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Unveiling soil degradation and desertification risk in the Mediterranean basin: a data mining analysis of the relationships between biophysical and socioeconomic factors in agro-forest landscapes

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Soil degradation and desertification processes in the Mediterranean basin reflect the interplay between environmental and socioeconomic drivers. An approach to evaluate comparatively the multiple relationships between biophysical variables and socioeconomic factors is illustrated in the present study using the data collected from 586 field sites located in five Mediterranean areas (Spain, Greece, Turkey, Tunisia and Morocco). A total of 47 variables were chosen to illustrate land-use, farm characteristics, population pressure, tourism development, rainfall regime, water availability, soil properties and vegetation cover, among others. A data mining approach incorporating non-parametric inference, principal component analysis and hierarchical clustering was developed to identify candidate syndromes of soil degradation and desertification risk. While field sites in the same study area showed a substantial similarity, the multivariate relationship among variables diverged among study areas. Data mining techniques proved to be a practical tool to identify spatial determinants of soil degradation and desertification risk. Our findings identify the contrasting spatial patterns for biophysical and socioeconomic variables, in turn associated with different responses to land degradation.

Keywords: data mining; human pressure; indicators; response assemblage; Mediterranean region

1. Introduction

Soil degradation and desertification risk (SD&D) is a globally acknowledged issue with ecological, socioeconomic, cultural and political implications at both the regional and local scales. SD&D processes occur in both developed and emerging countries and affect arid, dry and even sub-humid areas (Strijker 2005; Koulouri and Giourga 2007; Helming *et al.* 2011; Corbelle-Rico, Crecente-Maseda, and Sante-Riveira 2012; Omuto, Balint, and Alim 2013; Stringer and Harris 2014). Although research has been carried out with the aim to identify the spatial determinants of SD&D and to classify them into homogeneous classes (Salvati *et al.* 2011), a comparative approach to evaluate the impact

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of regional-scale drivers and to rank the importance of a number of site specific biophysical and socioeconomic factors deserves further investigation (Salvati and Zitti 2009; Bisaro *et al.* 2013). The development of proper indicators and comparative approaches to inform mitigation policies is a research priority identified by United Nations Convention to Combat Desertification (COP9 2009) with special focus for traditional agro-forest systems which seem to be particularly endangered by land degradation in southern Europe (Marathianou *et al.* 2000; Scarascia-Mugnozza *et al.* 2000; Basso *et al.* 2010; Kairis *et al.* 2014).

Considered as a crucial environmental problem in the Mediterranean basin (Zdruli 2013; Salvati 2014), SD&D includes complex phenomena involving a number of biophysical attributes of the landscape (e.g. climate, soil, vegetation) together with processes triggered by human activities (e.g. land-use changes, crop intensification, land abandonment, population density, industry and tourism concentration, among others). Indicator based methodologies have been developed mainly for permanent monitoring of biophysical factors at the base of SD&D processes (Basso *et al.* 2010; Salvati 2010; Ferrara *et al.* 2012). One of the most widespread methodologies adopted for the study of SD&D in the Mediterranean region is the environmentally sensitive area (ESA) framework (Kosmas, Kirkby, and Geeson 1999; Izzo *et al.* 2013). The ESA methodology produces a composite index (the so called ESAI) classifying land into different levels of sensitivity to desertification (i.e. “not affected” by SD&D, “potentially affected”, “fragile” and “critical”). Unfortunately, the ESAI underestimates and simplifies the complex system of relationships existing among biophysical and socioeconomic factors (Salvati and Zitti 2009).

A novel concept was recently introduced that points out the importance of the “syndrome” concept in Mediterranean SD&D processes (Weissteiner *et al.* 2011). The “syndrome” approach has been used to describe bundles of interactive processes and symptoms which appear repeatedly and in many places (Schellnhuber *et al.* 1997) in typical combinations and patterns (Lüdeke, Petschel-Held, and Schellnhuber 2004). The notion of “syndrome” has been extended to SD&D with the aim to identify and describe the intimate relationships among (and to infer the consequences of) relevant factors (Hill *et al.* 2008). Depending on data availability, SD&D processes and land degradation syndromes can be evaluated for both past and present environmental conditions and used as a baseline information when implementing sustainable land management (SLM) strategies at the desired geographical scale (Zdruli 2013). At the same time, SD&D syndromes are characterized by specific relationships among biophysical and socioeconomic variables depending on the impact of site specific factors and regional drivers (Reynolds *et al.* 2011). A comparative analysis of the relationships existing among a large number of biophysical and socioeconomic factors in different Mediterranean agro-forest landscapes may contribute to: (1) identifying and better characterizing SD&D processes; (2) quantifying SD&D environmental and socioeconomic impacts; and (3) developing mitigation policies with useful information to design adaptation strategies for regional based or local based syndromes (Salvati 2010).

The present study introduces an exploratory framework based on data mining techniques applied on indicators representing a wide set of biophysical and socioeconomic factors involved in SD&D processes in the Mediterranean basin. These factors possibly trigger land degradation syndromes at both the regional (i.e. study area) and local (i.e. field site) levels. The analysis procedure is intended to be statistically robust, simple to apply and flexible enough to be adapted to the different data-sets possibly available for the spatially varying agro-forest systems present in the

Mediterranean region. Understanding the main SD&D processes at the study area level and identifying the relationships among indicators in each field site, allows delineating specific mitigation strategies for land degradation at the basin scale.

2. Methodology

2.1. Study area

Five study areas have been selected in five Mediterranean countries (Greece, Spain, Turkey, Tunisia, Morocco) for a total of 586 examined field sites (more than 100 sites per area). Data were collected from the following areas: (1) Crete island, southern Greece; (2) Guadalentin basin, south-eastern Spain; (3) Eskischir plain, Turkey; (4) Zeuss Koutine, Tunisia; and (5) Mamora Sehoul, Morocco. Each study area covers a surface area ranging between 100 and 150 km² in which all field sites are located. Data were collected from a variety of environmental, social and economic conditions taken as a representative sample for Mediterranean agro-forest landscapes. The field sites are located in areas affected by desertification risk or vulnerable to soil degradation owing to the interplay of processes and causes determining soil erosion, salinization, compaction, sealing, water stress, overgrazing, forest fires and tourism pressure, among others. The climatic conditions of the field sites are mainly characterized as arid, semi-arid or dry with rainfall ranging between 200 and 600 mm in more than the 80% of the field sites with climate aridity due to high evapotranspiration (higher than 800 mm for the large majority of field sites).

2.2 Environmental indicators

A multistep approach to the selection and the analysis of a large set of variables derived from various data sources and field approaches was used for assessing the most relevant drivers of SD&D in each study area and field site (see the flowchart illustrating the analysis steps: [Figure 1](#)). This approach is based on a wide set of biophysical and socioeconomic variables describing the state of the environment and characterizing the territorial context at the local scale (see list in [Table 1](#)).

2.2.1. Variable selection

Candidate variables have been selected by: (1) reviewing existing literature (e.g. Kosmas, Kirkby, and Geeson 1999; Enne and Zucca 2000; Wascher 2000; OECD 2004; Salvati, Zitti, and Ceccarelli 2008; Salvati and Zitti 2009; Kosmas *et al.* 2013a, 2013b); (2) consulting with stakeholders including land users and managers, local politicians and research groups working on SD&D issues at both the national level and in each study area; and (3) using previous studies and scientific/technical reports (e.g. Salvati 2010). The collected variables were classified in nine themes (four themes dealing with biophysical factors and the remaining five themes describing socioeconomic processes): (a) climate (4 variables); (b) soil (10); (c) vegetation (3); (d) water runoff and fires (3); (e) agriculture (5); (f) cultivation practices and husbandry (6); (g) land management (10); (h) water use (2); and (i) demography and tourism (4).

Candidate variables include: (1) state indicators monitoring specific mitigation measures; (2) pressure indicators describing conditions where remedial intervention is needed to prevent soil degradation and desertification; and (3) response indicators

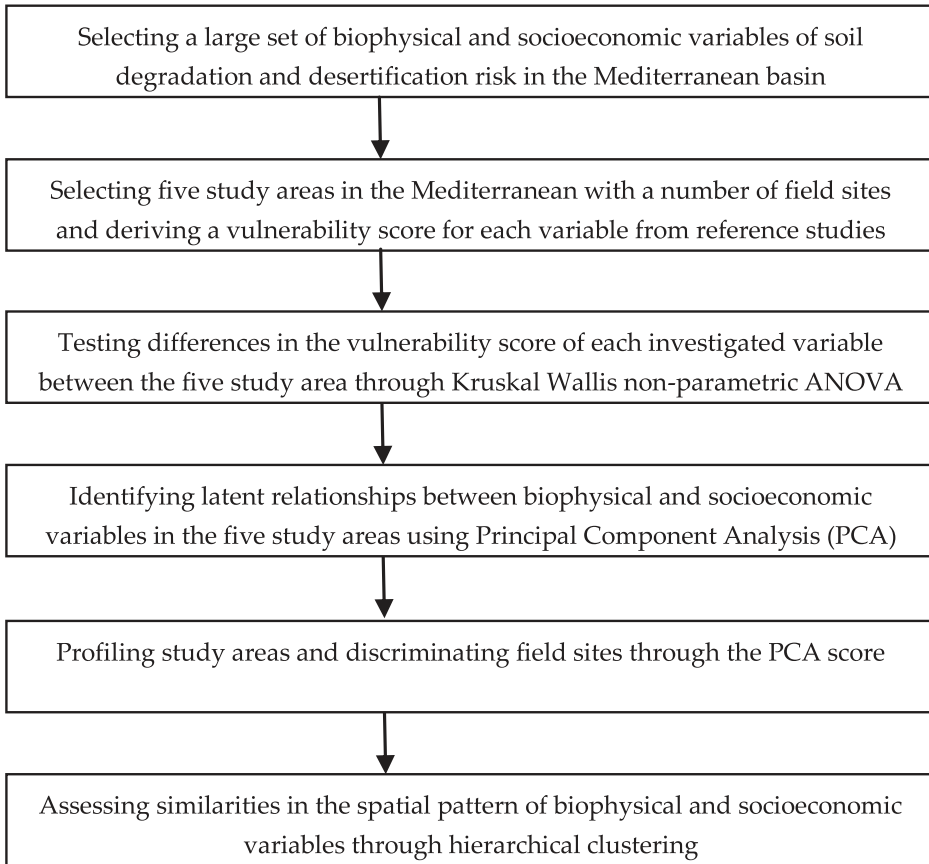


Figure 1. Flowchart describing the main analysis steps developed in the present study.

focusing on actions undertaken for land protection. Furthermore, the analysis included local scale (e.g. farm) variables, such as rainfall seasonality, land-use type, farm size, tillage operations and economic subsidies. The selected variables are considered representative for the socio-environmental complexity typical of the Mediterranean region (Salvati and Zitti 2009) and are supposed to be relevant to assess the joint impact of biophysical and socioeconomic factors on land quality and to evaluate the possible policy responses (Kosmas *et al.* 2013a).

2.2.2. Data collection

To harmonize data collection among the study areas, a manual and a questionnaire were compiled defining each variable and describing the assessment methodology (see Kosmas *et al.* 2013a for details on methodology, selected variables and technical details). Data were always collected at field site scale. Cultivated fields with an area usually ranging between 0.5 and 20 ha and having uniform soil, topography, land-use and management were considered as field sites (Kosmas *et al.* 2013b). Some field sites were identified from topographic maps or ortho-photographs in 400m grids by applying a systematic sampling design. However, this approach was not easily applied throughout the study areas since the presence of the land owner was necessary for the collection of some data

Table 1. The list of variables and research themes studied in the five Mediterranean areas.

Socioeconomic variables	Biophysical variables
<i>Agriculture</i>	<i>Climate</i>
Farm ownership	Annual rainfall
Farm size	Annual potential evapotranspiration
Land fragmentation	Rainfall seasonality
Net farm income	Rainfall erosivity
Parallel employment	<i>Soil</i>
<i>Cultivation practices and husbandry</i>	Parent material
Tillage operations	Rock fragments on soil surface
Tillage depth	Slope aspect
Tillage direction	Slope gradient
Frequency of tillage	Soil depth
Grazing control	Soil texture
Grazing intensity	Soil water storage capacity
<i>Land management</i>	Exposure of rock outcrops
Fire protection	Organic matter surface horizon
Sustainable farming	Degree of soil erosion
Reclamation of mining areas	<i>Vegetation</i>
Soil erosion control measures	Prevalent land cover
Soil water conservation measures	Vegetation cover type
Terracing (presence of)	Plant cover
Farm subsidies	<i>Water runoff and fires</i>
Policy implementation	Drainage density
Land use intensity	Impervious surface area
Period of existing land use	Burned area
<i>Water use</i>	
Irrigation percentage of arable land	
Runoff water storage	
<i>Demography and tourism</i>	
Elderly index	
Population density	
Population growth rate	
Tourism intensity	

related to land management and the socioeconomic context at the local scale. Therefore, the majority of the field sites were described after contacting the owner of the land. The location of each field site was pin-pointed using a GPS. The data-set collected for the 47 variables (with no missing values) was included in a harmonized database for further analysis (Kosmas *et al.* 2013a).

2.2.3. Data pre-processing

Using expert opinion, values for each collected variable were transformed numerically into a scale indicator describing the (positive or negative) contribution to SD&D and defined as distinct impact classes. Impact scores ranging between 1 and 2 were assigned

to the various classes of each variable based on existing classification systems such as the European georeferenced soil database (Finke *et al.* 1998) or reference research frameworks (Kosmas, Kirkby, and Geeson 1999; Kosmas, Danalatos, and Gerontidis 2000; Brandt and Geeson 2005). Higher scores indicate a negative impact of the studied variable to SD&D processes. Score systems are useful to scale and homogenize the values of the different indicators to a comparable range allowing comparison among regions and among different research themes (e.g. Salvati, Zitti, and Ceccarelli 2008; Benabderrahmane and Chenchouni 2010; Parvari *et al.* 2011). The definition of homogeneous class boundaries introduces a level of subjectivity, which is considered justifiable for application to a wide set of biophysical and socioeconomic variables (Ferrara *et al.* 2012; Salvati 2014).

2.3. Data analysis

A data mining strategy including non-parametric Kruskal–Wallis analysis of variance, principal component analysis (PCA) and hierarchical clustering was developed in the present study using STATISTICA 8 package (Tulsa, Oklahoma). Using the full sample size ($n = 586$ observations), a total of 47 comparisons based on Kruskal–Wallis statistic were run testing for significant differences in the statistical distribution of each variable observed in the five study areas.

However, previous studies carried out on a selection of the variables chosen here (Salvati *et al.* 2011, Kosmas *et al.* 2013a, 2013b) have shown that the biophysical and socioeconomic variables considered as SD&D factors are, in the majority of cases, intrinsically correlated. Moreover, it was demonstrated that both uni-variate and bi-variate statistical techniques failed sometimes to identify relevant variables influencing SD&D processes (Ferrara *et al.* 2012). A multivariate exploratory data analysis combining several variables together is better suited (1) to assess the complexity of the socio-environmental systems affected by soil degradation processes and (2) to identify the multiple, latent relationships among relevant variables (Salvati and Zitti 2009). The results of multivariate analyses also contribute to define and characterize the most common SD&D syndromes (Salvati, Zitti, and Ceccarelli 2008).

To address these issues, a multivariate framework has been developed in the present study by considering together all the collected variables in a PCA. The analysis was carried out on the matrix composed of the standardized values of the 47 selected variables observed at each of the 586 field sites. The PCA was aimed at exploring the latent patterns and relationships among the selected variables in field sites affected by a different degree of soil degradation and desertification risk taking into account the environmental specificity of each investigated area (Salvati 2014). Significant components have been selected according to the eigenvalue extracted by the PCA (Salvati and Zitti 2009). Due to the high number of variables elaborated in this study, only components with absolute eigenvalues >4 were extracted and analyzed. Finally, a hierarchical clustering based on classification trees (using Euclidean distance and Ward's agglomeration rule) was run on the same data matrix to study similarity patterns in the spatial distribution of the variables examined (Salvati, Zitti, and Ceccarelli 2008). Results from hierarchical clustering and from the previous statistical analysis were considered as a valid support to identify candidate land degradation syndromes in each study area (Salvati 2014). Variables with similar spatial patterns were considered as factors participating in the same syndrome.

3. Results and discussion

3.1. Non-parametric inference

Results of the pair wise non-parametric Kruskal–Wallis analysis of variance (Table 2) show the spatial distribution of 20 variables out of 47 diverges significantly in the five study areas. These variables include biophysical factors (e.g. total rainfall, aridity index, rainfall seasonality, organic matter surface horizon, drainage density) and socioeconomic

Table 2. Distribution of standardized scores for each examined variable in the five study areas (values <0 indicate a contribution to land degradation below the average of the five areas; the reverse applies to values >0).

Variable	Turkey	Tunisia	Morocco	Greece	Spain	H-K test
Number of sample plots	70	120	120	155	121	
Degree of erosion	0.06	-0.13	-0.45	-0.14	0.72	
Major land use	0.15	0.42	-0.24	0.38	-0.75	
Vegetation cover type	0.99	-0.33	0.34	-0.51	0.08	
Rainfall	-0.44	1.94	-0.44	-0.62	-0.44	*
Aridity index	-1.01	1.11	0.05	-0.47	0.05	*
Potential evapotranspiration	-1.41	0.81	-1.41	0.61	0.63	*
Rainfall seasonality	-0.56	-0.56	1.11	0.91	-1.39	*
Rainfall erosivity	0.47	-0.61	-0.61	1.20	-0.61	*
Parent material	-0.41	0.57	-0.85	0.06	0.45	
Rock fragments	-0.16	0.51	-0.03	-0.22	-0.09	
Slope aspect	0.47	-0.38	-0.30	0.11	0.26	
Slope gradient	-0.48	-0.62	-0.10	0.90	-0.17	
Soil depth	-0.39	0.42	-0.04	-0.37	0.32	
Soil texture	0.68	0.56	0.54	-0.55	-0.77	
Soil water storage capacity	-0.47	0.36	0.92	-0.55	-0.28	
Exposure of rock outcrops	0.64	0.49	-0.19	-0.54	0.02	
Organic matter surface horizon	-0.26	1.14	0.24	-0.69	-0.32	*
Plant cover	-0.49	0.71	-0.23	-0.64	0.63	
Drainage density	0.83	0.27	-1.00	-0.73	1.17	*
Impervious surface area	0.04	-0.80	-0.80	1.19	0.04	*
Burned area	-0.22	-0.22	-0.22	0.61	-0.22	
Farm ownership	-0.52	0.18	0.14	0.39	-0.52	
Farm size	-0.30	0.53	-0.67	0.98	-0.94	*
Land fragmentation	0.16	-1.16	-0.71	0.16	1.57	*
Net farm income	-0.12	1.19	-0.84	-0.12	-0.12	*
Parallel employment	0.43	0.19	0.03	-1.28	1.16	*
Tillage operations	0.62	0.09	0.02	-0.12	-0.31	
Tillage depth	0.69	-0.45	0.32	-0.38	0.21	
Tillage direction	0.91	0.20	-0.49	0.04	-0.29	
Grazing control	1.18	-0.25	0.66	-0.16	-0.88	*
Grazing intensity	0.12	-0.08	0.90	-0.10	-0.76	
Fire protection	0.87	0.87	0.59	-1.39	-0.18	*
Sustainable farming	0.82	-1.02	0.26	-0.42	0.82	*

(continued)

Table 2. (Continued)

Variable	Turkey	Tunisia	Morocco	Greece	Spain	H-K test
Number of sample plots	70	120	120	155	121	
Soil erosion control measures	0.58	-0.74	0.36	-0.33	0.46	
Soil water conservation measures	-0.97	-0.21	0.60	0.07	0.09	
Terracing	0.44	-0.42	0.44	0.26	-0.60	
Land use intensity	0.67	-0.50	-0.49	0.41	0.07	
Period of existing land use	2.24	-0.27	-0.29	-0.22	-0.46	
Irrigation percentage of arable land	-1.28	0.56	0.58	-0.76	0.58	
Runoff water storage	0.69	-0.36	0.13	-0.67	0.69	
Tourism intensity	-0.22	0.84	-0.22	-0.22	-0.22	
Elderly index	0.79	-0.77	-1.52	0.79	0.79	*
Population density	-0.76	-0.76	1.32	0.50	-0.76	*
Population growth	-1.06	-0.24	-1.06	1.47	0.02	*
EU farm subsidies	0.62	-0.20	-1.59	0.62	0.62	*
Policy enforcement	0.40	-0.35	0.70	-0.76	0.40	
Frequency of tillage	-0.45	0.19	0.32	-0.26	0.09	
Land abandonment	0.18	-0.26	-0.63	-0.63	1.58	*

Note: H-K test indicates the results of a Kruskal–Wallis non-parametric analysis of variance applied to the standardized scores of each variable observed in the five study areas.

Asterisks indicate significant tests at $p < 0.05$ after Bonferroni's correction for multiple comparisons.

factors (e.g. farm size, land fragmentation, parallel employment, old age index, population density and growth). The five study areas were classified according to the contribution of each studied variable to SD&D processes based on the standardized score calculated for each variable and field site. Scores less than zero indicate a contribution to SD&D below the average while the reverse pattern applies to values higher than zero.

3.2. Principal component analysis

The PCA extracted four components explaining together more than the 50% of the total matrix variance (Table 3). Component 1 explains the 16.0% of the total variance and was negatively correlated with rainfall erosivity, impervious surface area, elderly index and population growth while being positively correlated with fire protection. Component 1 identifies two candidate syndromes of SD&D, the one associated to the increase of impervious land and population growth (indicating urbanization, population densification, land consumption and habitat fragmentation) and the other represented by soil erosion processes possibly driven by rainfall erosivity and associated with population aging and land abandonment. Component 1 is also correlated with the potential of vegetation for fire protection; this result corroborates previous findings on the key role of vegetation cover in the mitigation of soil erosion in the Mediterranean region (Kosmas, Kirkby, and Geeson 1999, Koulouri and Giourga 2007, Salvati 2010, Kosmas *et al.* 2013a, among others).

Component 2 accounts for the 13.6% of the total variance and shows a positive correlation with rainfall seasonality and population density and a negative correlation with drainage density, land fragmentation, elderly index and land abandonment. These variables indicate climate conditions unfavorable to crop production (e.g. rainfall

Table 3. Loadings to the four components (1–4) extracted by the PCA (bold indicates loadings >|0.6|).

Variable	Component 1	Component 2	Component 3	Component 4
Degree of erosion	0.13	-0.39	0.12	-0.37
Major land use	-0.03	0.23	-0.09	0.27
Vegetation cover type	0.34	-0.06	0.56	-0.12
Rainfall	0.48	0.08	-0.74	0.17
Aridity index	0.33	0.09	-0.65	0.08
Potential evapotranspiration	-0.37	-0.31	-0.72	-0.18
Rainfall seasonality	-0.31	0.83	0.28	0.19
Rainfall erosivity	-0.68	0.19	0.18	-0.10
Parent material	-0.03	-0.24	-0.42	-0.26
Rock fragments	0.14	0.00	-0.18	0.19
Slope aspect	-0.12	-0.21	0.14	-0.05
Slope gradient	-0.48	0.19	0.07	-0.24
Soil depth	0.34	-0.02	-0.17	-0.52
Soil texture	0.52	0.35	0.00	0.09
Soil water storage capacity	0.59	0.35	0.03	-0.13
Exposure of rock outcrops	0.36	-0.08	-0.08	-0.32
Organic matter surface horizon	0.58	0.11	-0.37	0.26
Plant cover	0.45	-0.32	-0.29	-0.09
Drainage density	0.21	-0.79	-0.15	-0.03
Impervious surface area	-0.77	-0.16	0.04	0.16
Burned area	-0.34	0.24	-0.03	-0.28
Farm ownership	-0.11	0.47	-0.02	-0.46
Farm size	-0.46	0.25	-0.44	0.48
Land fragmentation	-0.35	-0.72	0.26	-0.35
Net farm income	0.16	-0.11	-0.56	0.17
Parallel employment	0.59	-0.56	0.04	-0.22
Tillage operations	0.09	-0.20	0.19	0.79
Tillage depth	0.20	-0.28	0.41	0.55
Tillage direction	-0.04	-0.31	0.14	0.70
Grazing control	0.21	0.41	0.53	-0.14
Grazing intensity	0.25	0.55	0.39	-0.31
Fire protection	0.87	-0.01	-0.02	0.17
Sustainable farming	0.11	-0.49	0.62	0.04
Soil erosion control measures	0.23	-0.18	0.57	-0.33
Soil water conservation measures	0.11	0.27	0.14	-0.60
Terracing	-0.04	0.33	0.39	-0.12
Land use intensity	-0.31	-0.32	0.35	0.34
Period of existing land use	0.04	-0.21	0.35	0.42
Irrigation percentage of arable land	0.53	0.07	-0.21	-0.48
Runoff water storage	0.42	-0.44	0.41	-0.04
Tourism intensity	0.24	0.05	-0.39	0.17
Elderly index	-0.68	-0.61	0.09	-0.13
Population density	-0.15	0.62	0.31	0.17
Population growth	-0.86	0.00	-0.28	-0.14
EU farm subsidies	-0.54	-0.56	-0.12	-0.15

(continued)

Table 3. (Continued)

Variable	Component 1	Component 2	Component 3	Component 4
Policy enforcement	0.52	-0.20	0.40	0.13
Frequency of tillage	0.20	-0.01	-0.09	0.27
Land abandonment	0.13	-0.82	0.01	-0.19
Explained variance (%)	16.0	13.6	11.4	9.3
Cumulated variance (%)	-	29.6	41.0	50.3

seasonality, poor drainage conditions), land fragmentation, cropland abandonment and population aging.

Component 3 accounts for the 11.4% of the total variance and is correlated positively with sustainable farming and negatively with average annual rainfall rate, aridity index and potential evapotranspiration. Variables' loadings on component 3 illustrate a typical rainfall gradient. Areas that receive low rainfall (<300 mm) experience aridity due to high crop and soil evapotranspiration. Interestingly, the application of sustainable farming practices was more often observed in the rural areas showing wetter climate regimes.

Component 4 extracts the 9.3% of the total variance and is associated positively with tillage operations and negatively with soil water conservation measures. Variables' loadings reflect the importance of soil variables and unsustainable crop practices contributing to SD&D processes in rural Mediterranean areas with special reference to tillage (Kairis *et al.* 2014 but also see García-Orenes *et al.* 2010). Soil water conservation measures were also identified as a possible response to soil degradation.

Figure 2 identifies field sites belonging to the five study areas according to their position along components 1 and 2 using PCA scores. The PCA discriminates among

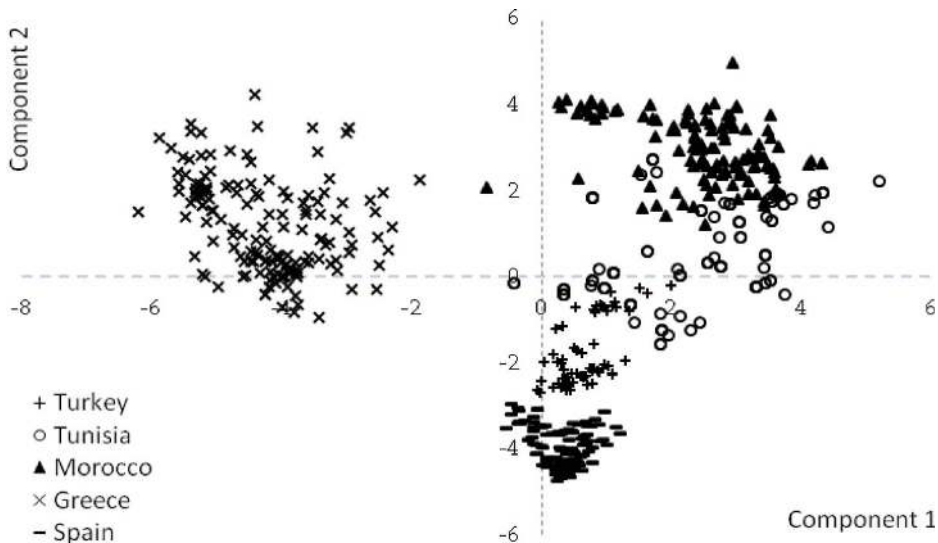


Figure 2. Score plot illustrating the distribution of the 586 sample sites over principal components 1 and 2.

study areas and underlines the homogeneity of field sites within each study area. Greek field sites are characterized by negative scores along component 1 contrary to Tunisia field sites, while Morocco field sites concentrate on the positive side of component 2 contrary to Spain field sites. Turkey field sites occupy an intermediate position between Spain and Tunisia field sites differentiating from both Greece and Morocco field sites. These results point out the considerable between-country variability in the factors contributing to SD&D processes. Site specific factors characterizing each study area are identified with the variables mostly associated to principal components (see above), contributing to characterize candidate land degradation syndromes. These findings also point out the importance of variables impacting land quality at the local scale and the relevance of specific mitigation measures developed at the regional scale. These measures may consider the set of variables identified by PCA components 1–4 as possible targets for mitigation strategies against soil degradation.

3.3. Hierarchical clustering

Figure 3 illustrates a classification tree evaluating the similarity in the spatial distribution of the 47 variables collected in the present study. Hierarchical clustering grouped variables in two main groups: (1) 13 variables (left side of the dendrogram) describing biophysical attributes (aridity, rainfall, soil depth, soil water storage capacity, organic matter surface horizon) and some possible responses to environmental constraints (e.g. irrigation, soil water conservation measures, farm subsidies, terracing, soil erosion

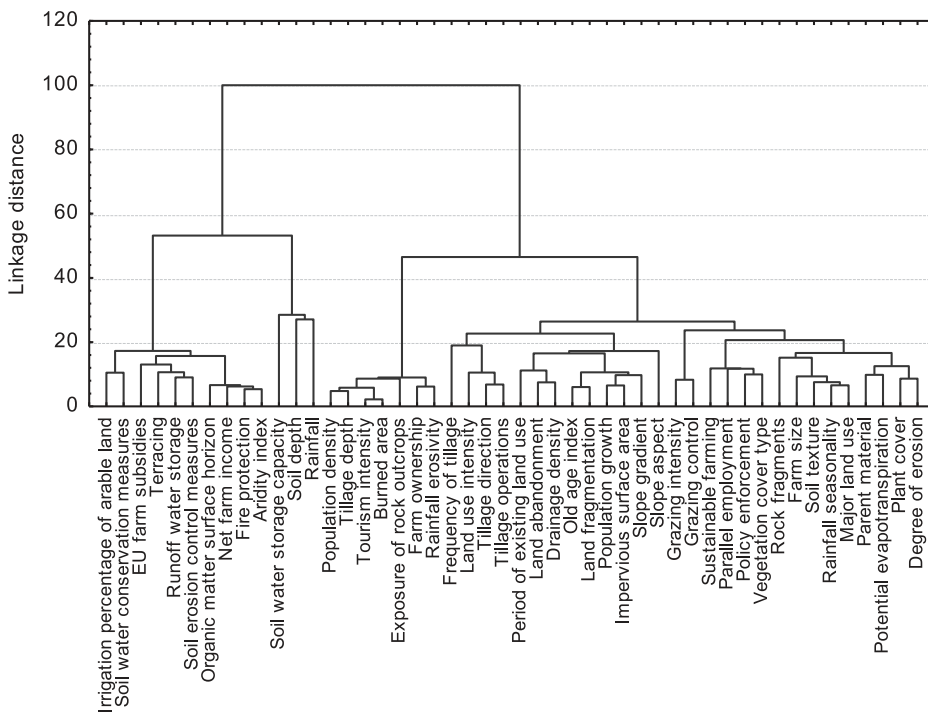


Figure 3. Cluster analysis exploring the spatial pattern of the collected variables in the five study areas.

control measures, fire protection); (2) the remaining 34 variables showing a higher heterogeneity compared with the group (1) and mainly formed by socioeconomic variables. Two sub-clusters were detected within the group (2): (a) population density, tillage depth, tourism intensity, rate of burned area, exposure of rock outcrops, farm ownership and rainfall erosivity (middle part of the dendrogram) clustered together and characterized field sites with high anthropogenic pressure; (b) the remaining variables clustered together and include both socioeconomic variables and site specific soil and vegetation variables associated to crop practices and the quality of land management. The responses associated to group (b) are grazing control and sustainable farming highlighting the role of intensive agriculture as a driver of SD&D in the Mediterranean basin.

4. Discussion and conclusions

Land degradation is a dynamic phenomenon in time and space and cannot be faced as a single step problem since it influences (and is in turn influenced by) several factors from both the biophysical and the socioeconomic side (Salvati and Zitti 2009). A better knowledge of the latent relationship among factors driving SD&D processes is a key issue to inform SLM practices and policy strategies mitigating land degradation in agro-forest systems (Symeonakis, Calvo-Cases, and Arnau-Rosalen 2007; Lavado Contador *et al.* 2009; Bisaro *et al.* 2013). Comparing SD&D vulnerability patterns and the most relevant biophysical and socioeconomic factors at both regional and local scale is a major concern for the identification of areas threatened by land degradation syndromes (Salvati 2010).

The approach illustrated in the present paper may inform the development of practical tools for: (1) selecting sets of relevant variables from a sample of candidate variables of SD&D; (2) assessing latent relationships among relevant variables and, based on these information; (3) identifying the spatial determinants of SD&D at both local and regional scales. Such a framework may shed light on key SD&D processes and candidate land degradation syndromes in various agro-forest landscapes of the Mediterranean basin by defining the biophysical variables and socioeconomic factors involved (Rubio and Bochet 1998). The final objective of the data mining approach proposed in this study is the identification of SD&D processes and the description of land degradation syndromes at the regional and local level. Previous studies candidate SD&D processes and land degradation syndromes as key policy targets for mitigation and adaptation measures (Hill *et al.* 2008; Reynolds *et al.* 2011; Bisaro *et al.* 2013) especially in traditional Mediterranean agro-forest landscapes (Marathanou *et al.* 2000; Symeonakis, Calvo-Cases, and Arnau-Rosalen 2007; Lavado Contador *et al.* 2009; Salvati 2010).

The multivariate exploratory analysis proposed here incorporates and expands the original framework proposed by Salvati and Zitti (2009) evaluating jointly a large number of candidate indicators. The analysis proved useful to classify the investigated sites into homogeneous groups with the aim to detect site specific differences in the candidate SD&D processes in the Mediterranean basin. Our results show that the SD&D processes identified in the five areas are characterized by different levels of desertification risk shaped by the existing ecological, economic, social, cultural and institutional conditions observed at the field site scale.

The spatial distribution of specific SD&D processes and the associated socioeconomic variables provide information on land degradation syndromes. A restricted number of SD&D processes was identified at the study area level showing specific, latent

relationships among biophysical and socioeconomic variables. The PCA candidates depopulation, population aging, economic marginality and dependence on farm subsidies as the most relevant variables associated with soil erosion and rainfall erosivity. Soil erosion and the related socioeconomic context may form a typical syndrome of land degradation in agro-forest systems (Sabbi and Salvati 2014). At the same time, population density, agricultural specialization, crop intensification, low dependence on farm subsidies, grazing intensity together with the predominance of a well defined land tenure regime (e.g. property land) were found associated with environmental conditions such as rainfall seasonality and low drainage density. These conditions shape land vulnerability to degradation and may determine another syndrome of land degradation based on the intensification of traditional agricultural systems (Salvati *et al.* 2011). A third candidate syndrome is mainly associated with biophysical processes such as climate aridity and low natural vegetation cover in turn associated with unsustainable farming and poor grazing/soil erosion control measures (Salvati *et al.* 2013). Finally, a restricted set of biophysical variables and socioeconomic factors including tillage practices in soils with moderate–low depths and poor soil/water conservation measures, may represent another environmental process that can be considered as a candidate land degradation syndrome in ecologically fragile rural landscapes (Kairis *et al.* 2014).

Detailed environmental and socioeconomic information at comparable spatial and temporal scales are required for monitoring environmental changes and modeling complex land-use patterns and transformations. A permanent assessment of land-use, anthropogenic pressures and policy responses to land degradation is hence essential for operational SD&D studies carried out in the light of the “syndrome” perspective, as our study pointed out. Improvement of analytical frameworks, e.g. using multivariate time-series and geostatistical approaches, appears as a promising tool evaluating changes in the candidate variables and processes of SD&D. This may also represent a relevant contribution to the development of soil degradation and desertification scenarios under dynamic environmental conditions.

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