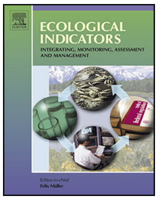
Ecological Indicators 48 (2015) 599–604

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind



Short communication

Assessing trends in climate aridity and vulnerability to soil degradation in Italy

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ARTICLE INFO

Article history:
Received 24 March 2014
Received in revised form 16 September 2014
Accepted 19 September 2014

Keywords:
Climate change
Agro-forest systems
Territorial disparities
Italy

ABSTRACT

The present study illustrates a framework to analyze changes in climate aridity and soil degradation on a country scale in Italy. The spatial distribution of an indicator of soil vulnerability to degradation (the SQI, soil quality index) was compared with an aridity index (the ratio of annual rainfall to annual reference evapotranspiration) estimated on a decadal basis during 1951–2010. The aridity index decreased by 0.38% per year indicating increased aridity and a non-uniform spatial distribution of soil vulnerability to degradation. Changes in the aridity index were found associated with the lowest SQI classes, suggesting that the largest increase in climate aridity affects land with high-quality soils. Territorial disparities in the aridity index between high-quality and low-quality soils decreased over time indicating a more homogeneous and dry climate regime prevailing in the more recent decades. Results may inform sustainable land management policies and National Action Plans to combat desertification in the Mediterranean region. Areas classified at increased aridity and high vulnerability to soil degradation should be identified as a key target for climate change mitigation policies. Sustainable land management strategies are required to address the dependency between climate variations, land-use changes and soil degradation processes.

1. Introduction

The mismanagement of drylands coupled with climate variations may lead to unsustainable socioeconomic development and desertification (Briassoulis, 2011). Climate change is a key driver of soil degradation especially in arid and semi-arid regions (Olesen and Bindi, 2002; Sivakumar, 2007; Verstraete et al., 2008). While soil is considered a key natural resource (European Commission, 2006), soil degradation accelerated on the global scale due to unsustainable human activities (European Environment Agency, 2009). Changes in the use of land have led to severe soil degradation processes including erosion, decline in organic matter, sealing, compaction and salinization (Montanarella, 2007).

Both research and policy are engaged in providing strategies to reduce the impact of climate change and soil deterioration on agro-forest ecosystems. Research contributed to define decision support systems enabling the assessment of long- and medium-term climate variations and their impact on soil (Fussel and Klein, 2006). However, up to now relatively few studies proposed diachronic approaches to analyze changes in selected climate and soil degradation variables over large areas on fine-grained spatial scales.

The Mediterranean region is a paradigmatic case for studying the implications of changes in climate, soils and agro-forest landscapes over time and space (Garcia Latorre et al., 2001; Moriondo et al., 2006; Rodriguez Diaz et al., 2007). Mediterranean climate includes a considerable rainfall uncertainty (Dünkeloh and Jacobeit, 2003) together with ample variations in thermometric regimes along defined gradients such as elevation or the urban-rural gradient (Brunetti et al., 2000). In southern Europe evidence for climate variations is characterized by temperature rise (e.g. Piervitali et al., 1997; Brunetti et al., 2004; Martínez et al., 2010), longer drought episodes especially during winter (e.g. Brunetti et al., 2002), high rainfall variability in time and space

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http://dx.doi.org/10.1016/j.ecolind.2014.09.031
1470-160X/

(Reiser and Kutiel, 2008) with a moderate decrease of total precipitation e.g. for winter (Martínez et al., 2004; Altava-Ortiz et al., 2011), spring (Brunetti et al., 2006a) or both (De Luis et al., 2010) – but with some controversial results at the local scale (e.g. Philandras et al., 2011) – as well as climate aridity (Costa and Soares, 2012) and extreme events (Brunetti et al., 2004) such as hot waves (Baldi et al., 2006; Founda and Giannakopoulos, 2009). These changes affect water budget inducing an increase of soil aridity with land productivity decline (Olesen and Bindi, 2002; Maracchi et al., 2005; Rodriguez Diaz et al., 2007; Mavromatis and Stathis, 2011).

The IPCC report (International Panel for Climate Change, 2013) shows that a shift towards sub-tropical climate has been recorded in the Mediterranean region during the last twenty years determining a rise in temperature especially in coastal areas, where increased vegetation stress caused by climate aridity was observed (Moriondo et al., 2006; Incerti et al., 2007; Salvati et al., 2008; Salvati and Mavrakis, 2014). Moreover, southern European coastal areas threatened by climate change are generally affected by high anthropogenic influence which lead to soil salinization, sealing, compaction and important landscape transformations (Garcia-Latorre et al., 2001; Salvati and Bajocco, 2011; Salvati et al., 2013).

Climate regimes in Italy were demonstrated to be largely variable in time and space (Piervitali et al., 1997; Brunetti et al., 2004; Salvati et al., 2008) due to different factors acting on a local and regional scale. A decrease by 5% per century in the annual precipitation amount was observed over 1865–2003 and is accompanied with a generalized increase in both minimum and maximum temperature (Brunetti et al., 2006). Central Italy is the region with the most evident negative trends in total precipitation, showing decreasing rates even larger in spring and summer (Brunetti et al., 2006). At the same time, northern Italian land experienced a relevant increase in climate aridity due to the concurrent action of warming and rainfall decline (Salvati and Bajocco, 2011).

Based on these premises, the present study investigates the relationship between indicators of soil vulnerability to degradation and climate aridity in Italy. According to a previous study (Salvati et al., 2013), changes in the aridity regime may impact sub-humid and dry land in a different manner. To verify this hypothesis, the spatial distribution of an indicator of soil vulnerability to degradation in Italy was analyzed together with an aridity index over six time windows between 1951 and 2010. Results may inform sustainable land management coping with a changing climate. The contribution to the practical implementation of an integrated policy strategy against climate change in Italy and, possibly, in other southern European countries, was finally discussed.

2. Methods

2.1. Study area and soil data

The analysis undertaken here is based on a climate analysis covering Italy (301,330 km^2) between 1951 and 2010 combined with the assessment of the level of soil vulnerability to degradation. Topography, latitudinal extension and proximity to the sea account for a great deal of variation in climate, soil and landscape types in Italy (Salvati and Bajocco, 2011). Soil vulnerability to degradation is considered a multidimensional concept representing the ability of a soil to sustain agricultural production and/or natural vegetation (Sposito and Zabel, 2003). Due to the national coverage of the present study, homogeneous data layers made available at a detailed resolution scale and derived from official data sources were considered as candidate indicators. The soil quality index (SQI) proposed by the European Environment Agency (2009) was adopted in this study and calculated using the information contained in the European Soil Database (Joint Research Centre, Ispra). The index was made available in a raster file covering the whole southern Europe and is disseminated at 1 km^2 resolution based on the spatial resolution of the composing variables (Salvati and Bajocco, 2011). Territorial coverage is complete (Perini et al., 2008) except for small, not evaluated surfaces areas (e.g. lakes, rivers, glaciers). The SQI is a composite index based on four variables (parent material, soil depth, texture and slope angle) derived from the European Soil Database that were combined to assess the level of vulnerability to soil degradation (Basso et al., 2000). A vulnerability score ranging from 1 to 2 (see Salvati et al., 2013) was assigned to every variable's value observed in each spatial unit with the aim to homogenize soil variables (European Environment Agency, 2009). The vulnerability score system was derived from statistical analyses and the fieldwork performed by previous authors (Basso et al., 2000; Perini et al., 2008; Salvati and Bajocco, 2011). The SQI was estimated for each spatial unit as the geometric mean of the scores attributed to each value of the four selected variables and ranges from 1 (the lowest soil vulnerability) to 2 (the highest soil vulnerability). Five vulnerability classes were identified in the SQI distribution observed in Italy (very low: $SQI < 1.4$; low: $1.4 < SQI < 1.5$; intermediate: $1.5 < SQI < 1.6$; medium-high: $1.6 < SQI < 1.7$; high: $SQI > 1.7$).

The layers considered in the analysis were regarded as the most reliable and referenced data currently available for use at the regional and national scale in Italy and, possibly, in the whole Mediterranean Europe (European Environment Agency, 2009). As a matter of fact, the national coverage of this study prevented us from using diachronic soil mapping whose availability is restricted to small areas and specific soil types in Italy. Although other physical, chemical or biological variables may provide important indications dealing with soil quality, they are generally mapped on a local scale or in larger areas but at a lower spatial resolution (Marzaioli et al., 2010) and for this reason they were excluded from the analysis. The coverage of the present study makes the results potentially more interesting than a pilot study confined to a limited test area. However, data material used in the study has obvious shortcomings. For example, soil depth can vary along prolonged time intervals and in places with site-specific characteristics possibly due to the effect of soil erosion (Salvati et al., 2013). Despite its acknowledged importance as a tool to detect soil quality, the SQI was hence regarded as static during the investigated time interval (Salvati and Bajocco, 2011). This may be acceptable when the purpose is to study a large area, since the cost of mapping is insurmountable for an individual research survey.

2.2. Climate data

We used an official dataset belonging to the Italian Ministry of Agriculture, Food and Forestry Policies (MiPAAF) and provided by the Agriculture Research Council, Research Unit of Climatology and Meteorology applied to Agriculture (CRA–CMA). The dataset refers to about 2000 weather stations and contains daily time series of precipitation, temperature, wind, air humidity and solar radiation that overall cover the period 1951–2010. The original data come from national weather networks belonging to the Italian governmental offices, like the Meteorological Service of Italian Air Force, the National Hydrological Service and the National Agro-meteorological service (technical details provided in Perini et al., 2008). Meteorological data were previously checked and validated in order to verify, according to WMO's operational criteria, the internal, temporal and spatial consistencies (Beltrano and Perini, 2004). The dataset is considered an adequate resource for scientific

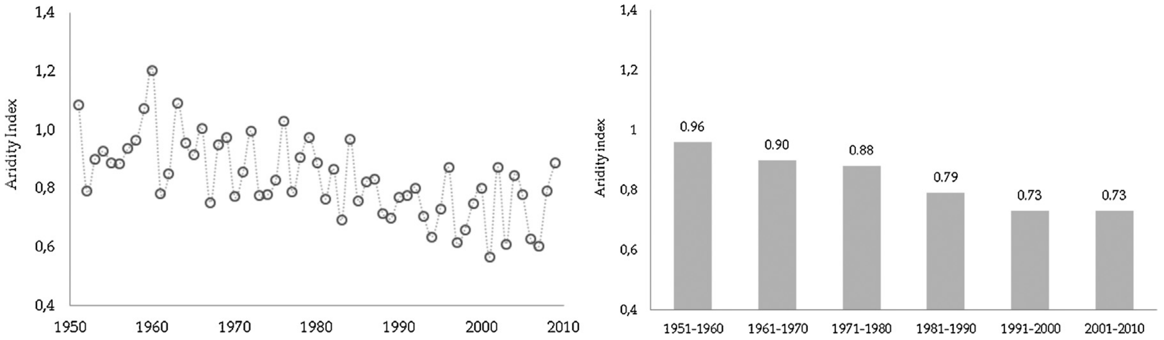

Fig. 1. Aridity index trend (left: annual average; right: decadal average) over the investigated period (1951–2010).

analysis at the country scale in Italy (Salvati et al., 2008; Salvati and Bajocco, 2011).

Starting from the above described dataset, to derive aridity maps regarding the whole Italian land and the entire investigated time period, we used kriging and co-kriging procedures applied to month and annual data of cumulated precipitation and temperatures (min–max) calculated by means of a Geographical Information System (Perini et al., 2008; Salvati and Bajocco, 2011; Salvati et al., 2013). First, ordinary kriging was applied to month (annual) rainfall over the investigated period producing raster maps at 1 km spatial resolution (Salvati et al., 2008). Grid size was chosen according to the density and spatial distribution of gauging stations with the aim of producing maps with the associated error below ±5% of the estimate (Liberta and Girolamo, 1991). Additional details were provided in Liberta and Girolamo (1992). Temperature, especially when we consider average values (month and/or annual values), shows an universally-recognized normal distribution and a substantially good linear correlation with topographic descriptors including elevation and distance to the sea (Joly et al., 2012). Due to the observed correlation with topographic variables, temperatures were regionalized using a co-kriging procedure which is able to incorporate and model the effect of ancillary variables with the aim to improve the final spatial resolution. Therefore, the month and annual mean temperature values were regionalized according to a co-kriging model using elevation, latitude, longitude, distance to the sea and slope as ancillary variables (Liberta and Girolamo, 1992). All these variables were derived from a Digital Elevation Model (DEM) made available at 20 m cell size resolution (Salvati et al., 2008). Based on the available DEM cartography and gauging station density, the co-kriging procedure applied to minimum and maximum temperature produced raster maps at 500 m spatial resolution.

The reference evapotranspiration, ET_0 (mm day^{-1}), was computed using the Penman–FAO methodology (Incerti et al., 2007). Following United Nations Environment Programme (UNEP) approach the aridity index (AI) was defined as AI = P/ET_0 where ET_0 is the reference evapotranspiration (mm) and P is the cumulated rainfall (mm) both calculated as annual averages (Salvati et al., 2008). The AI ranges from 0 to ∞ with higher values indicating wetter conditions. According to UNEP land classification (Salvati and Bajocco, 2011), the investigated area was divided into four classes: (i) AI < 0.50: dry areas, (ii) 0.50 < AI < 0.65: dry sub-humid areas, (iii) 0.65 < AI < 0.80: sub-humid areas, (iv) AI > 0.80: humid areas. Results from other procedures (e.g. Inverse Distance Weighting or Spline indicators) and comparison with maps produced by previous studies (Perini et al., 2008; Costantini et al., 2010; Salvati and Bajocco, 2011) were used to check for the reliability of the spatio-temporal pattern observed at the regional scale in the AI.

2.3. Statistical analysis

The spatial units representing soil with different SQI scores (1 km^2 grid; see Section 2.2) were considered as the elementary analysis domain (Salvati and Bajocco, 2011). A 'zonal statistics' procedure (ESRI, 2012) provided by ArcGIS software (ESRI Inc. Redwoods, USA) was applied to the six available AI raster maps by decade (1951–1960, 1961–1970, 1971–1980, 1981–1990, 1991–2000 and 2001–2010). The procedure calculates statistics on values of a raster (AI) within the zones of another layer (SQI). Descriptive statistics of the AI (mean, coefficient of variation, maximum and minimum) were calculated for each SQI class (see Supplementary materials). The relationship between the average AI observed in the first observation decade (1951–1960) for each SQI score and the AI percent increase recorded over the study period (1951–2010) was explored using non-parametric Spearman correlation analysis testing for significance at $p < 0.05$. Spearman analysis is suited to identify both linear and non-linear correlations, independently of the initial statistical assumption on each variable (normality or significant deviations from normality). Territorial disparities in climate aridity were defined as the range (maximum–minimum value) in both the AI average and AI coefficient of variation observed by decade for each SQI class in Italy.

3. Results

Climate aridity increased in Italy during the last sixty years (Fig. 1). The AI decreased on average by 0.38% per year from 0.96 during 1951–1960 to 0.73 during 2001–2010 being relatively stable in the two most recent decades (Table 1). The AI fluctuated between a minimum value of 0.49 and a maximum of 1.54, namely between conditions of semi-arid and hyper-humid climate. The lowest AI average values were found in southern Italy (generally

Table 1
Average aridity index measured in selected decades in Italy by SQI class.

Class	Class area (km^2)	1951–1960	2001–2010	Change (%)
Very low (SQI < 1.4)	1867	0.77	0.60	−22.9
Low (1.4 < SQI < 1.5)	149,378	1.05	0.80	−23.3
Intermediate (1.5 < SQI < 1.6)	64,603	1.02	0.77	−24.5
High (1.6 < SQI < 1.7)	58,745	1.09	0.74	−32.3
Very high (SQI > 1.7)	19,963	1.21	0.71	−41.6

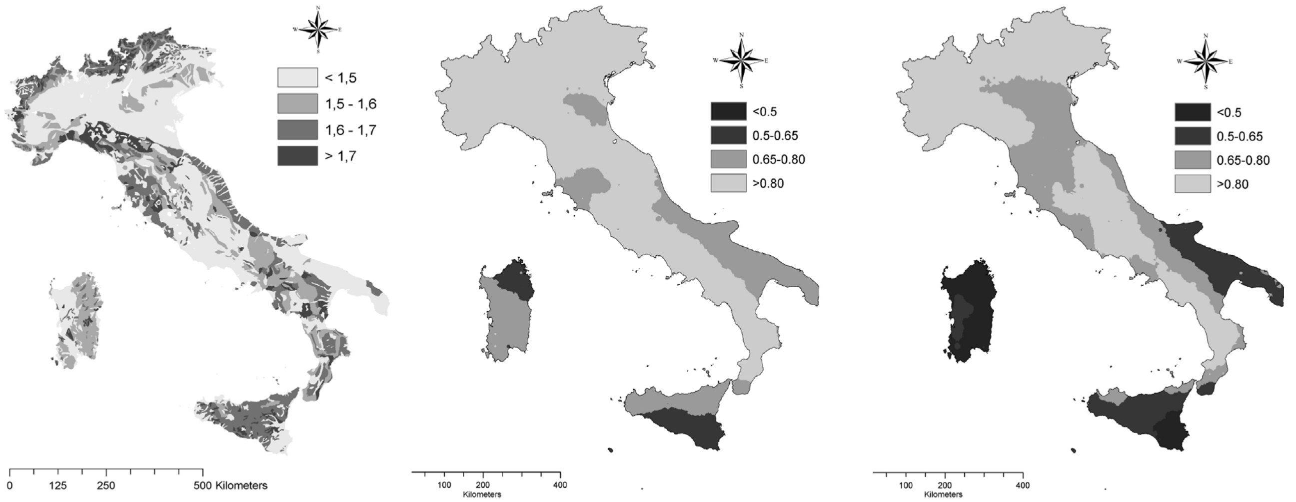

Fig. 2. Spatial distribution of the vulnerability level to soil degradation based on the SQI (left) and aridity index in Italy (middle: 1951–1980 long-term average; right: 1981–2010 long-term average).

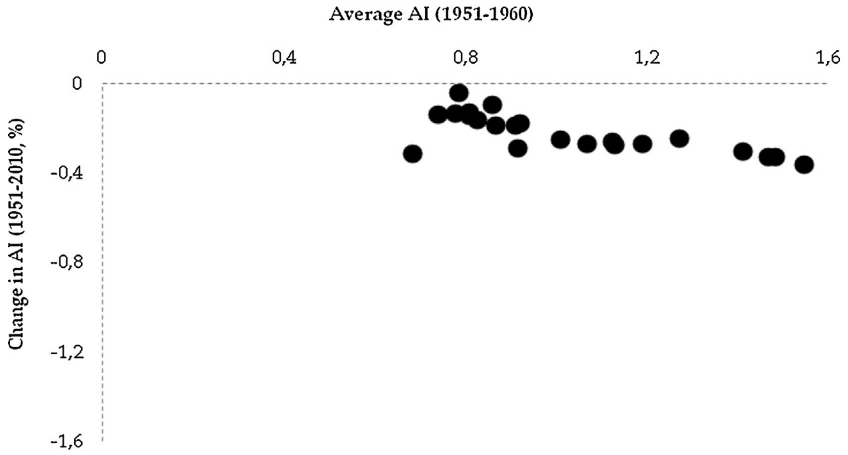

Fig. 3. Relationship between the average aridity index observed at the beginning of the study period (1951–1960) and changes in the aridity index (1951–2010) in Italy ($\rho = -0.57$, $p < 0.05$, $n = 22$).

ranging between 0.5 and 0.6) with annual, minimum values close to the aridity threshold (IA = 0.2). Average AI values close to or higher than 1 were observed especially in northern Italy owing to more abundant rainfall. Even in this area, however, the spatial variability of the AI was rather high fluctuating on average between 0.7 and 1.5.

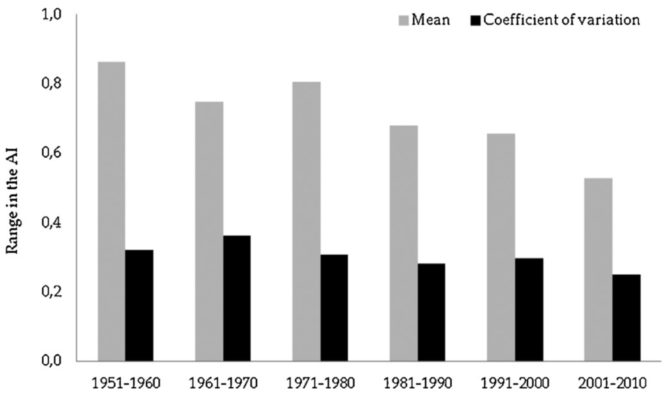

Fig. 4. Disparities in climate aridity defined as the range (max–min) in both the AI average and AI coefficient of variation observed for each SQI class during 1951–2010 in Italy by decade.

The decline in the AI was not homogeneous in space (Fig. 2) decreasing more (−0.83%) in areas with highly vulnerable soils (4.6% of Italian land) than in areas with low-vulnerable soils (−0.37%) covering 0.6% of Italian land (Supplementary materials). The decline of the AI was linear and negatively associated to the SQI suggesting that vulnerable soils experienced, on average, increased aridity than the remaining land. Moreover, while the most vulnerable soils experienced the lowest AI in 1951–1960, the ranking changed markedly in 2001–2010 with the lowest AI observed in both non-vulnerable (0.60) and highly vulnerable soils (0.71). This result suggests that soils exposed to degradation processes are more likely to be affected by the increased aridity.

Fig. 3 illustrates the negative relationship observed between the average AI during 1951–1960 for each SQI score and the percent change in the AI observed during the study period ($\rho = -0.57$, $p < 0.05$, $n = 22$). Soils with the wettest climate conditions in 1951–1960 experienced the largest decrease in the average AI during 1951–2010. This indicates that dry land with vulnerable soil was characterized by a relatively stable climate regime while sub-humid land was affected by increased aridity. Such a pattern contributed to the reduction in the AI disparities in Italy (Fig. 4):

the average range between the lowest and the highest AI observed for each SQI class on a country scale decreased significantly during the last sixty years ($\rho = -0.94$, $p < 0.005$, $n = 6$) and was accompanied by a moderate decline in the AI variability ($\rho = -0.88$, $p < 0.05$, $n = 6$).

4. Discussion and conclusions

The United Nations Convention to Combat Drought and Desertification (UNCCD) Annex IV identifies soil degradation as a key driver of desertification in the northern Mediterranean basin (Costantini et al., 2010). The European Commission has also recognised the crucial role of soil in ecosystem functioning. Soil conservation measures were therefore introduced in the European Common Agricultural Policy, and a specific thematic Strategy for Soil Protection (European Commission, 2006) has been proposed with the aim of coordinating policies against soil degradation.

Previous works demonstrated that soil degradation processes are associated to environmental phenomena, such as changes in climate regimes, forest fires and overgrazing, coupled with specific socioeconomic factors that affect agro-forest systems (Garcia Latorre et al., 2001; Rodriguez Diaz et al., 2007; Salvati and Bajocco, 2011) including unsustainable land management (Falcucci et al., 2007; Costantini et al., 2010; Briassoulis, 2011). The present study illustrates a procedure for monitoring climate aridity and soil vulnerability to degradation at the country scale in Italy. The approach is based on spatial analysis and may contribute to inform regional planning, habitat conservation measures and rural development policies in sensitive or degraded regions. The observed trends in climate aridity were analyzed for soils with different levels of vulnerability during the last sixty years. Our results indicate that climate aridity increased in Italy between 1951 and 2010 with heterogeneous trends in time and space, as described by Perini et al. (2008) and with a diverging spatial pattern for vulnerable and non-vulnerable soils. Our findings indicate a reduced polarization in vulnerable and non-vulnerable land in Italy based on climate aridity, in line with the hypothesis formulated by Salvati et al. (2013) and tested using different indicators.

To conclude, the present study indicates how a permanent assessment of climate-soil-landscape dynamics may contribute to design more effective land management strategies. Areas classified at increased aridity and medium-low vulnerability to soil degradation should be identified as a key target for climate change mitigation policies. In these areas, mitigation measures within the framework of the EU Soil Thematic Strategy should contribute to reverse the downward spiral possibly observed between soil vulnerability and changes in climate regimes towards aridity (Costa and Soares, 2012). Diachronic, high-resolution climate and soil maps covering large areas with homogeneous classifications systems and updated at regular intervals of 10–20 years are required as input data of assessment frameworks like the one proposed in the present study. Multi-temporal climate maps and continental-scale soil databases together with in-depth pilot studies have considerable potential for covering up complex climate-landscape-soil dynamics with the aim to ascertain both general spatial patterns and site-specific processes that cannot be revealed through a country-wide analysis.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecolind.2014.09.031.

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