ASSESSING LAND DEGRADATION SYNDROMES BY SOFT FUSION OF SOCIO-ECONOMIC AND ENVIRONMENTAL INFORMATION

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ABSTRACT:
Spatial mapping and assessment of environmental problems at regional scale involve the integration of information derived by the analysis of multiple, complex, multidisciplinary, and large-scale phenomena. This is the case of desertification and land degradation for which the poor knowledge of processes involved, influencing factors and their relationships, prevent the use of reliable models. A way to overcome this conceptual problem is the "syndrome approach", originally defined by the Potsdam Institute for Climate Change, PIK, and adapted for this work. The basic idea behind syndromes is to describe change processes by archetypical, dynamic, co-evolutionary pattern of civilization-nature interactions, which are called syndromes. In this context there is a strong need for framework able to handle data from heterogeneous sources in order to fuse them into synthetic indicators by modelling the uncertain and incomplete knowledge of the systems. The methodology here proposed is founded on fuzzy set theory and soft aggregation techniques: an example for Rural Exodus Syndrome is presented. The method integrates in a common framework multi-source spatial data, including biophysical related variables derived from Earth Observation as well as socio-economic information to define proxies for expected underlying processes and driving forces of the mentioned syndrome. Generalized Conjuction/Disjunction operators (GCD) are applied to compute intermediate indicator score maps representing the conditions that may affect the Rural Exodus syndrome, and an original bipolar operators is defined and applied to combine mandatory and favouring conditions to the aim of generating a synthetic overall indicator of Rural Exodus syndromes for the Mediterranean region.

1. INTRODUCTION

1.1 Land degradation: syndromes approach

Since the word 'desertification' was introduced different concepts have been developed and discussed over and over by scientists, politicians and the international aid and development society. Some key discussion topics were expressed by terms like 'irreversibility', 'decreasing productivity' and were related to the role of climate, drought and human impact. Currently, several definitions are still in use, leading to confusion and representing strong contradictions. The need for a more pragmatic view on desertification becomes apparent since the phenomenon itself evolves and represents an alarming threat for vulnerable areas of large extents. As a consequence, a completely new concept came up with the idea not to define desertification explicitly but to describe and characterize phenomena by a typical pattern of notable symptoms. To achieve this goal, the problem is approached through the developed paradigm of Global Change Syndromes, actively pursued by the Potsdam Institute for Climate Change Impact (PIK), providing a conceptual methodology (Schellnhuber et al., 1997; Cassel-Gintz & Petschel-Held, 2000, Downing and Lüdeke, 2002; Lüdeke et al., 2004)). In this framework, desertification can be described, modelled and analysed in terms of syndromes. Downing and Lüdeke (2002) suggested the following definition: the basic idea behind syndromes is not to describe Global Change by regions or sectors, but by archetypical, dynamic, co-evolutionary pattern of civilization-nature interactions, which are called syndromes. Cassel-Gintz and Petschel-Held (2000) and Lüdeke et al (2004) provide a detailed description of the symptoms of different syndromes, diagnostic element that can be observed, forming a typical pattern for each phenomena.

1.2 Exploit soft fusion strategies

In this context, a study has been conducted to test the potentiality of Geographic Information Systems and soft fusion strategies to spatially evaluate syndrome outcomes. In our approach, we try to represent or approximate symptoms using multisource spatially explicit real world data. Specifically, the objective is to combine some factor scores, derived by such real world data, based on the expert uncertain knowledge of the phenomenon, in order to map the plausibility degrees of occurrence of the syndrome. This is a typical data fusion problem as expressed by Wald (1999) where 'data fusion is a formal framework in which are expressed the means and tools for the alliance of data originating from different sources to the aims of obtaining information of greater quality'. The choice of a mathematical framework for formalizing the data fusion strongly depends on the type of knowledge available on the modeled process and on the characteristics of input data to be managed (Stroppiana et al., 2009). It is worth noticing that adopting the Syndrome approach considerable difficulties can arise in modeling Syndromes through data fusion methodsbased on classical decision-making approaches that cannot deal with the uncertainty and imprecision/vagueness inherent in complex environmental problem. The main source of this uncertainty is the incomplete and approximate

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knowledge of the syndrome phenomenon: in most cases, the contributing factors (proxies of symptoms) affecting the degree of the syndrome, their interrelationships and their influence on the phenomenon, can be defined only approximately. A further level of uncertainty is related to the typology and quality of data available to assess each symptom, both related to environmental characteristics and socio-economic conditions. A wide area of assessment of a phenomenon requires the fusion of spatial data from multiple sources, typically digital cartographic and Earth Observation (EO) data. The latter need to be analyzed and processed in a proper modeling framework to allow interpretation of the physical processes and environmental dynamics that are present in territory. On the other hand, socio-economic information must be acquired and interpreted exploiting existing databases that often are non consistent and/or complete. The methodology here proposed to deal with Syndrome complexity and related incomplete and vague knowledge is founded on fuzzy set theory and soft aggregation operators (Yager, 2004). The syndrome is here assessed through the Environmental Indicator (EI) approach. A complete description of the method we proposed for computing EI exploiting soft fusion techniques can be found in Carrara et al. (2008). In particular the paper provides a description of the fundamental terminology used and the methodological framework to evaluate EI. In this framework we define:

- *"Environmental Indicator"* a means to reduce a large quantity of data to a more simple form retaining the essential meaning (Ott 1978);
- *"Contributing factor"* any information source deemed relevant by the expert for the assessment of the EI.

1.3 Rural exodus example

In trying to test the proposed method on a phenomenon of high current interest, we focused on the Rural Exodus Syndrome (RES) in Mediterranean area. The RES has been proposed to deal with an "Environmental degradation through abandonment of traditional agricultural practices". The phenomenon is characterised by the migration of population to urban centres and with a consequent change of vegetation compound from cropping to natural systems. In general it is observed an increased biological productivity and vegetation cover, bush encroachment and changing species composition. The drawbacks of this situation are the rise of wildfire risk, the loss of accessibility to natural resources and the negative change in the hydrological cycle. At this point seems appropriate to mention also that the term degradation depends largely on a user's perspective view. We are talking about degradation but for someone this phenomenon might be of an advantage and not imply any degradation, e.g. for an ecologist or environmetal association. In other words, the perception of the negative aspect of a phenomenon is largely dependent on the user's perspective view.
Modelling Rural Exodus is certainly a big challenge because it is one of the most diversified syndromes in terms of symptoms. Its consequences are vast, affecting both nature and society. Also, the underlying causes are complex and diversified, ranging from socio-economic to biophysical causes, a fact that requires an integrated modelling approach, using remote sensing data, GIS layers and/or statistical data. Given the complexity of the syndrome and considering the underlying causes, we believe that the model approach should definitely include both biophysical and socio-economic component.
The aim of the study is to test the potentiality of a synthetic overall indicator of land degradation due to Rural Exodus syndrome generated by both representing the uncertainty in determining the contributing score of each factor to the final indicator through fuzzy sets and soft aggregation operators for the fusion of multi-source spatial data (Yager, 2004; Dubois and Prade, 2008) in order to take into account the uncertainty of the decision process.
The paper describes in the next paragraphs:

- the data used to select contributing factors (2) and to evaluate the results (2.3);
- the formal framework defined to evaluate each factor score (3.1) and to integrate results (3.2);
- the results obtained on the Iberian peninsula (4);
- the discussion of the results by comparing with previously published data (5).

2. MATERIAL AND METHODS

The study area comprises the comprises the Mediterranean basin. Results are here reported in particular for the Iberian Peninsula. An assessment of Rural Exodus for the year 2000 has been performed analysing layers that do not change during the examined period and temporal series of Remote Sensing data for the period 1989-2005.
The data have been evaluated to identify factors used to define the indicators that, according to our assumptions, reflect the typical symptoms of the analysed syndrome. Indicators used to quantify RES can be grouped in two categories: Vegetation Symptoms Likeliness and Land Abandonment Disposition (figure 1).

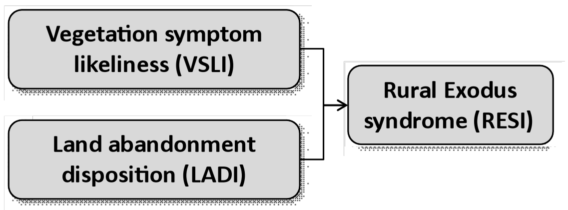


Figure 1. Groups of indicators considered to evaluate Rural Exodus Syndrome

The first category groups the hints of the phenomenon as observed by analysing the vegetation behaviour dynamics while the second helps highlighting areas where the phenomenon is likely to occur due to environmental, related to topography, climate, soil, and socio-economic conditions.

2.1 Vegetation symptom likeliness Indicator (VSLI)

The rural exodus syndrome is associated mainly with positive trends of vegetation cover due to the abandonment of former farmland that are progressively colonized by natural species. Hill et. al. (2008) showed an approach to map some aspects of rural exodus syndrome, monitoring vegetation changes as detected by remote sensing. In this study a similar approach has been conducted analysing three specific aspects of ecosystems related to productivity (Gross Primary Production, GPP) and vegetation dynamics (Permanence and Seasonality). The definition of the terms Permanence and Seasonality as well as the method to extract them from time series of satellite data are reported in Weissteiner et al. (2008a).
In particular, it was considered that factors that respectively describe GPP increase (F_GPP), Permanence increase (F_PER) and Seasonality decrease (F_SEA) are diagnostic of areas with a reduction of managed vegetation or agricultural activity. This information have been derived from MEDOKADS data set (Mediterranean Extended Daily One Km AVHRR Data Set),

provided by the Free University of Berlin (Koslowsky et al., 2006) which was further processed to derive an enhanced vegetation index (Green Vegetation Fraction/GVF) by a linear un-mixing approach, using NDVI and surface temperature. Further detail of the data processing chain and data validation can be found at Weissteiner et al. (2008b). The soft fusion strategy of the three above mentioned factors produce the Vegetation symptom likeliness Indicator (VSLI). High VSLI values are interpreted as symptoms of areas that are likely to be affected by abandonment. Nevertheless, VSLI alone is not sufficient to qualify the plausible occurrence of the rural exodus syndrome, since false positive situations may be highlighted as well. To eliminate false positives from the final result, the analysis of socio-economic and physical environmental conditions is performed (see 2.2) and used to confirm\reject the VSLI information. This final confirmation/rejection is based on the use of an original soft bipolar aggregation operator.

2.2 Land Abandonment Disposition Indicator (LADI)

Given the complexity of the syndrome and considering the underlying causes, in order to assess RES we include in the model the physical/environmental and socio-economic component considering that vegetation trends alone might not be sufficient to capture the concerned areas.

The Land Abandonment Disposition map was then calculated evaluating different contributing factors that take into account the tendency of a territory to be abandoned. The factors to be considered to estimate the territorial disposition should evaluate both the physical/environmental and the socio-economic conditions producing the PECI and the SECI indicators respectively. The following table summarises the factors selected and the source of data used to calculate them.

<table>
<tr><th>Indicator</th><th>Factors</th><th>Source</th></tr>
<tr><td rowspan="4">PECI</td><td>Available water holding capacity (F_WHC)</td><td rowspan="3">- Europe from http://eusoils/jrc.it
- Others from ISRIC-FAO data</td></tr>
<tr><td>Soil depth (F_DEP)</td></tr>
<tr><td>Soil organic matter (F_SOM)</td></tr>
<tr><td>Slope (F_SLO)</td><td>SRTM</td></tr>
<tr><td rowspan="3">SECI</td><td>Remoteness (F_REM)</td><td>Nelson, A. (2008)</td></tr>
<tr><td>Economic power (2000) (F_ECO)</td><td>DMSP-OLS (Doll et al., 2000)</td></tr>
<tr><td>Negative population trend (90-00) (F_POP)</td><td>http://sedac.ciesin.columbia.edu/gpw/</td></tr>
</table>

Table 1. Contributing factors selected to estimate the PECI and SECI

PECI and SECI are then integrated by applying a Generalized Conjuction/Disjunction aggregation operator (Dujmovic´and Nagashima, 2006) to calculate the final LADI map. Area with high LADI values describe territory that might be subjected to abandonment due to non-optimal environmental or unfavourable socio-economic conditions.

2.3 Evaluation of the results

Concerning validation, it is difficult to identify and collect appropriate datasets for comparison with the proposed indicator, especially over the African continent where data availability is poor. Nevertheless, environmental model outputs need to be tested and discussed to evaluate the reliability of the methods adopted. For this reason a comparison was conducted with an external data set and with previously published data.

In particular Corine Land Cover (CLC) change maps (EEA, 2009) representing the change in the Land Cover/use for Europe, occurred between 1990 and 2000 have been analysed. Land cover change matrix has been interpreted in order to consider only those changes that are likely to be related to abandonment of agricultural practices. Uncertainty on the causes of observed Land Cover changes has been taken into account by assigning a weight, from 0 to 1, to each CLC change class. The supposed related change classes of CLC 2000/1990 were utilized at level 3 and were weighted according to their expected relevance for the RE syndrome. The change classes were: Extension of agro-forestry (weight 0.8), Withdrawal of farming with or without woodland creation, Conversion from transitional woodland to forest, Forest creation, afforestation (weight 1.0). With those weighting factors and the area weigth was built a density map smoothed by a kernel, as provided for with the ArcGIS software. The highlighted patterns are also discussed in relation to the results of Hill et al. (2008).

3. FORMAL FRAMEWORK

3.1 Membership degree calculation

The factors estimated from the available datasets do not contribute directly to the Rural Exodus plausibility calculation. The contribution of each factor, i.e., the factor score in [0,1] associated to each pixel, is computed as the degree of satisfaction of a soft constraint, defined by a fuzzy set membership function on the domain of the factor's values. There are several advantages in using soft constraints. They are the mean to represent the vagueness of the expert's knowledge and to provide a more adequate representation of reality since the transitions from one environmental status to another are rarely abrupt but rather characterized by gradual changes. Soft constraints represent also a way to standardize the different factors in the same domain so to achieve consistency and comparability in the fusion process.

The specification of the factor conditions by membership functions is one of the key problems when applying fuzzy sets to spatial data. In this study both partially data-driven and user-driven approaches (Robinson, 2003) have been used to define the membership function. The detailed description of the different membership functions used for each factor and the motivation of each choice is argument of a paper in preparation. Figure 2 shows an example, i.e. the membership function used to quantify the influence of slope in affecting the disposition to abandonment. The function produces a score meaning that the higher is the slope of a territory the more it is difficult to use it. A threshold value was set for 30 % of slope, all the pixels above this value have the highest risk of abandonment.

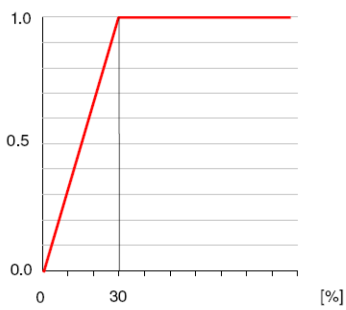


Figure 2. Membership function for "slope" factor.

Generalized Conjunction/Disjunction fusion A second important methodological aspect is related to the aggregation approach adopted to fuse the different factor scores. In order to take into account the uncertainty of the decision process we used the Generalized Conjunction Disjunction/ aggregation operators (*GCD*) (Dujmovic´and Nagashima, 2006), whose semantics can be flexibly tuned so as to model situations in which one requires that the factor scores are simultaneously satisfied (AND aggregation) or, conversely, replaceable one another (OR aggregation), or partially simultaneous and replaceable (mean like aggregations modelling either AND like or OR like aggregations).

The *GDC* (parameterized in r) of m values v_k in [0,1] with importance degrees i_k that sum to 1 is defined as follows:

$$GDC(v,i) = \left(\sum_{k=1}^{m} i_k * (v_k) \right)^{1/r} \quad (1)$$

$$\text{with } \left(\sum_{k=1}^{m} i_k = 1 \right)$$

Where v_k are the values to be aggregated
i_k are their relative importance weights
r is a parameter ranging from -∞ to +∞ and $r \neq 0$,

When r is very low ($r \rightarrow -\infty$) GDC models the full conjunction (pure AND- simultaneous satisfaction of all values is needed); when $r \rightarrow +\infty$, GDC models the full disjunctions (pure OR-replaceability of any values); for $-\infty << r < 1$ we have partial conjunctions (AND like, better to say "towards AND", partial simultaneity) for $1 < r << +\infty$ we have partial disjunction (OR like, better "towards OR"-partial replaceability). When $r = 1$ it models the weighted average (AND OR neutrality) .
By setting the r parameter, one can flexibly model the partial knowledge of the cumulative influence of factor scores in determining the result. In fact, by using a pure AND, i.e. a fusion defined as the minimum, one may obtain false drops since one single unsatisfied factor causes a null result. Conversely, by applying a pure OR, i.e. a fusion defined as the maximum, one may obtain false positives, since one single full satisfied factor causes the full satisfaction of the fused result. By using an AND like (or an OR like) aggregation one can still model an aggregation towards AND or OR, and at the same time can cope with these extreme undesired situations.
In our case all the factors have been considered with the same weight and we used respectively r = 0.26 and r =2.018 for AND like (weak simultaneity) and OR like (weak replaceability) aggregations. The values have been chosen according to the indication provided in (Dujmovic´and Nagashima, 2006).
The factors of VSLI (F_GPP, F_PER, F_SEA) are fused with the AND like operator. Factors of the PECI indicator (F_WHC, F_DEP, F_SOM and F_SLO) are fused with an OR like operator while factors of SEC Indicator (F_REM, F_ECO and F_POP) are fused with an AND like. To produce the LADI map, PECI and SECI are fused with an OR like operator.

3.1.1 The bipolar flexible aggregation: A different method was applied to produce the final Rural Exodus Syndrome Map integrating LADI and VSLI information. In this case, a kind of flexible bipolar aggregation operator (Dubois and Prade, 2008; Zadrozny and Kacprzyk, 2006) was defined in order to confirm the mandatory symptoms provided by VSLI with the favouring information provided by LADI. The choice of this approach relies on the different information provided by the two indicators: VSLI gives a quantification of hints (necessary but insufficient) of on-going changes related to rural abandonment, while LADI provides a static picture of territorial conditions that might favour rural abandonment.
To assess Rural Exodus Likeliness we need an aggregation function in which the two indicators are not symmetrically aggregated: LADI (i.e. territorial conditions) acts as a constraints with respect to VSLI (i.e. symptoms). In particular LADI value amplifies symptom values when they are greater than the conditions degree, while it decreases VSLI values when they are lower.
If we consider the VSLI and LADI degrees for one pixel i, the formal framework for the selected operator can be described by the function *Amplify* defined as follows:

$$Amplify : [0,1] \times [0,1] \rightarrow [0,1].$$

$$RESI = Amplify(VSLI, LADI) = 1 - \frac{1}{1 + e^{\left(\frac{VSLI - 1 + LADI}{s}\right)}} \quad (2)$$

Where (1-LADI) is the x coordinate of the flex,
s∈[0,1] is the steepness of the flex (the smaller the s the steeper the flex). s=0.04 was set

The x coordinate of flex (1-LADI) identifies a threshold between the values of VSLI that are necessary and those that are sufficient. Thus the steepness s models the expert uncertainty in the transition from necessity to sufficiency.
The Rural Exodus Syndrome Indicator is computed as an augmented VSLI when VSLI>LADI and a decremented VSLI when VSLI<LADI with an increase/decrement amount that is proportional/inversely proportional to LADI respectively

4. RESULTS

Figure 2 shows the VSLI (a) and LADI (b) maps obtained for the Iberian Peninsula. Patterns of changes in vegetation compound likely related to abandonment are clearly highlighted by orange/red colour (Indicator score >0.5). Some of these areas, in orange colour, present also negative conditions for rural activity from a socio-economic point of view (b). These area of matching are likely to represent hot spots of Rural Exodus.

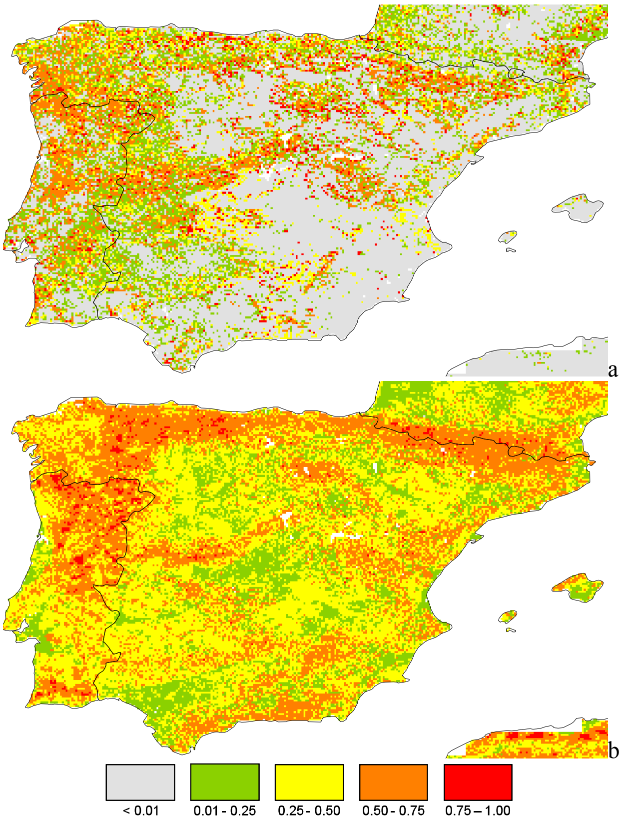
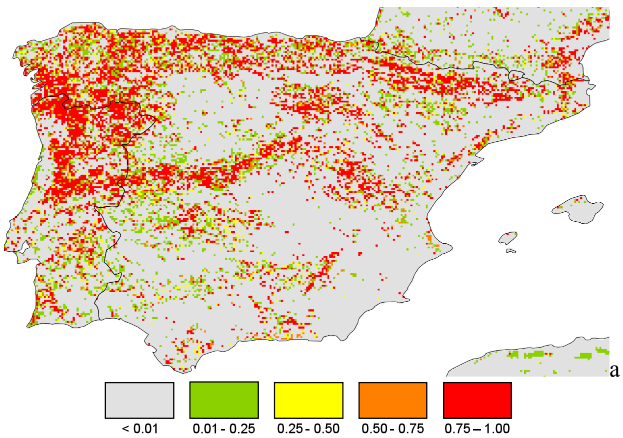


Figure 2. VSLI (a) and LADI (b) maps for the Iberian Peninsula

Figure 3 shows the Rural Exodus Likeliness map obtained by the integration of the previous shown maps. The use of the bipolar operator allowed to reduce false alarm requiring that medium/low VSLI have to be confirmed by high LADI. The obtained map (fig 3a) shows hot spot areas of high RESI values (red) and other in intermediate condition (orange-green). The comparison of the results with external data (i.e. CLC change) showed a good agreement. CLC 90-00 analysis allows to highlight areas of changes in vegetation cover highly related to rural activity abandonment.

Figure 3b shows hot spots (grey to black) in central part of Spain and northern Portugal that correspond to RESI map patterns.



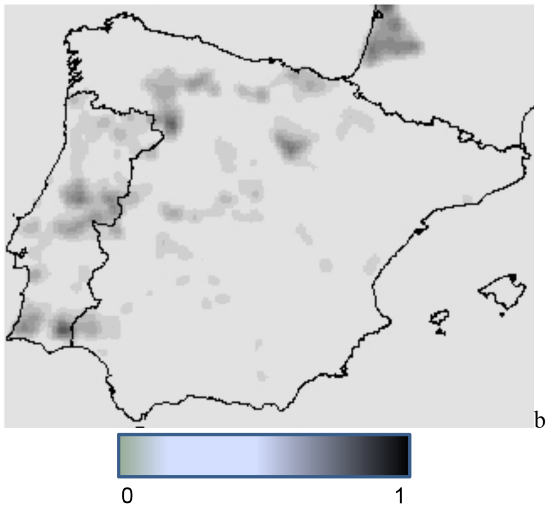


Figure 3. RESI map (a) compared with a Corine-Land cover Change Map (b)

5. DISCUSSION AND CONCLUSION

Global Change Syndromes result a reliable approach to face land degradation processes related to human/climate interrelated causes. However, their evaluation requires a formal framework able to deal with multi-source, heterogeneous and incomplete data. Moreover, these methods must manage vagueness and uncertainty related to the ill-knowledge of the complex analysed phenomena. To solve this problem fuzzy set theory and soft aggregations have been tested as a suitable candidate approach to proficiently manage the typology of the problems. A test has been conducted on the Rural Exodus Syndrome and factors able to represent specific symptoms. In particular two main aspects have to be taken into account when identifying RE: Vegetation Symptoms Likeliness and Land Abandonment Disposition. VSLI provides a quantification of vegetation hints of on-going changes related to rural abandonment, while LADI provides a static picture of territorial conditions that might influence rural abandonment. To merge this different information an original bipolar operator has been used. It allows to take into account VSLI evidences by considering the local critical situation as reported by LADI. The method is able to highlight hot spots of high degree of Rural Exodus starting from the two input indicators, VLSI and LADI: it is therefore effective in fusing different data sources producing information of higher level.

Evaluation of the result achieved by comparing with the analysis of CLC change map shows a good agreement for the Iberian Peninsula. Moreover, the highlighted patterns are common to those identified by Hill et al. (2008). With respect to this method, the one described here is able to handle different source of data by fusing proxies of bio-physical information with socio-economic and physical environmental data. Moreover, the produced output provides a score of the examined phenomenon, expressing by a continuous degree of plausibility the strength of the considered syndrome.

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