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Research Article

Fuzzy Analysis for Modeling Regional Delineation and Development: The Case of the Sardinian Mining Geopark

Germana Manca
Department of Geography and GeoInformation Sciences George Mason University

Kevin Curtin
Department of Geography and GeoInformation Sciences George Mason University

Abstract
Although defining geographic regions for analysis can be a complex exercise, involving both physical and human geographic perspectives, employing both qualitative and quantitative data, and integrating a wide range of social, economic, and political factors, it is frequently a necessary exercise in the pursuit of regional development. This article presents a method for modeling and delineating regions with fuzzy analysis for the purpose of regional development. A review of the literature regarding fuzzy analysis is provided, which demonstrates that this method is both novel and necessary. An application of this method is described in the context of the Sardinian Geopark. The fuzzy clustering analysis demonstrates how combinations of factors can inform decisions regarding where and how to initiate or continue regional development efforts. Suggestions for improvements and extensions to this process are provided.

1 Introduction

When regional development policy is being put into practice, feasible decisions must be made regarding where, when, and how to employ limited resources in order to maximize the benefits of the development program. This article presents a method for modeling and delineating regions with fuzzy spatial analysis for the purpose of regional development and planning.

In some instances government agencies decide the level and kind of development funding based on the intensity of economic activities in an area, and the types of activities

Address for correspondence: Germana Manca, Department of Geography and GeoInformation Sciences, George Mason University, 4400 University Drive, Fairfax, VA 22030, USA. E-mail: gmanca@gmu.edu.

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that predominate in that area (Legge Regionale 19 Gennaio 2011, n .1). It is clearly stated in art. 1, that the government supports the productive activities through the executive arm, the councillorships.

Development resources are used variously to encourage private investment, to provide public services to underserved populations, to protect the sustainability of environmental resources, and to improve quality of life. However, the determination of the mix of economic development activities to be encouraged and their relative intensities is not accurately represented by hard classification methods. The influence of economic activities on the regional landscape is neither well-defined nor uniform. Fuzzy logic can be used to recognize trends in activities across geographic regions. More specifically, fuzzy clustering allows one to determine a gradation of membership across several activity types. This gradation further allows researchers and government agencies to choose from a range of development scenarios and better determine which scenarios will provide the most beneficial results in terms of both economic and social benefits.

To this end, this article presents a method for modeling and delineating regions with fuzzy analysis for the purpose of regional development. An application of this method is described in the context of the Sardinian Geopark. The following section reviews the literature regarding the implementation of fuzzy analysis in GIS contexts, the nature of fuzzy sets and relationships, and the applications of fuzzy modeling. This is followed by a description of the Sardinian Geopark and the motivation for using fuzzy modeling to delimit regions for economic development and planning. The methodology and results sections specify the parameters employed and the spatial outcomes of the analysis. Conclusions regarding the policy and planning consequences of these regional descriptions are provided, along with suggestions for future research.

2 Background and Motivation: Fuzzy Modeling for Regional Delineation, and Integration with GIS

In the context of GIS, fuzzy modeling allows one to move beyond the extremes of the discrete and continuous data models, and to accept that geographic objects do not necessarily have well-defined boundaries or locations. It has been well established that many geographic phenomena can be defined in fuzzy ways (Leung 1983, Kollias and Voliotis 1991, Fisher and Wood 1998). Objects can be fuzzy in both their spatial extent (Wang and Hall 1996, Fonte and Lodwick 2004) and their thematic description (Woodcock and Gopal 2000, Cheng et al. 2001). The fuzzy nature of these geographic entities has consequences for the design and operation of geographic databases (Robinson 1988, Stefanakis et al. 1999), and for regionalization methods (Duque et al. 2007).

The degrees of membership expressed by fuzzy sets have been used as a way to formalize the uncertainty inherent in spatial data sets (Davis and Keller 1997, Zhu 1997) and to assess both the accuracy of thematic maps (Gopal and Woodcock 1994, Tran et al. 2005), and the similarity of categorical maps (Zhang and Stuart 2001, Hagen 2003, Hagen-Zanker et al. 2005). Perhaps most importantly, the value of fuzzy sets lies in the 'greater expressive power' they possess for articulating uncertainty in measurement and value (Robinson 2003).

Fuzzy modeling has been considered an alternative to more traditional modeling paradigms in order to deal with complex, ill defined and less 'tractable' systems (Tsekouras 2007). More specifically, Fuzzy Clustering Means (FCM) is a useful algorithm to cope with uncertainty and unclear boundaries. The FCM algorithm experiences the following related issues: according to the algorithm, the knowledge of the number of clusters has to be clear; second, how FCM controls the initialization of the iterative process; and last, the interpretability of the fuzzy model itself (Tsekouras 2005, 2007).

Fuzzy sets have also been combined with rough sets (those that approximate a conventional set by giving upper and lower approximations of it) (Ahlqvist et al. 2003), and higher order fuzzy sets (those where the degree of membership in a fuzzy set is in and of itself fuzzy) have been defined (Fisher et al. 2007). Using fuzzy classification for assessing the accuracy of thematic maps is perhaps the first stage in developing intelligent map update, or change detection, systems, and fuzzy classification may provide a cost-effective set of tools to address these increasingly complex problems of mapping (Robinson 2008).

Fuzzy topological relationships have been defined (Shi and Liu 2004, 2007; Liu and Shi 2006), and natural language fuzzy linguistic quantifiers (such as 'about 4 miles', 'less than 15 minutes drive') have been used to improve spatial queries (Wang 1994, Papadias et al. 1999, De Bruin 2000), and have been integrated into a GIS-based implementation of the analytical hierarchy process (Boroushaki and Malczewski 2008). Fuzzy set membership has been used to inform spatial processes such as fuzzy membership grade Kriging (Guo et al. 2007) and multi-criteria evaluation (Jiang and Eastman 2000), and has been integrated into the normally precise formulations of linear programming (Leung 1988). The fuzzy clustering of input data has been posited for forecasting systems that operate under uncertainty (Luchetta and Manetti 2003).

The problem of spatial decision-making, expressed by the issue of selecting a suitable location site, has been modeled from different perspectives. The use of a fuzzy decision table (FDT) represents decision making involving imprecision, especially when human behavior is involved in the process of decision (Witlox and Derubber 2005).

Integrations of fuzzy set methodologies and GIS have been used in a wide range of applications such as landscape assessment or evaluation (Hall et al. 1992, Sui 1992, Davidson et al. 1994, Steinhardt 1998), the mapping of soil qualities (Oberthur et al. 2000), the generation of alternative representations of in-stream habitats (Legleiter and Goodchild 2005), the comparison of alternate land cover maps of a single area (Fritz and Lee 2005), and post-conflict mine clearance operations (Landsberg et al. 2006) to name only a few.

Some researchers have found the use of expert knowledge superior to fuzzy analysis in capturing the nature of spatial phenomena (Ercanoglu et al. 2006), while other research has actively integrated expert knowledge into the fuzzy classification process (Lucieer and Kraak 2004). While one study has focused on the generation of regions for the purpose of planning (Hall and Arnberg 2002) they concentrate only on the physical geographic characteristics of the landscape. One notable exception used human geographic information as inputs to fuzzy sets (Wood et al. 2007), but their focus was not on regional delineation or development.

However, several pieces of literature known to the authors have employed fuzzy set techniques with both human and physical geographic characteristics for the purpose of regional delineation leading to regional planning and economic development. An overview of regionalization methods and a proposed taxonomy of the different regionalization methods, based on the strategy used to satisfy the contiguity constraints, is outlined by Duque et al. (2007), where conventional clustering and forced spatial contiguity through maximizing the regional compactness play a fundamental role.

In the Italian panorama, the FCM has been used to assess regional trends and development. Franco and Senni (1996) applied the FCM approach to a regional assessment of Lazio counties, (Italy), discriminating between rural and urban, and suggesting a development plan for the counties. Consequently they delineated the vocational area for the organic agriculture district, using the FCM technique (2006). Moreover, Franco and Senni (2003) outlined a methodological path to regionalize the Italian territory, based on the peculiar characteristics of its rural development. Further research, applying the FCM, carried out by Mason (2005) in the Italian counties, determined the rural index and its membership, aiming to define local labor systems.

In summary, fuzzy spatial descriptions have been accepted in the literature; fuzzy set membership is a construct that has proven valuable, particularly in expanding quantitative techniques of analysis, and the integration of fuzzy set techniques with GIS has been applied in a range of contexts. These inputs in the literature provide the motivation for pursuing the research presented in this article.

3 The Sardinian Mining Geopark: A UNESCO Sponsored Regional Development Effort

A second motivation for this research is the availability of a compelling case study in the form of the Sardinian Mining Geopark. In 2000, after 10 years of work through symposia on the conservation of geological heritage, the European Geoparks Network (EGN) was established. In the charter of the EGN a Geopark was defined as:

> [A] territory which includes a particular geological heritage and a sustainable territorial development strategy supported by a European programme to promote development. It must have clearly defined boundaries and sufficient surface area for true territorial economic development. A European Geopark must comprise a certain number of geological sites of particular importance in terms of their scientific quality, rarity, aesthetic appeal or educational value. The majority of sites present on the territory of a European Geopark must be part of the geological heritage, but their interest may also be archaeological, ecological, historical or cultural (European Geoparks Network 2000). The goals of the Geoparks network were to: (1) protect geodiversity; (2) promote geological heritage; and (3) support sustainable economic development.

In 2001 the United Nations Educational, Scientific and Cultural Organization (UNESCO) formally endorsed the EGN efforts, and in 2004 gave EGN full responsibility for regulating the membership of the UNESCO Global Network of Geoparks in Europe. UNESCO's goals of educating the public regarding the environment and promoting regional sustainable development were seen to be complementary to those of EGN. In order to become a UNESCO recognized Geopark, a region must have a coherent and strong management structure, with a sustainable economic development strategy. The Geopark must create enhanced employment opportunities for the local population, while linking geological heritage to 'broader aspects of the natural and cultural environment'.

Finally a Geopark must integrate public authorities, local stakeholders, and private interests in the development plans (UNESCO 2008). As of June 2008 UNESCO had recognized 53 National Geoparks in 17 countries.

The authors find it remarkable that, with the support of 17 national governments and a major international organization, and with regional participants from the public and private sectors and academia, there are only eight references to Geoparks in the Science Citation Index. Of these eight articles, four primarily give overview descriptions of the Geopark concept (Eder 1999, 2008; Keever and Zouros 2005, Mazumdar 2007), and three describe regional efforts at developing Geoparks and outlining the potential benefits of their establishment (Zouros 2004, Xun and Ting 2003, Zhao and Zhao 2004). Only one article moves beyond the descriptive to perform an analysis of the consequences of multiple, overlapping park designations on the effectiveness of park management (Lianyong 2007). This article seeks to add to the literature by performing repeatable analysis using the platform of the Sardinian Mining Geopark.

The Sardinian Mining Geopark was the first example of a Geopark to receive that designation, as it was conceived prior to the formal establishment of Geopark networks at the General Conference of UNESCO in Paris in 1997 (Manca and De Montis 1999). The Mining Geopark covers an area of 3,771 km^2, divided into eight areas throughout the autonomous region of Sardinia (Figure 1). Each of these areas has historically supported mining activities, particularly from rich deposits of lead, zinc, copper, tin, silver and iron. These areas have long been acknowledged as some of the most important metal mining districts of Western Europe. However, there is very little active mining today; all that remains is a rich heritage of mining and archaeological artifacts that describe a longstanding element of Sardinian culture.

Industrial mining has left evidence of construction techniques and architectural styles that present challenges to those who would preserve them and modify mining sites for economic development. In these cases environmental reclamation projects are being planned for abandoned mining areas. These projects include the conversion of mining buildings to hotels and restaurants, the treatment of water basins contaminated with heavy metals, the encouragement of specialized agriculture in underdeveloped areas, and in particular the development of Geo-tourism activities such as itineraries for environmental, geological, paleontological, archaeological-industrial, and flora and fauna education and appreciation tours. Education activities in the Mining Geopark are under development at a range of educational levels (elementary through graduate education), in addition to re-training programs that encourage the former mine workers to perform new environmentally and culturally sustaining activities.

The present economic conditions of the Geopark are a reflection of the economy of Sardinia. That is, the economy is generally regarded as weak. Encouraging a strengthening of the tourism sector represents a reasonable strategy, if it were possible to establish efficient linkages with other economic sectors. Sardinia in general is known as a tourist destination for much of Europe, with recognized natural beauty and favorable weather. Since regional policies are regularly aimed at boosting the development of tourism and promoting the island as an exclusive vacation destination, it follows that the Geopark is one of the most suitable areas for an increase in this kind of development. Moreover, since many of the former mining buildings are located in areas that are frequently forested, near to agricultural production areas, and near the coast, they are seen to be ideal locations for the development of both Geotourism and Agrotourism. Ideally this development would lead to a network of activities, connecting the inland areas to the

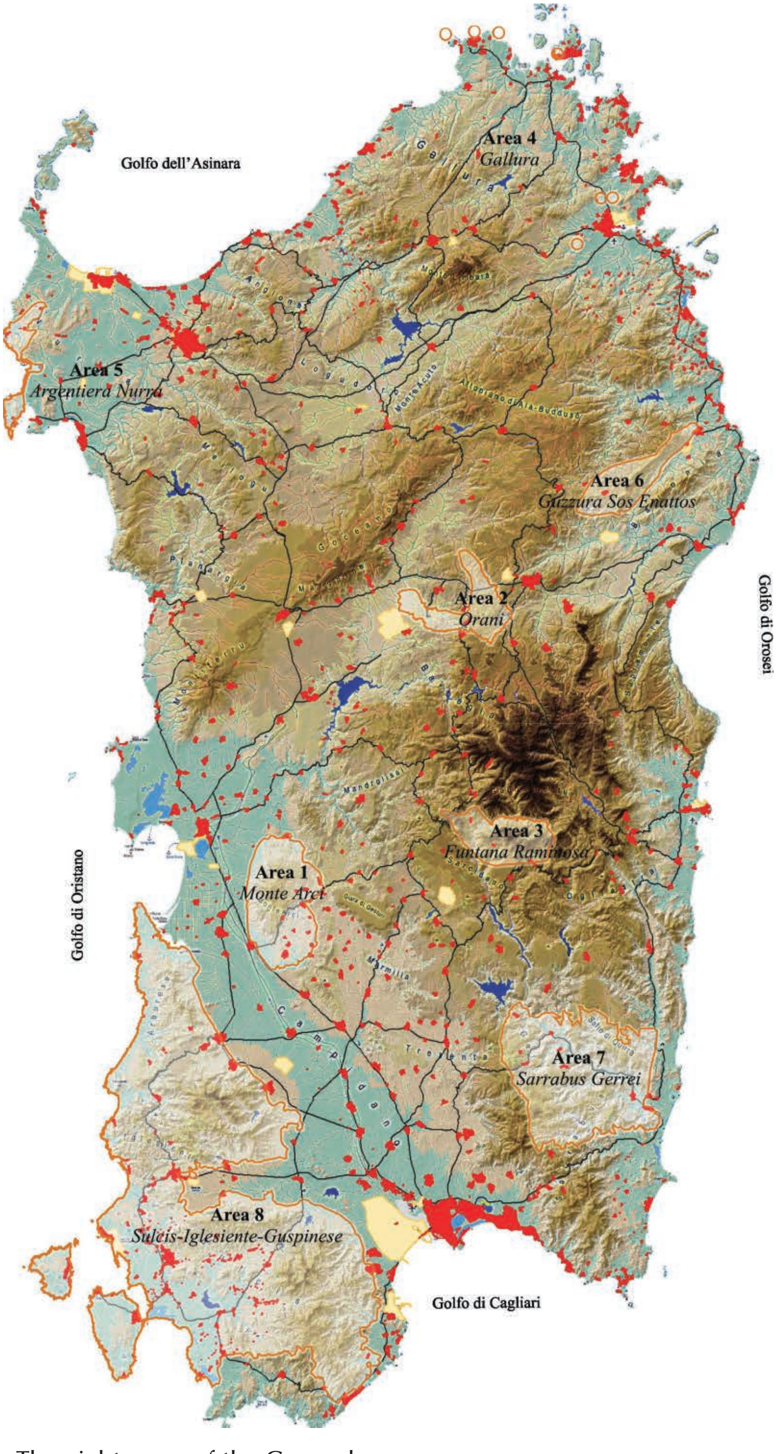

Figure 1 The eight areas of the Geopark

coastal zone, generating revenues from agriculture, geological interests, and traditional tourism activities. In this way the activities support each other in a sustainable economic system.

Attaining this ideal is much more difficult than describing it. The realities of funding priorities in the development plan require that priorities be established among the various possible projects. This research uses fuzzy spatial analysis to determine regions for development, in order to inform the process of prioritizing development plans.

4 Methodology: Fuzzy Spatial Analysis for Regional Development

4.1 Fuzzy Clustering and Coastal Territorial Phenomena

GeoTourism activities, with the opportunities they afford the local rural economy, can exploit the potential uses of the Geopark. The goal here is to evaluate the potential mutual benefit for both GeoTourism interests and the local rural economy through the use of fuzzy logic, in combination with geoinformation.

The geographical location of several criteria, selected and manipulated through GIS, allows one to regionalize the trend or development of each municipality. Depending on the membership value of the municipality to a certain cluster, a hypothesis might be formulated. In order to discriminate clearly among the eight areas of the Geopark, the most interesting development in terms of the cultural, environmental and social heritage, is Area 8 – Sulcis Iglesiente. This area is studied in particular details.

4.1.1 Urban/Industrial polarization

While rural clusters are a primary focus of development policy, so too are urban/industrial areas that have largely experienced decline, and are considered strategic for regional economic development. To determine the extent to which industrial activity is structured in this region, Manca and Paci (2004) applied the local measure of spatial autocorrelation, Local Moran's I, to measure the polarization of industrialized municipalities (Figure 2). This permitted an understanding of the dynamics of the different activities. The index 'average dimension of the companies' describes the attraction determined by them. The red color of the map implies that the production is sustained by the companies in surrounding areas. Porto Scuso and Pula unequivocally work as attractors in the sectors of services and industrial production, in the neighboring areas. Conversely Carloforte and San Giovanni Suergiu work as negative attractors vis-a-vis the surrounding municipalities, neither involving the neighboring activities nor, often, providing itself with self-sustainaing enterprises.

While mining is historically the predominant industrial activity in the abovementioned area of Sulcis Iglesiente, the notion of an industrial cluster encompasses many small enterprises associated with mineral production. Moreover, industrial development is related to the prevalence of urban sprawl. Over many decades, industrial towns spread over the territory, creating a pattern associated with industrialized development. Examples of this development have been documented across the islands of Sardinia. In this research we use population density (population per square kilometer) as the parameter chosen to describe the influence of the urbanized industrial population on land use.

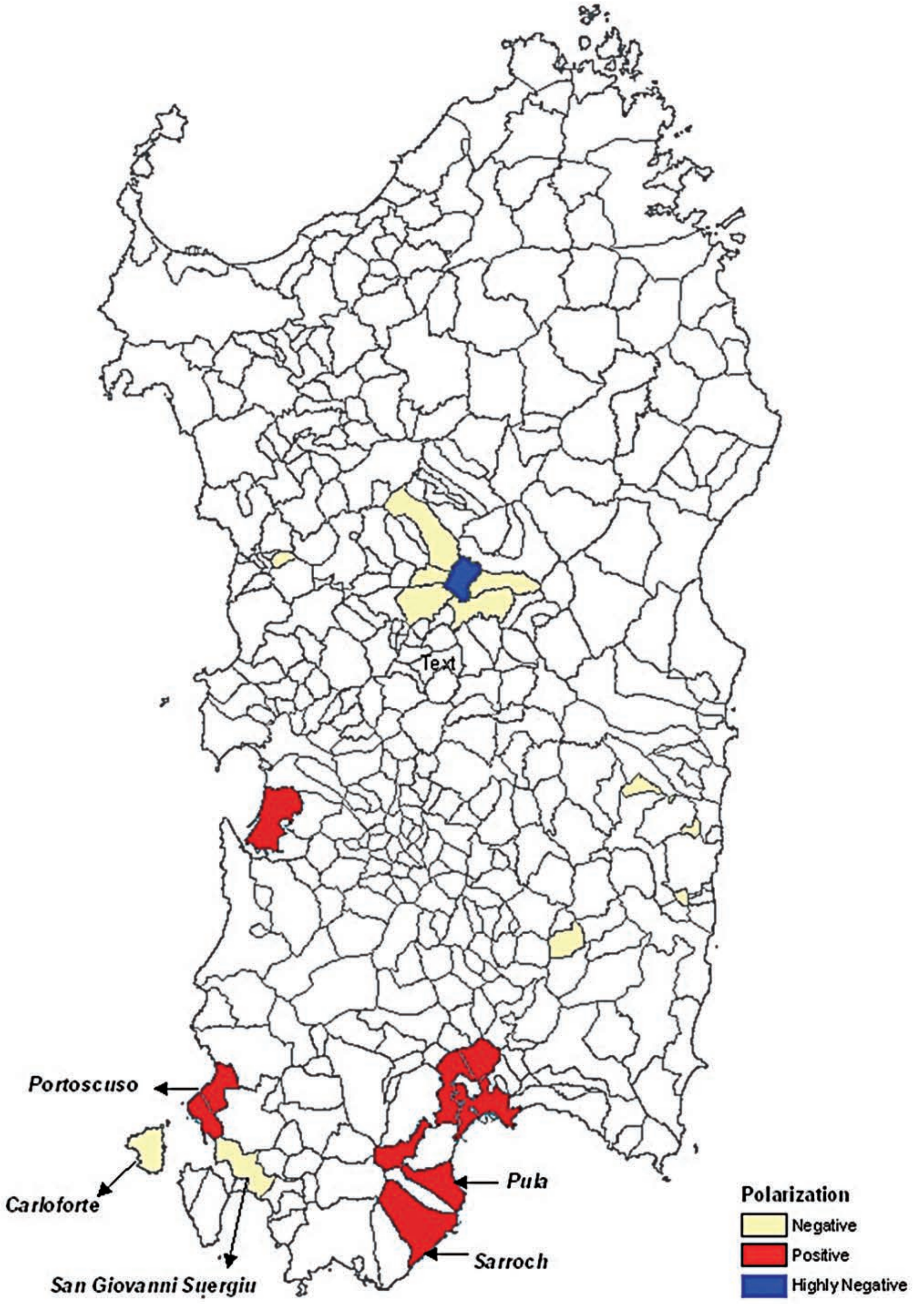

Figure 2 Grade of polarization of the average economic dimension of the companies

4.1.2 Agriculture trend

In addition to rural planning and industrial development issues, the area under consideration is also the scene of fervent agricultural political action, and agricultural interests have exerted influence over the development of the Rural Development Plans. New government funds have been allocated, and they support two strategic development areas: Monte Linas and Sulcis Iglesiente, as shown in Figure 3. In order to understand the

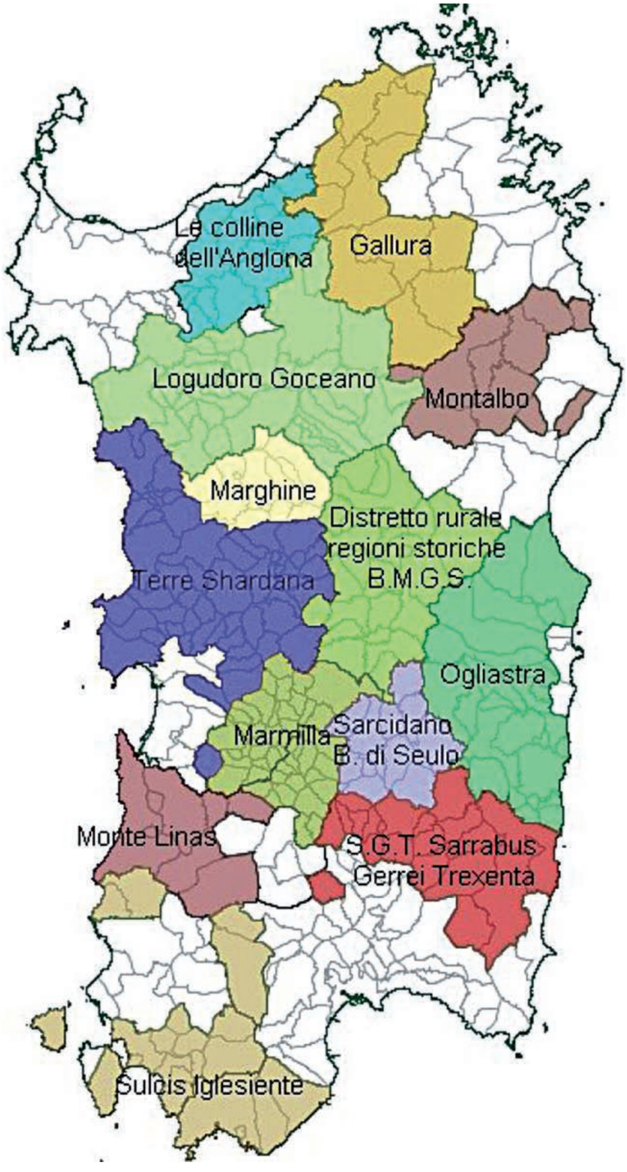

Figure 3 Area of agriculture encouragement and outreach (Source: Autonomous Region of Sardinia)

dynamics of the territory, a local economic development approach has been undertaken. The endogenous local factors promote the revitalization of the rural area, and allow for the creation of development, which appears as an alternative to modernization, generally suggested by the top-down approach. However the heterogeneity of this area, especially the geomorphology of the land, the geographical location, the climate, and the landscape, appears to create 'strategic actions/regional responses' adopted by farmers (Van der Ploeg 1992). More specifically, the farmers have interacted and planned to move forward toward a communal goal for the entire agricultural community. Heterogeneity acts as an attractor of development, building different patterns, each of them arising from a resultant agricultural/farming method. The farming method is determined by a set of actions leading to technology and adaptation to the market requirements.

A remarkable area is depicted, where important phenomena are taking place. It is the area of Sulcis-Iglesiente, defined as area number 'eight' in Figure 1. In order to focus on the dynamism of the Geopark, the following analysis focuses on this area.

4.1.3 Rural trend

The concept of the rural district of quality, defined as a cluster in this article, is borrowed from the theories of industrial development, primarily through the modeling of endogenous development. The increased interest in rural clusters is demonstrated through policy efforts that seek territorial integration, and through innovative forms of organization and relations among business groups or consortia, which are designed to lead to evolutionary growth of local economies. Each territory expresses and encompasses its development on the bases of tight collaboration, negotiation, consultation, and knowledge of the places and of the people. In the case of rural Sardinia, an alternative path of economic development is codified in the law 228/01 (DL228/01). This law focuses interest on the anthropological and local planning issues, and uses the results of investigations of those issues to delineate the geographical boundaries of the rural district of quality. These boundaries are fundamental to the subsequent landuse planning activities, which in turn are critical to the development of the region and the well-being of the population. The law emphasizes the enhancement of cultural traditions and the respect for local guidelines, while simultaneously tackling pressing social issues and performing land management duties. The structure of the district takes into account other factors, such as industrial integration, typical local production, and the interaction among economic activities. Commonly, rural districts have a connotation of being strongly linked to the agricultural sector, but the extent to which this is true is a function of both historical and cultural factors together with natural and territorial characteristics. Given these multiple variables, the identification of the cluster (as confirmed by the literature) should be based on the criteria of localization, concentration and specialization determinants.

Therefore, efforts to monitor the land and to identify rural areas for policy consideration require the application of a membership function to calculate the rural territorial index:

$$\mu c = \exp\{(\mathrm{d_c} / \mathrm{d_s}) * \ln(1/2)\} \qquad (1)$$

where c is the municipality considered, $\mathrm{d_c}$ is the population density of the municipality, and $\mathrm{d_s}$ is the population density threshold density (= 120 for this local system).

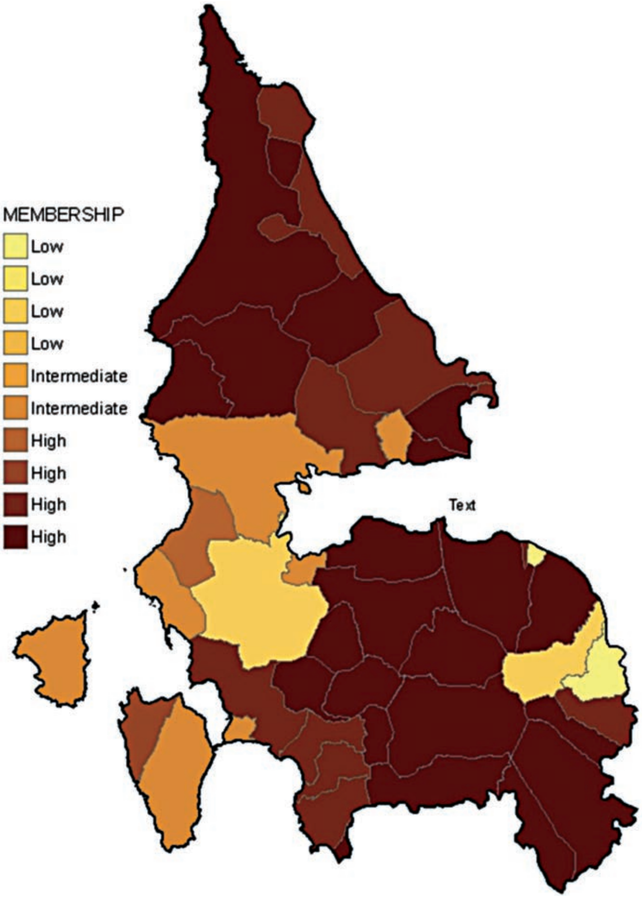

Figure 4 Grade of rural membership

The membership value can be interpreted as:

1. High population density related to a low rural level: $d_c > d_s \Rightarrow \mu_c < 0.5$
2. Low population density related to an high rural level: $d_c < d_s \Rightarrow \mu c > 0.5$
3. Population density equal to 120 people per square kilometre, related to a intermediate rural density: $d_c = d_s \Rightarrow \mu_c = 0.5$

Figure 4 shows the grade of membership, based on the fuzziness of the rural index by municipality. There is clearly a predominance of high rural index values.

4.1.4 Dynamism of the area

The natural and human environments in this area are not static. In order to understand the dynamism occurring in this research area a landuse change analysis has been carried out. Two time-series landuse layers have been analyzed and compared (1997, 2006), in order to determine the change. The graph reproduced in Figure 5 and the map show the amount of change for a set of natural and man-made resources. Due to the large number of

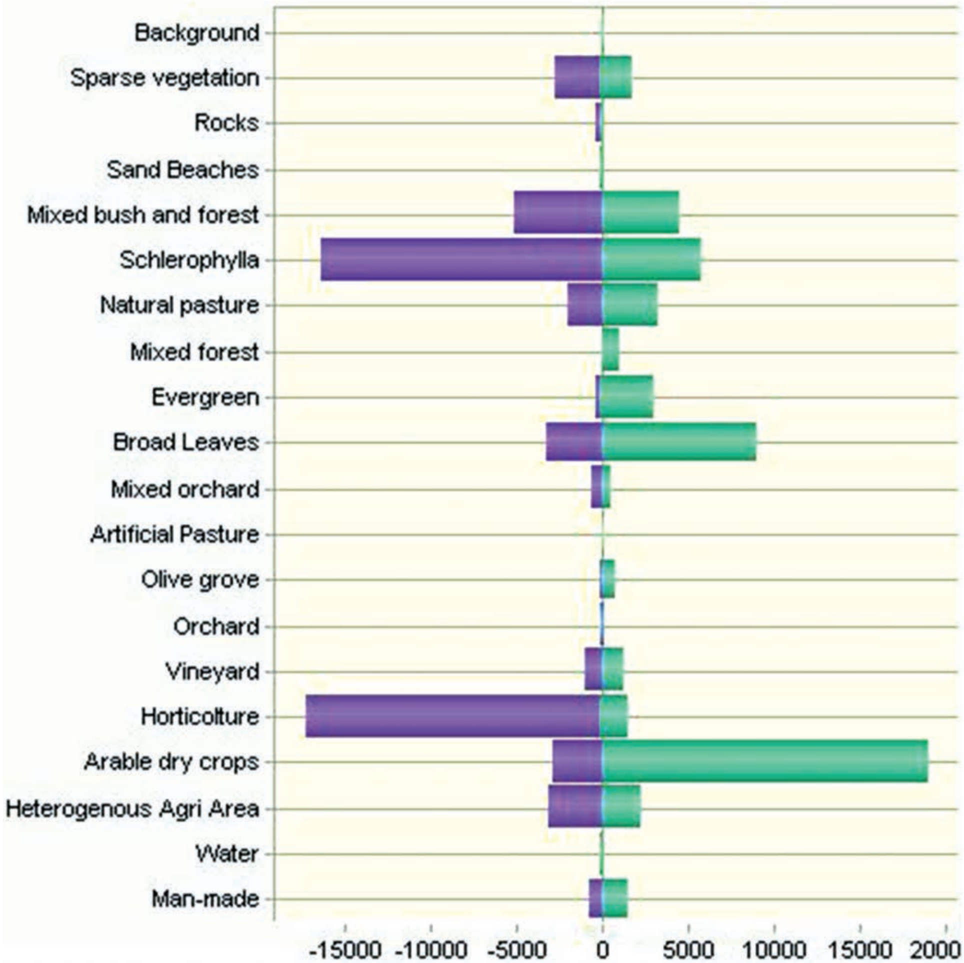

Figure 5 Cross tabulation analysis of vegetation. Gains and losses from 1997 to 2006

categories created by the calculation, a threshold of 100 ha has been chosen to cut out the smaller classes. Although this cutoff is arbitrary, it is believed that distinct landuses covering less than 100 ha are not significant given the regional scale of this study.

The remarkable changes occur for a small group of resources, as is shown in Figures 6 and 7. The most dramatic change occurred when horticulture (or irrigated agriculture) changed to arable dry crops. The presence of invasive sclerofilla may have increased the amount of loss, and contributed to the presence of broad leaves and mixed bush. The criterion used as input for the fuzzy analysis is based on the assumption of the landuse variation change among categories; in this specific situation the graph summarized the trend, determining the hypothetical dynamism of the area, and allowing measurement of the degree of change. A measure of potential vegetation or naturalness is used to describe the status of changing, and more specifically it identifies the level of systems disturbance, vegetation response, and sequence. The sequence has been outlined with either decreasing or increasing levels, adhering to the definition of potential

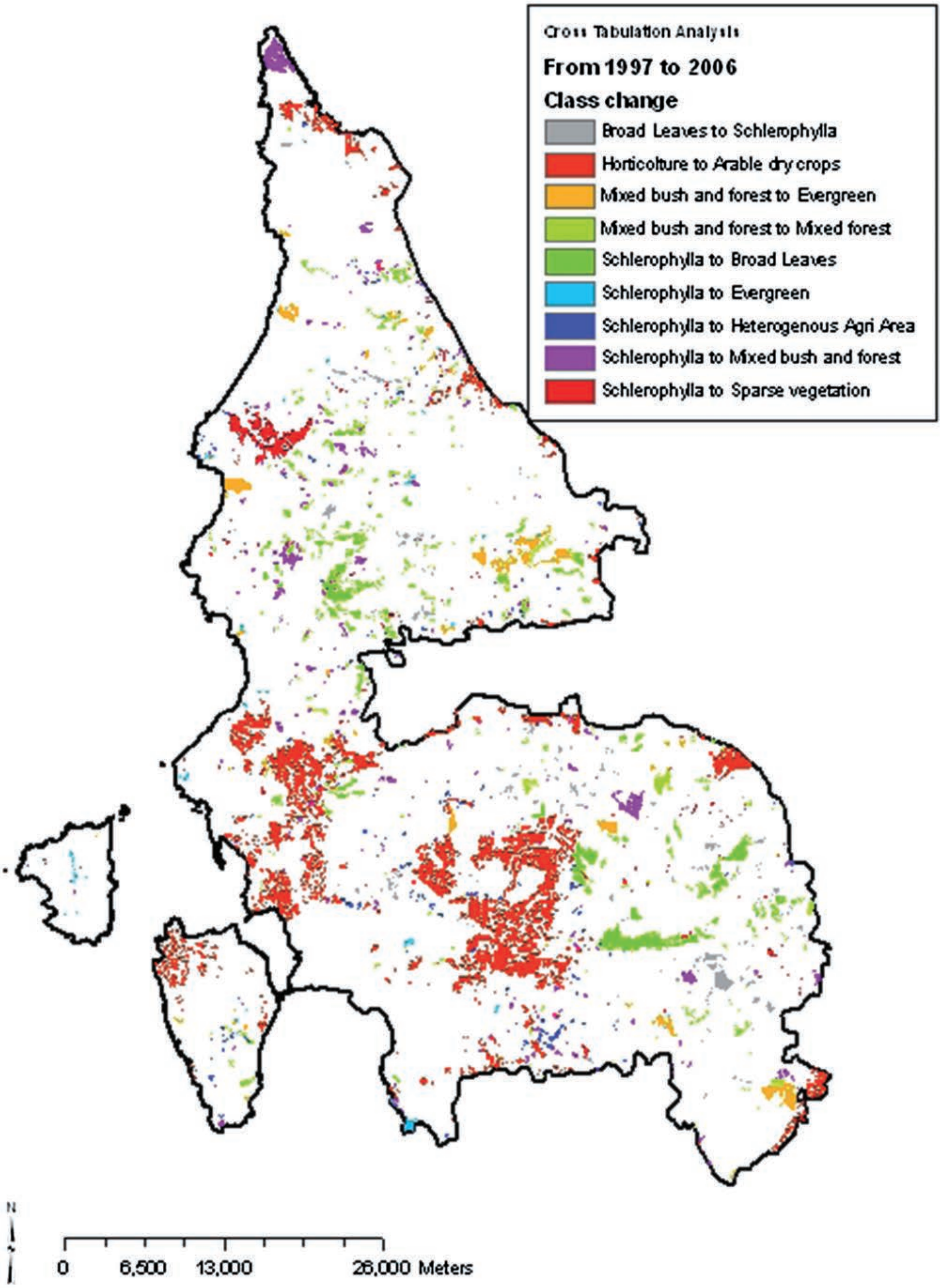

Figure 6 Vegetation change from 1997 to 2006 based on cross tabulation analysis

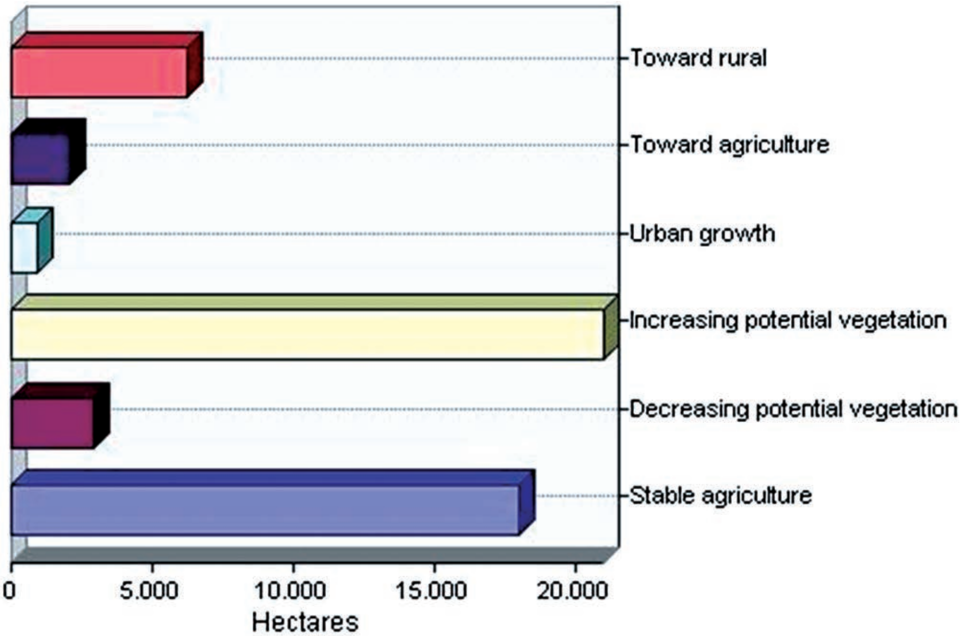

Figure 7 Landuse trend

vegetation. The above landuse units have been placed in this range, employing the discriminating factor, characterizing the developing vegetation, or describing the stable landuse. For example, the case of 'Schlerophilla to Evergreen or Broad Leaves' belongs to the 'Increasing potential vegetation', while the opposite relationship belongs to the 'Decreasing potential vegetation' class.

4.1.5 Scattered houses

Another important criterion, which determines the fuzziness of the territory, is the number of scattered houses (Figure 8). A dataset is derived from an accurate geographical calculation, which determines the spatial relationship of buildings from a continuous urban area to scattered buildings. This layer is generated by examining intra-building distances. A distance of 30 m, plus an additional measured buffered area of 10 m, among buildings has been chosen. Moreover the buildings identified have an approximate area of 2000 m^2, which is the starting point for the calculation. This methodology is broadly applied and widely accepted in the literature (Astengo and Nucci 1990).

Many of the problems encountered in determining policy in the Geopark area are related to the fact that activities and features of the territory may interact in such a way as to create an unfavorable feedback among them. Each set of interactions has its own capacity to influence different development targets such as tourism, environmental protection, human geography, and agricultural production. The kind of effort required to convert a former mine area into a new productive business and attraction must be carried out by local people with an enterprising spirit, substantially supported by government funds. So while interaction among elements is necessary, the consequences of those interactions are not always known in advance.

Figure 8 Geographical locations of the scattered houses

A single action might not produce the same effect as a set of coordinated actions. Indeed merging the efforts from individual actors and from the government creates a synergy, which can act to boost economic development. Consequently the aim of the government support should be to encourage 'winning' economic activities, whose future success is likely given the local development trends and opportunities. While there is nearly always enthusiasm for economic development policies in theory, there is a danger in simply stating the general aim to 'do something'. Even the simplest questions arise, regarding what to do, where to do it, and how much it will cost. This fuzzy analytic procedure is intended to address those questions.

Based on the assumption that a single actor cannot decide these questions in isolation, in order to tackle these emerging issues, the lead must be taken by the government. The 'longa mano'(long hand) of the government should generate the guidelines to provide common rules to follow and suggest practical approaches for economic development. To achieve this, a shared knowledge of the area's dynamism is the key to establishing a successful set of development policies. In order to improve the knowledge of the area, specific spheres of influence must be taken into account.

The principal human geographic spheres of influence include social, economic, and political spheres. The agricultural nature of the fuzzy area has been studied through a cross-sectional analysis. It shows the interaction between other elements within the area under investigation. The rather complex farming and agricultural systems interact with the coastal tourism environment. The cross-tab analysis represents a combination of researcher and government employee understanding of the human management strategies in a natural resource environment, based on a system in equilibrium. This equilibrium has been built by the physical environment, measured and qualified, with the unseen mental organization of environmental knowledge, past experience and management practices. The overall environment gives the input for a necessary policy for decision making. The ability to identify the dominant processes, activities and issues, has a significant influence on the whole system.

5 Fuzzy Clustering

In order to classify the municipalities into urban, rural, and endogenous local agriculture, the FCM method is applied. Clustering is one of the most fundamental issues in pattern recognition. It plays a key role in searching for structures in data. Cluster analysis generally refers to a wide range of methods that attempt to assign labels to objects, in the way that they can be considered to be 'natural subgroups' in X, a finite set of data.

These 'c' subsets are pairwise disjoint, all non-empty sets, and reproduce X through union. They are called a non-fuzzy c-partition of X. The fuzzy approach allows the characterization of an individual point's similarity to each of the clusters. This concept is instantiated by a membership function, and refers to the shared membership between classes. Consequently each sample will have a membership in every cluster. Membership close to unity signifies a high degree of equivalence between the sample and cluster, while membership close to zero implies little similarity between the sample and that cluster.

The FCM algorithm is associated with the generalized least-squares error function:

$$J(U,V) = \sum_{k=1}^{n} \sum_{i=1}^{c} (u_{ki})^m \cdot \|x_k - v_i\|^2 \tag{2}$$

where $1 \le m \le \infty$ and $\mathbf{u}_{ki}$ = degree of membership of x_k in the cluster center v_i; **c** = number of clusters; $\boldsymbol{m}$ = 'fuzziness index', a real number governing the influence of membership grade; $\mathbf{x}_k$ = is the *i*th or d-dimensional measured data; and **v** = is the dimension of the cluster centers;

Equation (2) attempts to locate minimal solutions to a selected objective weighted function, within groups, given by the sum of squared errors objective function (Bezdek 1981). The fuzziness exponent *m* controls the level of membership sharing among classes. As *m* increases toward infinity, the amount of membership grows, and the created classes are not well defined. As a matter of fact, hard clustering determines an *m* value approaching 1, which means that the membership is not shared.

The territorial system is split into the three clusters, c, one belonging to the urban class, the second to the rural class, and the third to the endogenous agriculture class. Although some of the criteria are calculated using a geographical dataset and are well fitted to the environmental behavior of the environmental variables, others are calculated based on the statistical dataset and have a county relevance.

The sample data (counties) have 16 variables, the values of which are spread over the territory, thus there are 16 dimensions (and coordinates in those dimensions) for each observation in the study. Consequently, a cluster's centroid has 16 coordinates as well. The calculation of the clusters'centroids is an iterative process. As a first step the centers are randomly chosen. In order to reach the best center, the FCM algorithm is applied. The best center depends on *m*, and a small number 'epsilon'(ε) that serves as a criterion to end the iteration. In this case its value is set in a range of $1e^{-3}$ to $5e^{-4}$, and it serves as a criterion to stop the iteration process.

5.1 Building the Fuzzy Municipalities

The criteria used as input for the analysis is as follows:

Criteria belonging to economic issues:

1. Rural Index
2. Income
3. Workers in the agricultural farms
4. Workers in the industrial/tertiary sector
5. Number of holiday farms, geographically located
6. Urban growth in the last decade, based on the urban sprawl pattern, determined from landuse analysis based on two time series.

Criteria related to social issues:

7. Forestation Regulation 2080. This regulation helps to convert the agricultural area, devoted to crops, to forest area. This further check shows the grade of penetration of European law for the conversion of traditional agricultural activities to forest. The criterion is depicted as a geographical area, or as hectares of the agricultural area involved, with geographical locations defined.
8. Residents in scattered houses, determined from the census 2001.
9. Population Density.

Criteria related to geographical and landuse issue or landuse transformation. The concept used to determine the landuse trend and its modification is based on potential vegetation, which evolves to reach a stable balance with the natural resources in a certain geographical location. This includes:

10. Trend from irrigated agriculture toward dry arable crops
11. Agriculture toward rural
12. Established agriculture

13. Increasing potential vegetation
14. Decreasing potential vegetation
15. Distance from the sea, calculated by the centroid of the municipality polygon
16. Number of scattered houses, determined by geographical criteria

6 Results

Before applying the fuzzy clustering algorithm, the correlation coefficient matrix (Table 1) has been calculated to describe the relationship among the variables. This does not necessarily mean there is a cause-effect relationship between two variables, and would not explain a logical connection. Nevertheless, the correlation between permanent agriculture, rural trend, and forestation has been noted. This is reasonable, because forestation takes the place of the agricultural field, as proposed by the EU legislation, for those famers who have requested funds to convert agriculture to forested areas. Moreover the correlation between people living in countryside homes and potential vegetation reflects a 'Modus Vivendi', where people are attracted to live in a more rural place, instead of an urban area. The high potential vegetation has an effect on the low potential vegetation. High potential vegetation occurs on low vegetation. Another correlation between industrial workers and density brings to the attention the urban development of the last 60 years in Italy. Furthermore, the correlation among the remainder of the matrix's variables is understandable, based on the description and cause-relation effects of the chosen criteria.

The mentioned three clusters are depicted by the fuzzy c means algorithm. Euclidean distance has been chosen, as the distance metric for the clusters, and the results are shown in Table 2, which determines the membership values used to calculate them.

The result shows that many municipalities maintain their cluster association, regardless of the fuzziness membership. This is the case of the agriculture cluster, where Villacidro, Guspini, Villasor, Pula and Gonnosfanadiga are clearly related. Essentially, their economy is based on a particular kind of developed agriculture/transformation product, and the major income comes from this activity; and there are well-defined boundaries between these activities and the industrial and rural clusters. Relaxing the boundary of the clusters and changing the membership value allows us to observe that some municipalities join the agriculture cluster. This is the case of San Giovanni Suergiu, geographically a neighbor of the core cluster, belonging to the rural cluster. This means that the aforementioned county is in 'limbo', fluctuating from rural to agriculture (similar to Assemini is fluctuating from rural to the agriculture cluster.

The industrial cluster is well determined by a clear group of counties within a short distance from the cluster center. Sarroch, S. Antioco, Portoscuso and Iglesias are famous for their industrial activities, ranging from heavy to light industry with a satellite of service settlements. This justifies the membership of historical industrial counties. Nevertheless Carbonia shows an undefined behavior. It is well known that Carbonia, was developed during a a period of fascism, and was created to be an important industrial area. It does not belong emphatically to this cluster, but fluctuates in the cluster clouds, especially considering its uncertain distance from the cluster center, when relaxing the membership value. Furthermore its development is growing toward agriculture and recreational activities.

Over the last decade, Teulada, Arbus, Bugerru, Siliqua, and Fluminimaggiore have been focusing on a new kind of tourist industry, never developed before. It is based on a

Table 1 Coefficient correlation matrix

	Density	Rural Level	Income	Sprawl inhabitants	Sprawl house number	Forested actions	Sea Distance	Agri Tourism	Stable Agriculture	High Potential Vegetation	Low Potential Vegetation	Urban Growth	Agriculture Trend	Trend rural	Agriculture worker	Industry worker
Density	1	–0.962	0.262	0.357	0.218	0.202	0.083	–0.120	0.028	–0.096	–0.100	0.137	0.072	–0.115	0.079	0.602
Rural Level	–0.962	1	–0.373	–0.363	–0.353	–0.287	0.041	0.190	–0.073	0.064	0.111	–0.206	–0.160	0.078	–0.090	–0.687
Income	0.262	–0.373	1	0.265	0.506	0.294	–0.151	0.154	–0.057	0.411	0.150	0.097	0.244	0.260	0.178	0.380
Sprawl inhabitants	0.357	–0.363	0.265	1	0.201	0.201	0.258	0.020	–0.113	0.462	0.537	0.040	0.033	0.136	0.298	0.373
Sprawl house number	0.218	–0.353	0.506	0.201	1	0.259	–0.591	0.069	0.254	0.299	0.082	0.267	0.560	0.429	0.105	0.030
Forested action	0.202	–0.287	0.294	0.201	0.259	1	–0.054	0.046	0.630	0.391	0.297	0.366	0.637	0.344	–0.006	0.111
Sea Distance	0.083	0.041	–0.151	0.258	–0.591	–0.054	1	–0.077	–0.183	0.020	0.253	–0.356	–0.401	–0.253	0.139	0.104
Agri Tourism	–0.120	0.190	0.154	0.020	0.069	0.046	–0.077	1	–0.153	0.438	0.447	–0.080	0.246	0.609	–0.073	–0.178
Stable Agriculture	0.028	–0.073	–0.057	–0.113	0.254	0.630	–0.183	–0.153	1	0.083	0.044	0.507	0.698	0.233	0.072	–0.108
High Potential Vegetation	–0.096	0.064	0.411	0.462	0.299	0.391	0.020	0.438	0.083	1	0.601	0.043	0.480	0.595	0.072	0.059
Low Potential Vegetation	–0.100	0.111	0.150	0.537	0.082	0.297	0.253	0.447	0.044	0.601	1	0.024	0.289	0.490	–0.001	–0.001
Urban Growth	0.137	–0.206	0.097	0.040	0.267	0.366	–0.356	–0.080	0.507	0.043	0.024	1	0.412	0.164	0.002	0.171
Agriculture Trend	0.072	–0.160	0.244	0.033	0.560	0.637	–0.401	0.246	0.698	0.480	0.289	0.412	1	0.698	–0.038	–0.008
Trend rural	–0.115	0.078	0.260	0.136	0.429	0.344	–0.253	0.609	0.233	0.595	0.490	0.164	0.698	1	0.002	–0.008
Agriculture worker	0.079	–0.090	0.178	0.298	0.105	–0.006	0.139	–0.073	0.072	0.072	–0.001	0.002	–0.038	0.002	1	0.187
Industry worker	0.602	–0.687	0.380	0.373	0.030	0.111	0.104	–0.178	–0.108	0.059	–0.001	0.171	–0.008	–0.008	0.187	1

Table 2 FCM result (Euclidean distance)

Cluster Exponential Weight 1.2					
Agriculture		Industrial		Rural	
0.999967	VILLACIDRO	0.999918	SARROCH	0.999999	SANT'ANNA ARRESI
0.999941	GONNOSFANADIGA	0.999764	SANT'ANTIOCO	0.999996	PISCINAS
0.999019	GUSPINI	0.999682	SILIQUA	0.999996	NUXIS
0.992775	PULA	0.998818	CARLOFORTE	0.999995	TRATALIAS
0.955688	VILLASOR	0.998803	TEULADA	0.999988	VILLA SAN PIETRO
		0.997594	FLUMINIMAGGIORE	0.999979	VILLAPERUCCIO
		0.995913	ARBUS	0.999967	PERDAXIUS
		0.991609	PORTOSCUSO	0.999912	MASAINAS
		0.98468	IGLESIAS	0.99991	NARCAO
		0.97291	BUGGERRU	0.999195	DOMUSNOVAS
		0.936844	CARBONIA	0.993198	VILLAMASSARGIA
		0.829851	CALASETTA	0.989542	VALLERMOSA
		0.821056	GONNESA	0.984274	UTA
		0.459812	DOMUS DE MARIA	0.97109	SANTADI
		0.45456	ASSEMINI	0.936113	CAPOTERRA
				0.755151	GIBA
				0.677821	SAN GIOVANNI SUERGIU
				0.540064	DOMUS DE MARIA

Cluster Exponential Weight 1.5					
Agriculture		Industrial		Rural	
0.964588	VILLACIDRO	0.973572	TEULADA	0.996799	SANT'ANNA ARRESI
0.94548	GONNOSFANADIGA	0.971503	SARROCH	0.992753	PISCINAS
0.92912	GUSPINI	0.935414	BUGGERRU	0.99168	TRATALIAS
0.921111	PULA	0.935023	FLUMINIMAGGIORE	0.988081	VILLAPERUCCIO
0.720815	VILLASOR	0.916055	SILIQUA	0.987025	VILLA SAN PIETRO
0.395631	SAN GIOVANNI SUERGIU	0.912078	SANT'ANTIOCO	0.986002	PERDAXIUS
0.353884	ASSEMINI	0.883002	CARLOFORTE	0.982139	NUXIS
		0.838554	ARBUS	0.974967	MASAINAS
		0.798792	DOMUS DE MARIA	0.953342	NARCAO
		0.774011	PORTOSCUSO	0.793236	DOMUSNOVAS
		0.728686	GONNESA	0.776884	UTA
		0.718282	CALASETTA	0.696668	SANTADI
		0.715146	GIBA	0.585994	VILLAMASSARGIA
		0.680684	IGLESIAS	0.541253	VALLERMOSA
		0.563477	CARBONIA	0.469596	SAN GIOVANNI SUERGIU
		0.497086	CAPOTERRA	0.466331	CAPOTERRA
		0.441426	VALLERMOSA		
		0.400162	VILLAMASSARGIA		
		0.390102	ASSEMIN		

Cluster Exponential Weight 1.8					
Agriculture		Industrial		Rural	
0.854271	PULA	0.871947	TEULADA	0.962874	SANT'ANNA ARRESI
0.750877	VILLACIDRO	0.823524	SARROCH	0.946861	PISCINAS
0.726572	GUSPINI	0.819541	BUGGERRU	0.942531	TRATALIAS
0.701341	GONNOSFANADIGA	0.770417	FLUMINIMAGGIORE	0.922871	VILLA SAN PIETRO
0.678356	VILLASOR	0.707624	DOMUS DE MARIA	0.921292	VILLAPERUCCIO
0.419187	SAN GIOVANNI SUERGIU	0.690502	SILIQUA	0.910667	PERDAXIUS
0.407122	ASSEMINI	0.659745	CARLOFORTE	0.891159	NUXIS
0.379742	CARBONIA	0.651514	SANT'ANTIOCO	0.878437	MASAINAS
0.361746	IGLESIAS	0.649514	GIBA	0.790314	NARCAO
		0.620419	ARBUS	0.616287	DOMUSNOVAS
		0.564362	PORTOSCUSO	0.58513	UTA
		0.563185	GONNESA	0.510809	SANTADI
		0.544367	CALASETTA	0.452854	VILLAMASSARGIA
		0.503424	VALLERMOSA	0.418168	VALLERMOSA
		0.49323	CAPOTERRA	0.380676	CAPOTERRA
		0.487062	IGLESIAS	0.377267	SAN GIOVANNI SUERGIU
		0.47689	VILLAMASSARGIA		
		0.432575	CARBONIA		
		0.346181	ASSEMINI		

Cluster Exponential Weight 2					
Agriculture		Industrial		Rural	
0.71614	PULA	0.749300	TEULADA	0.912742	SANT'ANNA ARRESI
0.585219	GUSPINI	0.744414	BUGGERRU	0.850525	PISCINAS
0.560221	SANT'ANTIOCO	0.711395	DOMUS DE MARIA	0.84572	TRATALIAS
0.556836	VILLASOR	0.663609	GIBA	0.832271	VILLAPERUCCIO
0.543058	VILLACIDRO	0.615525	FLUMINIMAGGIORE	0.828761	PERDAXIUS
0.514208	GONNOSFANADIGA	0.612946	SARROCH	0.815106	VILLA SAN PIETRO
0.441768	IGLESIAS	0.597764	VALLERMOSA	0.784613	MASAINAS
0.428317	SILIQUA	0.576273	VILLAMASSARGIA	0.770511	NUXIS
0.428239	CARBONIA	0.522101	CAPOTERRA	0.699722	NARCAO
0.401456	ASSEMINI	0.485216	CARLOFORTE	0.548333	UTA
0.384218	CALASETTA	0.477937	GONNESA	0.451776	DOMUSNOVAS
0.368986	PORTOSCUSO	0.471396	ARBUS	0.448900	SANTADI
0.35862	GONNESA	0.464406	SILIQUA	0.398306	SAN GIOVANNI SUERGIU
0.357368	CARLOFORTE	0.456822	CALASETTA		
0.347254	ARBUS	0.441500	PORTOSCUSO		
0.346832	SAN GIOVANNI SUERGIU	0.440947	DOMUSNOVAS		
		0.384155	IGLESIAS		
		0.364662	SANT'ANTIOCO		
		0.363277	CARBONIA		
		0.343795	ASSEMIN		

Table 3 Validation results

N° Cluster (C)	Membership 1.3				Membership 1.6			
	F	H	NFI	S	F	H	NFI	S
2	0.8771	0.2103	0.7541	0.5417	0.7432	0.4036	0.4864	0.5337
3	0.8642	0.2430	0.7963	0.3821	0.7021	0.5314	0.5531	0.3488
4	0.8525	0.2791	0.8034	0.5999	0.6616	0.6399	0.5488	0.6372
5	0.8424	0.3050	0.8030	0.6363	0.6616	0.6399	0.5589	0.6372
6	0.8684	0.2776	0.8421	0.4770	0.6474	0.7545	0.5769	0.4367
7	0.8850	0.2545	0.8658	0.4228	0.6486	0.7909	0.5901	0.4235
8	0.9061	0.2115	0.8927	0.3449	0.6544	0.8021	0.6051	0.3844

web of territorial connections, among B&Bs, hotels, and agritourism, defining a new organization called 'albergo diffuso'. This has been increasing the income and the employment of workers in this emerging sector in this particular area. Arbus, Bugerru and Fluminimaggiore, especially, show a strong membership of this group. The effect of the Geopark, and its collateral activities, undoubtedly promoted sustainable economic development, as defined by the UNESCO guidelines.

Nevertheless, the uncertain behavior of several counties, switching from one cluster to another one, shows up and requires further analysis. A validation analysis has been carried out.

7 Cluster Validation

In order to assess the characteristics of clusters, three types of cluster validity have been estimated on each fuzzy c-partition of the considered matrix. Validity of the FCM partition may be accomplished by cluster performance indices. This issue addresses the cluster validity procedure, which is able to determine the optimal number of clusters.

The validation analysis has been carried out, choosing the following indices:

- Partition coefficient (F) (Bezdek 1981);
- Partition entropy (H) (Bezdek 1981);
- Nonfuzzy index (NFI) (Robubens 1978); and
- Compactness and separation index (S) (Xie and Beni 1991).

The validation analysis returns the results in Table 3. Given the fixed Euclidean distance options and membership value of 1.2, the optimal number of clusters is obtained when F is maximum and H is minimum, and NFI is maximum.

The validation result returns a high value of F and a minimum of H for eight clusters, which means an optimal number of clusters. Seven clusters and two clusters deserve analogous comment. Three clusters does not appear to be the perfect choice. In regard to the separation index, S, the best choice is eight clusters, because this index is minimum over the range of values for the clusters. Nevertheless, looking at cluster 3, it appears as a possible choice, especially when the membership value is 1.6. Three clusters mean a feasible choice, when the reality is shadowed by a fuzziness leading through an unclear reality.

8 Conclusions

The analysis determined the clusters of municipalities involved in the described development, switching from the urban to the rural, and crossing through agriculture. Despite the fuzzy behavior of certain municipalities, on the one hand a group of them still adheres to their cluster, barely moving through the fuzzy space, keeping a stable position there. These are ancient settlements, maintaining their cultural traditions and ancient activities. Certainly, their development is designed by their heritage and centennial addressed growth by transferring the knowledge from father to son.

On the other hand Carbonia, newly settled in the late 1930s, built to provide housing to the mining workers, wanders among the three clusters. Its recent urban growth and related economy may switch from one side to another, because it does not have a strong heritage and ancient roots in the settled population.

By definition, human and social behavior is well explained through a fuzzy concept. Including environmental changes, the scenario becomes softened and reality more nuanced. Identifying this reality as fuzzy, the key of interpretation opens to a space defined by the clusters (rural, agriculture, urban/industrial). In this categorized space, the freedom of action is not limited, but it is addressed in the direction of a specific development. The effort to change the direction of development toward another cluster is quantified by the grade of membership of a certain cluster. In this study, several municipalities show the tendency to move toward a diverse development, relaxing the cluster boundaries. This change would happen with a probability determined by a quantified level of effort, sustained by political action.

Further research will address a fuzzy clustering model for multivariate spatial time series. This accomplishes the aim of taking into account the spatial nature of the clusters, together with the characteristics of the feature space. Moreover the uncertainty associated with the assignment of spatial units to specific clusters is deployed by the complexity of the feature space (Coppi et al. 2010).

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