm (*sensu* Penman)
217 was observed in the majority of field sites. Soils are formed mainly on sedimentary and
218 unconsolidated parent materials. Soil organic matter content in the soil surface has been
219 identified as low to moderate (0.5%-1.5%) in most of the study sites. Dominant vegetation
220 cover types include cereals, olives, vineyards, garden crops and cotton. The agricultural
221 holdings are characterized as owner-farmed in 58% of the sites with farm size ranging from
222 less than 2 hectares to more than 100 ha, and there is a high degree of land fragmentation
223 (Salvati et al., 2015).

224

225 2.2. Data collection

226

227 Data were collected at the scale of field sites, extending 0.5 to 20 ha and having homogeneous
228 soil, topography and land management (Kairis et al., 2014). Field sites were identified from
229 topographic maps and/or ortho-photographs in 400 m grids by applying a systematic sampling
230 design, with precise location being pin-pointed using a GPS (Ferrara et al., 2016). Most
231 information were collected directly from land owners (Kosmas et al., 2015). A digital
232 questionnaire and guidance notes were compiled defining each elementary variable and
233 assessment methodology with the aim of harmonizing data collection across field sites (see

234 Salvati et al., 2015 and references therein for technical details). A total of 49 variables with no
235 missing values were derived from information collected on the field.

236 Values for each variable collected were transformed into a scale indicator (with scores ranging
237 between 1 and 2) describing the (positive or negative) relationship with LD. Increasing scores
238 indicate a higher contribution to land degradation (Kosmas et al., 2015). Existing classification
239 systems (Rubio and Bochet, 1998), reference research frameworks (Lavado Contador et al.,
240 2009) and expert opinion were used to set up the scoring system. Scores are suitable to scale
241 and homogenize the values of the studied variables to a comparable range allowing comparison
242 across space or between different research dimensions (Ferrara et al., 2012).

243

244 *2.3. Indicators*

245

246 A comprehensive set of 40 'state' and 'pressure' indicators assessing LD factors and describing
247 biophysical and socioeconomic conditions where remedial interventions are required to prevent
248 desertification risk were prepared according to Kosmas et al. (2015) and Salvati et al. (2015).
249 Candidate indicators were selected by (i) reviewing the existing literature (Rubio and Bochet,
250 1998; Wilson and Juntti, 2005; Basso et al., 2010; Kairis et al., 2014; Kosmas et al., 2015), (ii)
251 consulting with stakeholders (land users/managers, politicians and research groups working on
252 LD issues at both national and study site level) and (iii) using scientific, technical or planning
253 reports, including National or Regional Action Plans to Combat Desertification. Indicators (list
254 in Table 1, Supplementary materials, and technical details in Table 2, Supplementary materials)
255 were classified into 9 dimensions (4 dimensions assessing biophysical aspects and the
256 remaining 5 dimensions quantifying socioeconomic factors): (a) climate (4 indicators), (b) soil
257 (10), (c) vegetation (3), (d) water runoff and fires (3), (e) agriculture (5), (f) cultivation practices
258 and husbandry (6), (g) land management (10), (h) water use (2) and (i) demography and tourism
259 (4). The overall level of desertification risk in each site was derived according to the
260 Environmentally Sensitive Area (ESA) approach (Lavado Contador et al., 2009), originally
261 produced by EU-funded Mediterranean Desertification and Land Use (MEDALUS) project
262 (Ferrara et al., 2012).

263 Eight indicators (protected areas, terracing, grazing control, fire prevention, economic subsidies
264 to farms, sustainable farming, soil erosion control and soil water conservation) were used to
265 assess land management practices or policy actions with a (supposed) positive impact on LD
266 (Sabbì and Salvati, 2014). These practices were regarded as important interventions against
267 desertification in the study areas and were classified as candidate responses to LD (Salvati et

268 al., 2015). In this sense, response indicators considered in this study cover a representative set
269 of actions undertaken for sustainable land management, landscape conservation or
270 environmental quality protection (Kosmas et al., 2015). However, the selected response
271 indicators are possibly not exhaustive of the entire set of candidate responses to LD since other
272 practices/actions can be important in different territorial contexts.

273

274 *2.4. Statistical analysis*

275

276 A data mining strategy incorporating Principal Component Analysis, Spearman correlations,
277 step-wise multiple regression, non-parametric Mann-Whitney inference and Canonical
278 Correlation Analysis was run on the full sample ($n = 586$ observations). The multivariate
279 techniques considered here were aimed at (i) assessing variety of local socio-ecological
280 systems, (ii) identifying indicators associated with the level of desertification risk, and (iii)
281 evaluating spatial relationships between candidate responses to LD and the related
282 biophysical/socioeconomic background. The indicators considered in each statistical analysis
283 are listed in Table 1.

284 To explore multiple spatial relationships between response indicators, a Principal Component
285 Analysis (PCA) was run on a data matrix including values of all response indicators at each of
286 the 586 field sites. Relevant components with eigenvalue > 1 were analyzed. Non-parametric
287 Spearman rank tests were run with the aim of correlating pair-wise response indicators and
288 biophysical/socioeconomic indicators profiling field sites. Significance was set up at $p < 0.05$
289 after Bonferroni's correction for multiple comparisons.

290 A multiple linear regression model was run to identify response indicators most associated with
291 the level of desertification risk in each field site. The model was developed using a forward
292 stepwise approach with response indicators as predictors and the level of desertification risk as
293 the dependent variable. Predictors were included in the model when the p -level associated to
294 the respective Fisher-Snedecor test was below 0.01. Results of the regression model were
295 illustrated using standardized coefficients and tests of significance for each indicator (an overall
296 Fisher-Snedecor's F-statistic testing for the null-hypothesis of non significant model and a
297 Student's t -statistic testing for the null hypothesis of non significant regression coefficient). A
298 Durbin-Watson statistic testing for the null hypothesis of serially uncorrelated errors was
299 applied separately to regression residuals.

300 Response indicators were analyzed separately using non-parametric Mann-Whitney U statistics
301 testing for significant differences ($p < 0.05$) in the two EU countries (Greece and Spain)

302 compared with the three Mediterranean countries outside of the EU (Morocco, Tunisia,
303 Turkey). This statistic analyzes the occurrence and intensity of different land management
304 actions/practices within and outside the European Union, providing an indirect evaluation of
305 the effectiveness of some EU policies relevant to LD (e.g. farm subsidies). A Canonical
306 Correlation Analysis (CCA) was finally run to investigate the spatial relationship between the
307 20 biophysical indicators (or the 20 socioeconomic indicators) and the 8 response indicators at
308 the spatial scale of field site. The general objective of the CCA is to combine two sets of
309 indicators (e.g. biophysical indicators vs land management actions; socioeconomic indicators
310 vs land management actions) into a common structure formed by few factors (roots) that explain
311 a high proportion of the matrices' variance. The roots' structure was analyzed on the basis of
312 the correlation coefficients with input indicators. The final aim of the CCA was to summarize
313 the results derived from previous analysis' steps providing a comprehensive overview of the
314 complex spatial patterns within the studied indicators, and the spatial relationship between
315 desertification risk, local context and candidate responses to LD.

316

317 **3. Results**

318

319 *3.1. Principal Component Analysis*

320

321 The PCA run on the 8 response indicators at the spatial scale of field site extracted 3 relevant
322 components explaining together more than 65% of the total variance (Table 1). Component 1
323 accounts for 28.5% of the total variance and was correlated positively with soil erosion control
324 measures, soil water conservation measures and the extent of protected areas. Component 2
325 accounts for 19.5% of the total variance with positive loadings assigned to terracing and farm
326 subsidies and a negative loading assigned to fire prevention. Component 3 accounts for 17% of
327 the total variance and outlines the counter-correlation between sustainable farming and grazing
328 control. Figure 1 illustrates the position of each field site over the factorial plane based on
329 components 1 and 2. Component 1 discriminates field sites mainly within non-EU countries
330 (Tunisia, associated with negative or slightly positive scores; Morocco and Turkey associated
331 exclusively with highly positive scores); component 2 discriminates field sites in EU countries
332 (Greece and Spain, receiving positive scores on average) from sites situated in non-EU
333 countries (receiving negative scores on average).

334

335 *3.2. Non-parametric correlations*

336

337 A non-parametric correlation analysis investigating pair-wise relationships between the spatial
338 distribution of response indicators and biophysical or socioeconomic attributes was illustrated
339 in Table 3(Supplementary materials). The level of desertification risk in each field site was
340 correlated positively with the extent of protected areas, fire prevention and grazing control. The
341 remaining 5 response indicators were not associated with desertification risk. Fire prevention
342 was the response indicator with the largest number of significant correlations with biophysical
343 and socioeconomic indicators at the field site scale (78%) preceding sustainable farming (68%)
344 and protected areas (58%). Responses totaling an intermediate number of significant
345 correlations with context indicators were grazing control (54%) and farm subsidies (49%). Soil
346 water conservation measures (46%), terracing (44%) and soil erosion control measures (42%)
347 showed a lower percentage of significant correlations in respect to the other response indicators.
348 Level of fire prevention was found relatively high in field sites with medium-high population
349 density and positive demographic growth rate, tourism intensity and net farm income. By
350 contrast, level of fire prevention was low in areas characterized by semi-arid climate, poor soils,
351 moderate-low plant cover, land fragmentation and small farm size. Based on these evidences,
352 level of fire prevention seems to increase in wealthier rural contexts with suitable conditions
353 for cropping. Similar results were found for sustainable farming, a practice frequently observed
354 in contexts with good climate conditions and farms with young owners and high returns.
355 Protected areas were associated to contexts with good soil and climate quality, being the highest
356 in sites with considerable soil depth and water storage capacity and medium-high plant cover.
357 Protected areas were preferentially observed in areas with stable or moderately increasing
358 population growth, sustainable farming (depending on tillage depth, intensity and direction)
359 and moderate-low rate of land abandonment.

360 Grazing control was a practice more frequently observed in semi-arid and arid land with low-
361 quality soils and in local contexts with high grazing intensity, land abandonment and
362 fragmentation. Farm subsidies were associated with biophysical and socioeconomic indicators
363 reflecting place-specific factors more evidently than regional environmental conditions. Soil
364 water conservation measures were especially observed in rural sites with a young population
365 structure and where sustainable farm practices are routinely applied. Terracing was mainly
366 observed under semi-arid and arid climate regimes and in socioeconomic contexts with intense
367 grazing, high land ownership rate, low tourism intensity and high land abandonment rates.
368 Finally, soil erosion control measures were preferentially observed in areas with high risk of

369 soil erosion, low plant cover, high grazing intensity, parallel employment of farmers in non-
370 agricultural sectors, depopulation and land abandonment.

371

372 *3.3. Multiple regression model*

373

374 Results of a step-wise multiple regression with level of desertification risk as the dependent
375 variable and response indicators as predictors are illustrated in Table 2. The best regression
376 model incorporates four predictors with adjusted $R^2 = 0.25$ and a significant Fisher-Snedecor F
377 test. Model's outcomes are in partial agreement with the findings collected from the non-
378 parametric Spearman analysis (section 3.2). Protected areas and grazing control were the
379 predictors with the highest regression coefficient, preceding terracing and farm subsidies.
380 Desertification risk was higher in field sites with extensive terraces and economic subsidies,
381 decreasing in sites with protected areas and high grazing control.

382

383 *3.4. Non-parametric inference*

384

385 Results of the pair-wise non-parametric Mann-Whitney U test comparing the spatial
386 distribution and intensity of response indicators in EU (n = 276 sites) and non-EU countries (n
387 = 310 sites) indicate that 4 indicators out of 8 were highly different ($p < 0.0001$) in the two
388 groups of countries (grazing control: adj-Z = 11.5; fire prevention: adj-Z = 21.5; farm subsidies:
389 adj-Z = -14.1; protected areas: adj-Z = 7.1). Frequency of sustainable farming (adj-Z = -3.3)
390 and terracing (adj-Z = 3.9) was different ($0.001 < p < 0.05$) between EU and non-EU countries.
391 Two indicators (soil erosion control measures: adj-Z = 0.2; soil water conservation measures:
392 adj-Z = -1.7) show a homogeneous distribution ($p > 0.05$) in both EU and non-EU countries.

393

394 *3.5. Canonical correlation analysis*

395

396 A separate Canonical Correlation Analysis (CCA) was run on the standardized data matrices
397 respectively composed of 20 biophysical indicators (Table 3) and 20 socioeconomic indicators
398 (Table 4), each contrasted with the 8 response indicators observed at the spatial scale of field
399 site. The CCA assessing biophysical indicators extracted 7 roots respectively with 59.6% (left
400 set of input variables) and 94.2% (right set of input variables) in total variance. Each root
401 identified specific response indicators associated with a restricted number of context indicators.
402 Root 1 (respectively 12% and 21% in total variance) was correlated positively with fire

403 prevention and negatively with farm subsidies. The biophysical indicators correlated with Root
404 1 were soil texture and soil water storage capacity (positive coefficients), potential
405 evapotranspiration and rainfall erosivity (negative coefficients). Root 2 (13% and 16% in total
406 variance) was correlated positively with terracing, grazing control, soil drainage and 4 climate
407 indicators (rainfall, aridity index, potential evapotranspiration and rainfall seasonality). The
408 loading's structure of this root suggests that grazing control and terracing are actions strictly
409 dependent on the biophysical context. Root 3 (12% and 19% in total variance) was correlated
410 positively with soil erosion control measures and sustainable farming, in turn associated with
411 the overall degree of soil erosion and runoff water storage (positive coefficients), rainfall and
412 aridity index (negative coefficients). The structure of root 3 indicates that application of soil
413 erosion control measures is dependent on the overall degree of soil erosion. Root 4 (6% and
414 12% in total variance) was correlated positively with farm subsidies, grazing control and rainfall
415 erosivity. Negative coefficients to root 5 (8% and 13% in total variance) were assigned to soil
416 water conservation measures and vegetation cover. Root 6 (5% and 6% in total variance)
417 outlines the association between extent of protected areas and dominant use of land at each site:
418 protected areas were typically associated with priority habitats including forests, high-
419 biodiversity pastures and crop mosaics. Finally, root 7 (5% and 7% in total variance) identified
420 a negative relationship between soil erosion and terracing, confirming that this traditional land
421 management option is an indirect response to biophysical factors triggering erosion risk.

422 The CCA assessing socioeconomic indicators extracted 8 roots respectively with 64.6% (left
423 set of input variables) and 100% (right set of input variables) in total variance. Each root
424 identified one-to-three response indicators in turn associated with a restricted number of
425 contextual indicators. Root 1 (15% and 22% in total variance) was correlated negatively with
426 farm subsidies and positively with fire prevention and grazing control. Three socioeconomic
427 indicators correlated negatively with root 1 (impervious surface area, population growth, aging
428 index). Farm subsidies and sustainable farming were negatively correlated with Root 2 (14%
429 and 15% in total variance), together with 3 socioeconomic indicators (land fragmentation, aging
430 index and land abandonment). Root 3 (14% and 15% in total variance) was associated with
431 grazing control and grazing intensity (negative coefficients) and land abandonment (positive
432 coefficient). Root 4 (6% and 15% in total variance) indicated that impact of farm subsidies
433 (negative coefficient) and sustainable farming (positive coefficient) is counter-correlated in the
434 sample, with population density and net farm income associated with Root 4 with positive and
435 negative sign, respectively. A negative coefficient to root 5 (10% and 10% in total variance)
436 was assigned to both soil water conservation measures and percentage of irrigated arable land.

437 Protected areas (root 6), soil erosion control measures (root 7) and terracing (root 8) were not
438 correlated with any socioeconomic indicator.

439

440 **4. Discussion**

441

442 Research, participatory processes, tools for policy makers and local-scale responses are seen as
443 key components of an integrated strategy to fight desertification in the Mediterranean basin
444 (Reynolds et al., 2011). The positive (research) and normative (policy) interest in human
445 responses to LD usually focuses on sectoral policies and single-target measures that are
446 designed to mitigate environmental degradation in affected or vulnerable areas (Omuto et al.,
447 2013). Conversely, actions targeting either the resources impacted and/or the drivers and
448 proximate causes of degradation are considered 'best practices' in strategies designed to mitigate
449 LD. Policy implementation in different socioeconomic and biophysical contexts necessitates
450 responses which support adaptive management and effective local governance (Thomas et al.,
451 2012), because human responses to LD are inevitably context-specific and contingent (Wilson
452 and Juntti, 2005).

453 The study reported in this paper contributes to the debate on the characterization of candidate
454 responses to LD, trying to identify specific 'response assemblages' based on spatial convergence
455 of different land management practices across a range of local contexts. The approach proposed
456 here contributes to a decision support system that can be used by various stakeholders for joint
457 monitoring drivers and candidate responses of land degradation in local contexts characterized
458 by different environmental and socioeconomic conditions. The approach is distinctively based
459 on the exploratory analysis of a comprehensive set of indicators collected in 586 field sites
460 identifying (apparent or latent) relationships between LD drivers and candidate responses,
461 depending on the intimate characteristics of each local context. In this sense, our results outline
462 the role of 'state' and 'pressure' variables of a local system (e.g. climate dryness, soil quality,
463 vegetation cover, land abandonment), confirming the results of earlier studies (Basso et al.,
464 2010; Kosmas et al., 2015; Salvati et al., 2015). The evident complexity in the system of
465 relationships between drivers and candidate responses to LD allows distinguishing biophysical
466 factors (often characterized by one-to-one relationships between drivers and responses) from
467 socioeconomic factors (more frequently characterized by relationships among multiple drivers
468 and one response), corroborating the interpretative framework provided in Salvati et al. (2015).
469 Evidences of this study may encourage more refined research applied to the comprehensive
470 analysis of a local system (Stavi et al., 2015) and its evolution in terms of ecological aspects

471 (e.g. soil quality, geo-diversity and vegetation) or socioeconomic conditions (e.g. changes in
472 the social and economic base with impact on the produced value added).

473 Candidate responses to LD can be classified as 'broad' or 'narrow' spectrum based on the
474 observed correlation with the local background and the overall level of desertification risk (e.g.
475 Salvati and Zitti, 2009). Fire prevention, sustainable farming and protected areas were identified
476 as broad-spectrum actions (Kosmas et al., 2015). Grazing control and farm subsidies were
477 classified as medium-spectrum actions since they operate at the farm scale with indirect impact
478 on LD in terms of economic and environmental sustainability. By contrast, soil conservation
479 measures and terracing practices are intended to cope specifically with soil degradation
480 processes and are correlated primarily with soil indicators. Results of non-parametric inference
481 confirm the local-scale target of soil conservation measures - possibly less relevant in EU policy
482 in respect with actions classified as 'broad-spectrum', such as farm subsidies or land protection,
483 or in national/regional strategies in respect with sectoral measures such as fire prevention,
484 grazing control, sustainable farming or terracing.

485 Moreover, the candidate responses investigated in this study show distinct spatial relationships
486 depending on the level of desertification risk and the underlying territorial context (Salvati et
487 al., 2015). These evidences may outline divergent responses of the socio-environmental local
488 systems to ecological disturbances, highlighting possible mismatches between single-action
489 responses and the related biophysical conditions prevailing at the time (Garcia-Orenes et al.,
490 2010) For example, our data indicate that measures for soil conservation were more frequently
491 adopted in regions with high soil quality. Whilst most sites experienced a single-action response
492 in our sample, the analysis of the spatial relationship between responses indicates a diversified
493 set of candidate 'response assemblages' based on the co-existence of different actions with
494 positive (or negative) feedbacks within the local context. Although practices considered in this
495 study are seen as particularly important in the field sites investigated, different practices/actions
496 can be relevant in other socioeconomic contexts or better suited to mitigate LD in other
497 environmental conditions. An improved knowledge of latent relationships between local
498 contexts and a comprehensive set of actions/practices seen as candidate responses to LD is
499 therefore a key issue to inform policy strategies which target desertification (Bisaro et al.,
500 2013).

501 In this sense, the approach illustrated in this paper may inform the development of practical
502 tools for (i) analysis of response indicators derived from a comprehensive set of LD indicators,
503 (ii) assessment of spatial relationships between context and response indicators and, based on
504 this background, (iii) characterization of 'response assemblages' to LD at both local and regional

505 scales. Data mining is a promising tool to classify field sites and candidate responses into
506 homogeneous groups according to specific territorial conditions.

507 PCA results indicate both convergent and divergent patterns characterizing the spatial
508 distribution of response indicators, identifying three homogeneous sets of actions/practices
509 respectively coping with (i) soil conservation, (ii) sustainable farm management and (iii) natural
510 vegetation protection. Measures impacting soil degradation (containing soil erosion or
511 improving soil water conservation) were more frequently observed in sites where a considerable
512 proportion of land is protected, indicating a high level of environmental policy enforcement
513 (Kosmas et al., 2015). While suggesting that measures of soil conservation are more frequently
514 applied in protected areas compared with other measures protecting natural habitats, such as
515 fire prevention, our evidences contribute to shed light on the multiple spatial relationships
516 between candidate LD responses. However, these results need further empirical verification
517 against a larger sample of sites representative for vastly different land-use, socioeconomic and
518 environmental conditions.

519 Measures contributing to farm sustainability (sustainable farming, grazing control) were found
520 uncorrelated with soil conservation and fire prevention actions in the studied sites. This
521 evidence suggests how candidate responses are critically influenced by short- and long-term
522 land-use decisions, acting with a variable intensity on a (more or less) wide spectrum of land
523 cover types and landscapes (Salvati et al., 2015). In this sense, measures specifically designed
524 to protect natural vegetation (e.g. fire prevention) were demonstrated to be spatially associated
525 with specific measures dealing with sustainable management of farmland (i.e. terracing and
526 farm subsidies). These evidences are in agreement with earlier studies (Weissteiner et al., 2011;
527 Kelly et al., 2015; Kosmas et al., 2015). Economically-disadvantaged rural districts preserving
528 high-diversity crop mosaics may benefit from a set of actions against LD that include protection
529 of natural vegetation, economic subsidies and interventions for land consolidation supporting
530 traditional cropping systems (Ferrara et al., 2016). Such correlation patterns may indicate a
531 process of spatial divergence in the studied actions/practices, shaping the effectiveness of
532 candidate 'response assemblages' at the local scale. Spatial convergence of different
533 environmental measures is an interesting issue in the analysis of responses to LD requiring
534 further investigation on theoretical frameworks and empirical evidences from representative
535 environments (Salvati and Zitti, 2009).

536 Although data mining techniques provide useful information to improve our knowledge on the
537 multiple relationships characterizing complex socio-environmental systems, there are
538 limitations to this approach because correlation and similarity patterns do not necessarily imply

539 causation processes (Kosmas et al., 2015). As many other quantitative exercises based on a
540 large number of input variables, our approach proposes a standardized selection and
541 classification of biophysical and socioeconomic indicators in fixed groups based on objective -
542 but possibly questionable - criteria and value's thresholds (Salvati et al., 2015). In this sense, a
543 mixed framework integrating exploratory quantitative approaches with a qualitative and
544 descriptive analysis based on a deep knowledge of test areas through bibliographic analysis,
545 interviews with local stakeholders and field observation is adequate to improve knowledge of
546 complex socio-environmental systems (Kelly et al., 2015).

547

548 **5. Conclusions**

549

550 Our study suggests how land management actions/practices, intended as candidate responses to
551 LD, are largely dependent on the local context. Mitigation plans and SLM strategies are
552 increasingly committed to promote a policy shift from single-driver and process-specific targets
553 to a more comprehensive set of practical actions integrating responses adapted to local contexts.
554 In this way, research is required to indicate mechanisms involving stakeholders in problem
555 analysis and solution-finding for application of adaptable and context-specific responses to LD.
556 Since stakeholders have different perceptions of desertification risk, establishing (or
557 intensifying) dialogue between stakeholders, policy-makers and the general public will
558 contribute to increase effectiveness of land management actions in LD containment. An
559 improved analysis of environmental indicators assessing practical actions combating or
560 reversing LD and investigation on the effectiveness of joint responses to LD at various spatial
561 scales is hence essential to design mitigation strategies based on the identification of appropriate
562 response assemblages.

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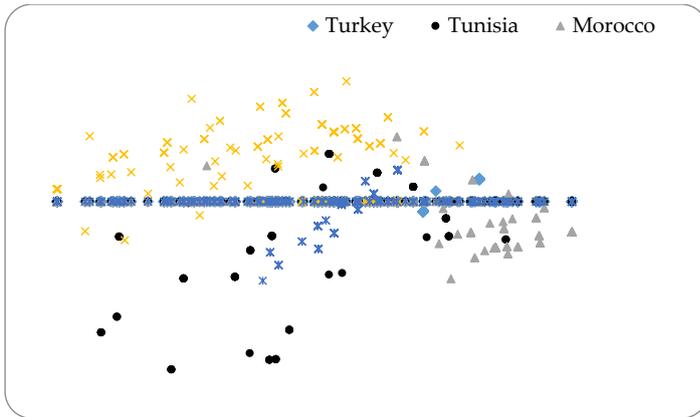
706

707 Table 1. Principal Component Analysis loadings (> |0.5|).

Variable	PC 1	PC 2	PC 3
Farm subsidies		0.50	
Protected areas	0.69		
Fire prevention		-0.65	
Sustainable farming			0.67
Soil erosion control	0.71		
Soil water conservation	0.50		
Terracing		0.60	
Grazing control			-0.52
<i>Explained variance (%)</i>	<i>28.6</i>	<i>19.5</i>	<i>17.0</i>

708

709 Figure 1. Principal Component score plot of the 586 field sites investigated in the present study by country (PC 1: x-axis *vs* PC 2:
710 y-axis).



711

712

713 Table 2. Results of the step-wise multiple linear regression with desertification risk as the dependent variable and the 8 response
714 indicators to land degradation (predictors) observed at each of the 586 plots investigated in the present study (adjusted R² =
715 0.248, $F_{(4,581)} = 49.3$, $p < 0.001$).

Variable	Beta	Std.Err.	<i>t</i> (581)	<i>p</i> -level
Intercept	0.000	0.030	1.342	0.180
Protected areas	0.442	0.038	11.624	0.000
Grazing control	0.277	0.039	7.030	0.000
Terracing	-0.186	0.039	-4.790	0.000
Farm subsidies	0.128	0.039	3.321	0.001

716

717 Table 3. Canonical analysis run between biophysical indicators and response indicators in the 586 plots investigated in the
 718 present study (bold indicates significant correlations with coefficient > |0.5|).

Variable	Root 1	Root 2	Root 3	Root 4	Root 5	Root 6	Root 7
<i>Biophysical indicators</i>							
<i>% variance</i>	0.12	0.13	0.12	0.06	0.08	0.05	0.05
Degree of erosion	-0.07	-0.06	0.52	0.21	-0.42	0.13	-0.50
Major land use	0.08	0.01	-0.17	0.41	0.05	0.66	0.23
Vegetation cover type	0.41	0.29	0.47	0.30	-0.11	0.05	-0.14
Rainfall	0.37	-0.51	-0.56	0.24	-0.14	-0.07	-0.08
Aridity index	0.21	-0.50	-0.54	-0.21	-0.39	-0.24	0.05
Potential evapotranspiration	-0.66	-0.51	-0.22	0.13	-0.25	0.00	-0.12
Rainfall seasonality	-0.11	0.78	-0.40	-0.15	0.05	0.14	0.21
Rainfall erosivity	-0.51	0.30	-0.01	0.52	0.25	0.27	0.00
Parent material	-0.19	-0.26	-0.05	0.18	-0.08	0.09	-0.12
Rock fragments	0.12	-0.06	-0.16	-0.14	0.11	-0.16	0.11
Slope aspect	-0.09	-0.06	0.23	0.06	0.16	0.13	-0.42
Slope gradient	-0.43	0.26	-0.06	-0.01	-0.04	0.37	-0.29
Soil depth	0.14	0.04	0.03	0.27	-0.47	-0.02	-0.15
Soil texture	0.56	0.16	-0.22	0.21	0.03	0.04	-0.24
Soil water storage capacity	0.50	0.25	-0.17	0.00	-0.49	0.33	-0.08
Exposure of rock outcrops	0.30	-0.09	0.12	0.48	-0.10	-0.20	-0.14
Organic matter surface horizon	0.49	-0.29	-0.30	-0.05	-0.20	0.25	-0.04
Plant cover	0.18	-0.36	0.06	-0.05	-0.53	0.17	-0.23
Drainage density	0.09	-0.70	0.47	-0.03	0.22	-0.01	-0.26
Runoff water storage	0.33	-0.10	0.71	0.03	-0.44	0.16	0.24
<i>Response indicators</i>							
<i>% variance</i>	0.21	0.16	0.19	0.12	0.13	0.06	0.07
Farm subsidies	-0.59	-0.43	0.40	0.54	0.10	-0.02	0.03
Protected areas	0.48	0.03	0.47	-0.35	-0.16	0.62	-0.04
Fire prevention	0.94	-0.30	-0.02	0.07	-0.12	0.00	-0.03
Sustainable farming	0.10	0.11	0.80	-0.43	0.10	-0.31	0.09
Soil erosion control	0.16	0.29	0.67	0.02	-0.47	-0.14	-0.25
Soil water conservation	-0.05	0.40	0.04	0.07	-0.79	-0.06	-0.02
Terracing	0.09	0.54	0.11	0.33	-0.22	-0.02	0.68
Grazing control	0.42	0.66	0.13	0.51	0.27	-0.03	-0.17

720 Table 4. Canonical analysis run between socioeconomic indicators and response indicators in the 586 plots investigated in the
 721 present study (bold indicates significant correlations with coefficient > |0.5|).

Variable	Root 1	Root 2	Root 3	Root 4	Root 5	Root 6	Root 7	Root 8
<i>Socioeconomic indicators</i>								
<i>% variance</i>	0.15	0.14	0.10	0.06	0.10	0.05	0.02	0.02
Impervious surface area	-0.69	-0.32	-0.18	-0.01	0.34	-0.02	-0.08	-0.14
Burned area	-0.27	0.22	-0.27	-0.16	-0.15	0.35	0.29	0.03
Farm ownership	-0.07	0.38	-0.57	-0.08	-0.25	-0.16	-0.01	0.09
Farm size	-0.40	0.30	0.15	-0.30	0.34	0.41	-0.05	0.00
Land fragmentation	-0.44	-0.67	0.11	0.14	-0.24	-0.11	-0.21	0.01
Net farm income	-0.01	0.22	0.33	-0.54	-0.29	0.08	-0.17	-0.26
Parallel employment	0.40	-0.33	0.41	0.05	-0.28	-0.38	0.02	0.21
Tillage operations	0.20	-0.31	0.34	0.12	0.42	0.28	0.04	0.04
Tillage depth	0.28	-0.38	0.21	0.16	0.25	0.29	-0.26	-0.03
Tillage direction	0.07	-0.45	0.22	-0.05	0.44	0.20	0.22	0.01
Grazing intensity	0.46	0.16	-0.72	0.05	-0.19	0.18	-0.02	0.14
Land use intensity	-0.16	-0.49	-0.03	0.04	0.14	0.44	0.04	-0.06
Period of existing land use	0.34	-0.44	0.00	-0.30	0.28	0.02	0.03	-0.31
Irrigation percentage of arable land	0.21	0.39	0.23	0.33	-0.69	-0.04	0.02	0.23
Tourism intensity	0.12	0.19	0.23	-0.20	0.17	0.12	-0.13	0.20
Aging index	-0.64	-0.64	-0.06	-0.31	-0.13	-0.02	0.01	-0.06
Population density	-0.02	0.30	-0.33	0.61	0.46	0.11	-0.12	-0.19
Population growth	-0.93	0.07	-0.20	-0.13	0.00	0.10	0.01	0.04
Frequency of tillage	0.09	0.12	0.25	0.05	0.07	0.22	-0.38	0.04
Land abandonment	-0.11	-0.52	0.52	-0.01	-0.34	-0.08	0.11	-0.25
<i>Response indicators</i>								
<i>% variance</i>	0.22	0.15	0.15	0.15	0.10	0.06	0.06	0.11
Farm subsidies	-0.57	-0.53	-0.03	-0.57	-0.23	-0.04	0.01	-0.10
Protected areas	0.46	-0.26	0.31	0.41	-0.25	0.53	-0.33	-0.06
Fire prevention	0.89	0.10	0.36	-0.18	-0.18	-0.08	-0.02	-0.05
Sustainable farming	0.16	-0.75	0.09	0.58	0.00	-0.20	0.14	-0.04
Soil erosion control	0.24	-0.41	-0.32	0.28	-0.37	-0.31	-0.58	-0.14
Soil water conservation	-0.07	0.32	-0.24	0.49	-0.71	-0.11	0.08	-0.27
Terracing	0.12	0.03	-0.48	0.06	0.11	0.03	-0.04	-0.86
Grazing control	0.55	-0.09	-0.77	-0.09	-0.07	0.19	0.19	0.05

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736 **SUPPLEMENTARY MATERIALS**

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738 Table 1. List of the indicators used in the data mining approach presented in this study (see Table
739 2(Supplementary materials), for a complete description of variables including technical details).

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Variable	Class	PCA	SRC	MLR	MWU	CA
Desertification risk	D		•	•		
Degree of erosion	B		•			•
Major land-use/cover	B		•			•
Vegetation cover type	B		•			•
Rainfall	B		•			•
Aridity index	B		•			•
Potential evapotranspiration	B		•			•
Rainfall seasonality	B		•			•
Rainfall erosivity	B		•			•
Parent material	B		•			•
Rock fragments	B		•			•
Slope aspect	B		•			•
Slope gradient	B		•			•
Soil depth	B		•			•
Soil texture	B		•			•
Soil water storage capacity	B		•			•
Exposure of rock outcrops	B		•			•
Organic matter surface horizon	B		•			•
Plant cover	B		•			•
Drainage density	B		•			•
Runoff water storage	B		•			•
Impervious surface area	S		•			•
Burned area	S		•			•
Farm ownership	S		•			•
Farm size	S		•			•
Land fragmentation	S		•			•
Net farm income	S		•			•
Parallel employment	S		•			•
Tillage operations	S		•			•
Tillage depth	S		•			•
Tillage direction	S		•			•
Grazing intensity	S		•			•
Land use intensity	S		•			•
Period of existing land use	S		•			•
Irrigation percentage of arable land	S		•			•
Tourism intensity	S		•			•
Population aging index	S		•			•
Population density	S		•			•
Population growth	S		•			•
Frequency of tillage	S		•			•
Land abandonment	S		•			•
Farm subsidies	P	•	•	•	•	•
Protected areas (policy enforcement)	P	•	•	•	•	•
Terracing	P	•	•	•	•	•
Grazing control	P	•	•	•	•	•
Fire prevention	P	•	•	•	•	•
Sustainable farming	P	•	•	•	•	•
Soil erosion control	P	•	•	•	•	•
Soil water conservation	P	•	•	•	•	•

741 D = dependent variable; B = biophysical context variables; S = socioeconomic context variables; P = policy-relevant indicators
742 assessing the intensity of land management actions. PCA = Principal Component Analysis (results in Table 1, Figure 1), SRC:
743 Spearman Rank Correlation analysis (results in Table 3, Supplementary materials); MLR: Multiple Linear Regression (results in
744 Table 2); MWU = Mann-Whitney U-test (results in main text, section 3.4); CA = Canonical Analysis (results in Tables 3 and 4).

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746 Table 2. List of indicators with class ranking and the related score.

CLIMATE								
Annual rainfall (mm)	<280	280-650	650-1000	>1000				
	2	1.6	1.3	1.0				
Aridity index	<50	50-75	75-100	100-125	125-150	>150		
	1.0	1.2	1.4	1.6	1.8	2.0		
Annual potential evapotranspiration (mm)	<500	500-800	800-1200	1200-1500	>1500			
	1.0	1.2	1.5	1.8	2.0			
Rainfall seasonality	<0.19	0.20-0.39	0.40-0.59	0.60-0.79	0.80-0.99	1.00-1.19	>1.20	
	1.0	1.2	1.4	1.6	1.8	1.9	2.0	
Rainfall erosivity (mm/h)	<60	60-90	91-120	121-160	>160			
	1.0	1.2	1.5	1.8	2.0			
SOIL								
Parent material	Limestone-marble	Acid Igneous	Sandstone, flysh	Marl, clay, conglomerates	Basic Igneous	Shale Schist	Alluvium, colluvium	
	2.0	1.8	1.6	1.3	1.4	1.2	1.0	
Rock fragments on soil surface (%)	<15	15-40	40-80	>80				
	2.0	1.0	1.6	1.8				
Slope aspect	N, NW, NE	S, SW, SE	Plain					
	1.0	2.0	1.0					
Slope gradient (%)	<2	2-6	6-12	12-18	18-25	25-35	35-60	>60
	1.0	1.2	1.4	1.6	1.7	1.8	1.9	2.0
Soil depth (cm)	<15	15-30	30-60	60-100	100-1500	>150		
	2.0	1.8	1.6	1.4	1.2	1.0		
Soil textural class	Very coarse	Coarse	Medium	Moderate fine	Fine	Very fine		
	2.0	1.8	1.6	1.2	1.3	1.4		
Soil water storage capacity (mm)	<50	50-100	100-200	200-300	>300			
	2.0	1.8	1.5	1.3	1.0			
Exposure of rock outcrops (%)	None	2-10	10-30	30-60	>60			
	1.0	1.3	1.5	1.8	2.0			
Organic matter of surface horizon(%)	High >6.0	Medium 2.1-6.0	Low 2.0-1.1	Very low <1.0				
	1.0	1.3	1.6	2.0				
Degree of soil erosion	None	Slight	Moderate	Severe	Very severe			
	1.0	1.2	1.5	1.8	2.0			
VEGETATION								
Major land-use	Agriculture	Pasture	Shrubland	Forest	Mining	Recreation		
	1.5	1.6	1.4	1.0	2.0	1.2		
Agricultural cover type	Cereals	Olives	Vines	Almonds	Oranges	Vegetables	Cotton	
	2.0	1.0	1.4	1.3	1.6	1.8	1.5	
Plant cover (%)	<10	10-25	25-50	50-75	>75			
	2.0	1.8	1.5	1.3	1.0			

WATER RUNOFF								
Drainage density (km of channels per km ²)	Coarse <5 km	Medium 5-10 km	Fine 10-20 km	Very fine >20 km				
	1.0	1.3	1.7	2.0				
Impervious surface area (ha/10 km ² of territory / 10 years)	Low <10 ha	Moderate 10-25 ha	High 26-50 ha	Very high >50 ha				
	1.0	1.3	1.7	2.0				
Burnt area (ha burnt land over 10years/10km ² of territory)	Low (<10 ha)	Moderate (10 - 25 ha)	High (26 - 50 ha)	Very high (>50 ha)				
	1.0	1.3	1.7	2.0				
AGRICULTURE								
Farm ownership	Owner – farmed	Tenant – farmed	Shared – farmed	State – farmed				
	1.0	2.0	1.5	1.7				
Farm size (ha)	<2	2 – 5	5 – 10	10 – 30	30 - 50	50 – 100	>100	
	2.0	1.8	1.6	1.5	1.3	1.1	1.0	
Land fragmentation (Number of parcels)	1-3	4-6	7-9	10-12	13-15	16-19	>19	
	1.0	1.2	1.4	1.6	1.8	1.9	2.0	
Net farm income	Low (<Local mean - St.	Moderate (>Local mean -	High (> Local Mean < Local	Very high (> Local Mean + St.				
	2.0	1.7	1.3	1.0				
Parallel employment	NO	Industry	Tourism	State	Municipality			
	1.0	2.0	1.4	1.7	1.5			
CULTIVATION PRACTICES AND HUSBANDRY								
Tillage operations	NO	Plowing	Disking, harrowing	Cultivator				
	1.0	2.0	1.7	1.4				
Frequency of tillage (number)	NO	1	2	3	4			
	1.0	1.2	1.4	1.7	2.0			
Tillage depth (cm)	NO	<20	20-30	30-40	>40			
	1.0	1.1	1.3	1.7	2.0			
Tillage direction	Down-slope	Up-slope	Parallel to Contour up-	Parallel to Contour down-	Down-slope Oblique	Up-slope Oblique	Other (No tillage)	
	2.0	1.4	1.2	1.5	1.8	1.3	1.0	
Grazing intensity (livestock density, SR, vs. grazing capacity, GC, in each site)	Low (SR<GC)	Moderate SR=GC to	High (SR>1.5GC)					
	1.0	1.5	2.0					
LAND-USE								
Land-use intensity (% class area of intense use of land)	Low (< 25%)	Medium (25- 75%)	High (> 75%)					
	1.0	1.5	2.0					
(Period) of existing land use	< 1 year	1-5 years	5-10 years	10-20 years	30-50 years	> 50 years		
	2.0	1.8	1.6	1.4	1.2	1.0		
Land abandonment (10ha/years/10km ²)	Very high (> 50)	High (26-50)	Moderate (10- 25)	Low (< 10)				
	2.0	1.6	1.3	1.0				
WATER USE								
Irrigation percentage of arable land	< 5	5-10	10-25	25-50	> 50			
	2.0	1.8	1.6	1.3	1.0			
Runoff water storage	No	Low	moderate	adequate				
	2.0	1.8	1.4	1.0				

DEMOGRAPHY AND TOURISM						
Population aging index (population >65 / total population = R, %)	Low R<5	Moderate R=5-10	High R=10-20	Very high R>20		
	1.0	1.3	1.7	2.0		
Population density (inhabitants / km ²)	Low <50	Moderate 50-100	High 100-300	Very high >300		
	1.0	1.3	1.7	2.0		
Population growth rate (% per year)	Low <0.2	Moderate 0.2-0.4	High 0.4-0.6	Very high >0.6		
	1.0	1.3	1.7	2.0		
Tourism intensity (number of overnight stays /10 km ² =R)	Low R<0.01	Moderate R=0.01-0.04	High R=0.04-0.08	Very high R>0.08		
	1.0	1.3	1.7	2.0		
RESPONSE INDICATORS						
Fire prevention (land protected from fires in total area)	NO	Low < 25%	Moderate 25-50%	High 50-75%	Very high > 75%	
	2.0	1.8	1.6	1.3	1.0	
Grazing control	NO	Sustainable number of	Fencing	Avoidance of soil compaction (wet soil)	Fire Protection	
	2.0	1.0	1.2	1.4	1.3	
Sustainable farming	No sustainable	No tillage	Minimum tillage	Inducing plant cover	Up-slope tillage	Minimum ploughing
	2.0	1.0	1.3	1.1	1.4	1.5
Soil erosion control (% area protected in total area, %, excluding terracing)	NO	Low, <25% protected	Moderate, 25-75% protected	Adequate, >75% protected		
	2.0	1.7	1.4	1.0		
Soil water conservation	Weed control	Mulching	temporary storage	inducing vapor adsorption	No	
	1.0	1.0	1.0	1.2	2.0	
Terracing (% area under terracing)	No area	Low, <25%	Moderate, 25-50%	High, 50-75%	Very high, >75%	
	2.0	1.7	1.5	1.2	1.0	
Farm subsidies (by motivation)	NO	Environmental protection	Per-area subsidies	Per-animal subsidies	Per-product	
	1.2	1.0	2.0	2.0	2.0	
Protected areas (policy enforcement)	Adequate > 75% of the area	Moderate (25-75% of the area)	Low (< 25% of the area)	No		
	1.0	1.4	1.7	2.0		

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Table 3. Non-parametric Spearman pair-wise rank correlation analysis between biophysical (or socioeconomic) indicators and response indicators to land degradation in the 586 plots investigated in the present study (bold indicates significant correlations tested at $p < 0.05$ after Bonferroni's correction for multiple comparisons).

Variable	Grazing control	Fire prevention	Sustainable farming	Soil erosion control measures	Soil water conservation measures	Terracing	Farm subsidies	Protected areas
Desertif risk	0.21	0.26	0.06	0.07	-0.06	-0.07	-0.08	0.30
Degree of erosion	0.01	-0.05	0.21	0.40	0.18	-0.06	0.29	0.16
Major land use	0.40	0.14	-0.41	0.03	0.16	0.22	-0.01	-0.01
Veget. cover type	0.50	0.31	0.28	0.38	0.23	0.23	-0.05	0.34
Rainfall	-0.15	0.59	-0.31	-0.19	-0.13	-0.19	-0.17	-0.03
Aridity index	-0.46	0.22	-0.41	-0.24	-0.07	-0.20	-0.16	-0.19
Pot. evapotransp.	-0.55	-0.38	-0.30	-0.20	0.00	-0.28	0.48	-0.45
Rain seasonality	0.36	-0.21	-0.22	-0.11	0.18	0.44	-0.41	-0.09
Rainfall erosivity	0.22	-0.54	-0.06	-0.03	-0.14	0.28	0.48	-0.36
Parent material	-0.22	-0.21	-0.12	-0.11	0.00	-0.18	0.34	-0.22
Rock fragments	-0.09	0.14	0.00	-0.09	-0.12	-0.06	-0.13	-0.05
Slope aspect	0.02	-0.10	0.08	0.12	-0.11	-0.12	0.18	0.05
Slope gradient	-0.01	-0.46	-0.09	-0.05	0.12	0.03	0.11	-0.06
Soil depth	0.13	0.13	0.02	0.18	0.33	0.01	-0.10	0.14
Soil texture	0.40	0.48	-0.12	0.08	-0.03	0.08	-0.35	0.18
Soil water storage	0.27	0.42	-0.01	0.21	0.36	0.06	-0.44	0.45
Expos. rock outcrops	0.22	0.35	0.07	0.17	0.00	0.06	0.14	0.04
Org. matt. surf. horiz.	-0.07	0.58	-0.26	-0.12	-0.06	-0.10	-0.32	0.22
Plant cover	-0.23	0.27	-0.07	0.15	0.09	-0.24	-0.02	0.21
Drainage density	-0.32	0.18	0.27	0.04	-0.30	-0.47	0.37	0.14
Impervious surf area	-0.30	-0.64	0.30	0.07	-0.22	0.00	0.62	-0.26
Burned area	0.12	-0.29	-0.29	-0.16	0.14	0.05	0.14	-0.21
Farm ownership	0.37	-0.17	-0.34	0.11	0.33	0.22	-0.05	-0.29
Farm size	-0.26	-0.21	-0.44	-0.41	-0.23	-0.03	0.10	-0.29
Land fragmentation	-0.28	-0.53	0.47	0.24	-0.04	-0.15	0.57	0.01
Net farm income	-0.16	0.36	-0.44	-0.16	-0.02	-0.10	0.06	-0.04
Parallel employment	-0.09	0.34	0.45	0.26	-0.04	-0.26	-0.01	0.37
Tillage operations	-0.04	0.23	0.26	-0.09	-0.36	-0.11	-0.10	0.23
Tillage depth	-0.04	0.21	0.35	0.00	-0.32	-0.15	-0.08	0.35
Tillage direction	-0.06	0.12	0.32	-0.12	-0.40	-0.13	0.06	0.13
Grazing intensity	0.76	0.22	-0.07	0.27	0.21	0.36	-0.28	0.11
Land use intensity	0.01	-0.22	0.29	0.03	-0.19	0.00	0.28	0.07
Period exist. land use	0.05	0.11	0.09	0.00	-0.41	0.06	0.16	0.00
Irr. % arable land	-0.01	0.28	-0.07	0.09	0.49	-0.22	-0.37	0.32
Runoff water storage	0.09	0.40	0.41	0.41	0.15	0.08	0.04	0.53
Tourism intensity	-0.11	0.21	-0.21	-0.19	-0.19	-0.23	-0.10	0.05
Pop. aging index	-0.26	-0.63	0.25	0.10	-0.18	-0.08	0.81	-0.30
Pop. density	0.16	-0.19	0.02	-0.04	0.18	0.32	-0.47	0.05
Pop. growth rate	-0.41	-0.82	-0.24	-0.21	0.08	-0.06	0.56	-0.56
Freq. tillage	-0.30	0.13	-0.04	-0.25	-0.15	-0.32	-0.27	0.27
Land abandonment	-0.34	0.00	0.46	0.18	-0.15	-0.27	0.39	0.23

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