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Integrated Indicators for the Estimation of Vulnerability to Land Degradation

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Additional information is available at the end of the chapter

1. Introduction

The setting up of sustainable development strategies, able to balance the opposite demands of economic growth and environmental protection, is one of the fundamental challenges for the international community. Our developing world is experiencing growing pressures on its land, water, and food production systems and the role of the human society in determining change within the Earth environment is becoming ever more central [1]. In this context, preserving the land productivity is a prior goal, especially in those areas, such as drylands, which are particularly fragile from an ecological point of view.

One of the most serious problem threatening these areas is land degradation, which is defined as the (persistent) reduction of biological and economic productivity [2] or, equivalently, as the reduction in the capacity of the land to provide ecosystem goods and services and to assure its functions [3,4]. Land degradation is due to a mix of predisposing factors (thin soil horizons, low soil organic matter, sparse vegetation cover, etc.) frequently accentuated by human mismanagement and periodic drought.

As a crucial component of terrestrial ecosystems, soil plays a prominent role in triggering or exacerbating land degradation. The combined action of climatic factors (aridity, extreme events, rainfall erosivity) and human pressure (overgrazing, deforestation, intensification of agriculture, tourism development, see e.g., [5]) can result in a general soil degradation and in some cases in a irretrievable loss of lands suitable for agricultural/grazing/forest use [6].

In particular, as far as the anthropic pressure is concerned, the demographic boom and the economic growth have caused a rapid and unplanned change of land use patterns [7-9] as a

consequence of the conversion of natural and semi-natural areas in areas often managed through intensive farming techniques. These mainly consist in the use of a considerable amount of external inputs (frequent use of fertilizers, pesticides and genetically modified organisms, see [10-12]) and in a set of unsuitable management practices (too deep ploughing, large irrigation schemes, monoculture, etc., [13]). It is evident that the progressive intensification of agricultural practices can accelerate soil degradation phenomena especially in those areas marked by poor soil qualities [14]. In fact, cropping and grazing cause land degradation more than non-agricultural uses of soil [15].

According to the European Commission, six soil degradation processes (water, wind and tillage erosion, loss of soil organic carbon, compaction, salinization and alkalinization, contamination, and decline in biodiversity) were identified as induced or worsened by bad agricultural practices [13].

Also livestock husbandry can represent a potential degradation driver when a high number of head of cattle is strongly concentrated in limited areas, as it often occurs in Southern Europe (overgrazed land, e.g., [16]).

Furthermore, degradation phenomena affect land surface processes and particularly vegetation covers which play a decisive role in the surface energy exchanges and water balance [17,18]. Therefore vegetation assessment is crucial for evaluating land degradation vulnerability, particularly in areas that are still productive. Stressed vegetation, characterized by a decrease of photosynthetic activity and/or patch fragmentation processes, can have negative repercussions on the other biophysical components (soil and climate, [19]). This is particularly true for Mediterranean landscapes, often marked by a gradual reduction of biological productivity (e.g., [20, 21]), low resilience of vegetation [7,9] and abrupt modifications due to wildfires [22,23] and land use/land cover changes [24,25].

On the whole, today, a quarter of world population is threatened by the effects of degradation phenomena [26], which affect nearly 84% of agricultural lands [26]. Then it is clear the reason why land degradation is listed among the most important socio-environmental issues having direct and indirect effects on food security, climate change at local scale, eco-refugees and wars linked to the exploitation of natural resources [28-30].

The need to halt and prevent soil/land degradation has urged the international scientific community to improve the knowledge on causes and consequences of the interest phenomena and identify efficient monitoring tools. These have to help policy makers in developing effective conservation/rehabilitation measures adapted to each involved area. In particular, scientists must provide efficient tools for the early detection of sensitive areas by classifying them in different levels of land degradation vulnerability [8]. At this aim many different methodologies have been used to study land degradation (field measurements, visual interpretation, social enquiries, mathematical models, remote sensing, environmental indicators, etc.), including the use of simple models based on indicators that synthesize information on the state and tendency of complex processes [31].

In particular, in the context of the Mediterranean basin the most used methodology is the indicator-based Environmentally Sensitive Areas (ESA) model developed within the MEDA-

LUS project [32]. This combines information concerning the biophysical component (climate, soil and vegetation) and the anthropic one to detect areas prone to degradation and defines, at the same time, relative values of vulnerability. The standard scheme of the ESA model is not free from faults consisting in too little detailed guidance on the choice and the distribution in vulnerability classes of anthropic indicators, lack of dynamical information on the vegetation component and lack of an objective weighting system based on statistical analysis for the used indicators [33,34]. Nevertheless, the ESA model is the most frequently applied in the Mediterranean basin enabling comparability with other similar studies. This is due to the immediacy of the adopted approach in dealing with land degradation and the consequent easy and rapid interpretation of the produced cartography. Moreover, the flexibility of the model, allowing inclusion/exclusion of variables, is particularly suitable to match local biophysical and socio-economic peculiarities of each examined area [35].

In this chapter we approach the assessment of the vulnerability to land degradation of a typical Mediterranean environment using a modified version of the ESA model. This approach combines analyses of the socio-economic component with analyses of the vegetation trends.

According to the standard ESA strategy, different indicators representing the impact of agricultural and grazing activities are used. The main feature of these indicators is that they are census-based and consequently suitable only for the analysis at municipal scale. Therefore we have also elaborated a mechanization index (proxy for soil compaction induced by agricultural machineries) that uses land cover and morphological data [36], enabling high spatial resolution and faster rate of update.

The indicators related to the anthropic impact are integrated into an overall Land Management Index (LMI) and in each area it is possible to enhance the main contributing factors to highlight the prevailing forces that drive human-induced degradation processes.

In order to include vegetation in the vulnerability map we analyze satellite vegetation index NDVI (Normalized Difference Vegetation Index) which is recognized as ideal tool for monitoring long term trends of degradation phenomena and assessing different values of severity of the concerned processes [37,38].

The final result of our analyses is an integrated vulnerability map of the investigated region, accounting for management and vegetation factors, which allows us to identify priority sites where restoration/rehabilitation interventions are urgent.

The adopted procedure can be easily applied to geographic contexts characterized by high complexity in terms of land cover type and economic vocation (intensive agriculture, grazing, industrial activities) thus enabling an early detection of the areas most vulnerable to land degradation.

2. Study area

The Basilicata region covers an area of about 10000 km² in the core of Southern Italy (Fig. 1). This is recognized as a region at potential risk of land degradation by several studies [39-41].

In this area, as in all the Southern Italy, vulnerability to land degradation results from the co-occurrence of some specific bioclimatic features (uneven reliefs with steep slopes, highly erodible soils, wide climate variability, recurrent drought) and from an improper land use (urbanization intensive farming, industrial pollution). For example, inappropriate agricultural practices may significantly contribute to land degradation, determining a strongly impact on the economic value of the lands [42].
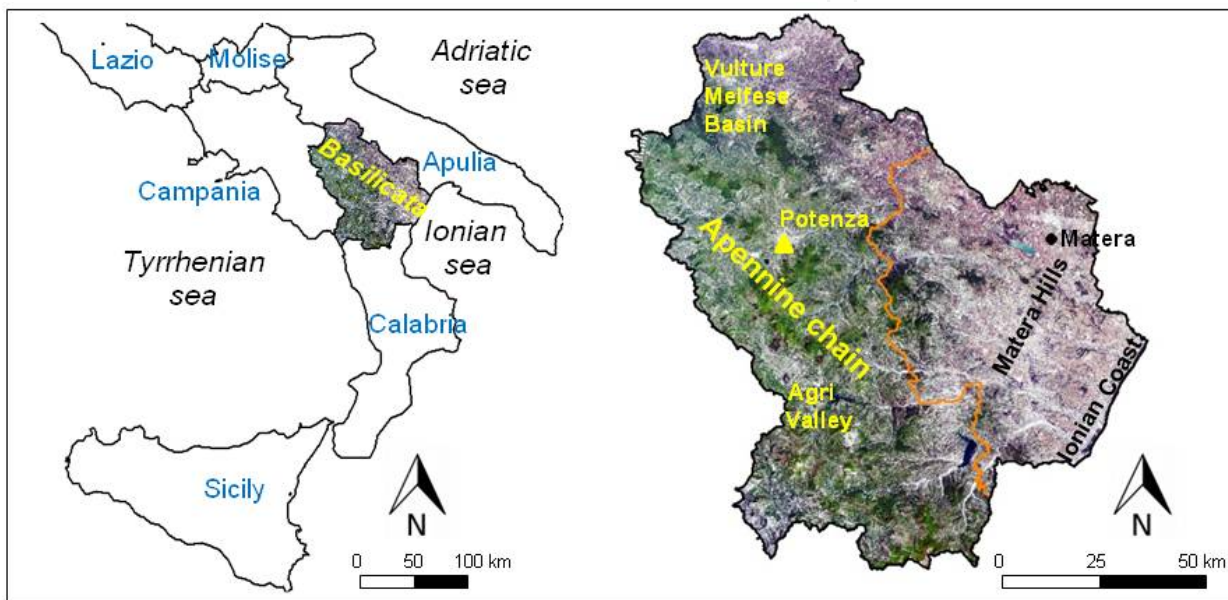
Figure 1. Location of the study area within Southern Italy and its main placenames

From a geographic point of view, Basilicata is a mountain region, including only a small percentage of lowland (less than 10% of the total surface) in the Ionian coastal area.

In the study area, soils often show a high susceptibility to degradation due to different causes. In the Ionian coastal area (Metaponto plain) we find soils affected by salinization phenomena caused both by coastline regression and by an incorrect agro-forestry management [43,44]; in the Central-Eastern hills, soils show singular geo-mineralogical composition, irregular morphology and are exposed to strong climatic fluctuations shaping the badlands (see e.g., [45,46]).

Vegetation is highly heterogeneous according to the different orography: dense and widespread vegetation in the central area, occupied by the Apennine chain, where broad-leaved forests, maquis and pastures are dominant; sparse vegetation and bare soils in the Eastern part of the region. On the Ionian coast several irrigation schemes enable a diversified agri-

culture including different cultivation types: orchards, permanent crops and arable lands. These last are also prevalent in the Northern zone, near to the Apulia region.

The Basilicata region is not univocally classified in a single climatic zone. Along the coasts climate is typically Mediterranean (rainy and mild autumns-winters, hot and dry summers) while the mountain areas are characterized by cold winters and by abundant precipitations; finally, inland areas, (Melfi industrial area, Basento valley and Agri valley), are characterized by very warm summers and mild winters with annual rainfall lower than 600 mm. In these areas, the period 1994-2003 has shown a significant decrease of the average annual and winter precipitation compared with the precipitation observed from 1916 to 1980s [47] thus evidencing an increase of dryness also in the wettest periods of the year.

The specific geomorphological characteristics of this region and a limited infrastructure network determine the concentration of industrial districts in small dedicated areas (Melfi area, Basento valley and Agri valley area). At now the tertiary is the prevalent economic sector. In the agriculture sector, though farms and cultivated lands decreased in the last decade (-31.9% and -4.7 respectively, [48]), the number of employees is still very high (about one fifth of the total employees, [49]).

Intensive and often inadequate farming practices have worsened degradation phenomena under way especially where climatic conditions are particularly unfavorable (e.g. badlands, [50]); mountainous areas have experienced a remarkable dynamism in the zootechnical sector, with a net increase in the number of head of cattle and in the size of farms.

3. Data

3.1. Satellite data

In order to evaluate the state of vegetation cover and its variations we used a vegetation index time series (2000-2010) acquired by the MODIS (Moderate Resolution Imaging Spectroradiometer) sensor. We analyzed NDVI (Normalized Difference Vegetation Index) values available at full spatial resolution (250m) as 16-day composite from the MODIS dataset by NASA LP DAAC (Land Processes Distributed Active Archive Center). Among different vegetation indices available in literature, NDVI is one of the best-known and best-working indices, and is recognized as a suitable proxy for vegetation activity. It is defined as the ratio [51,52]:

$$NDVI = \frac{NIR - RED}{NIR + RED} \tag{1}$$

where RED is the reflectance in the red band of the sensor and NIR is the reflectance in the near infrared band. NDVI takes values between -1 and 1; negative values indicate water and thick clouds, very low positive values correspond to barren areas (mainly rock, sand) or

snow cover, whereas high positive values correspond to vigorous and healthy vegetation cover (Fig. 2).

The choice of MODIS sensor has been determined by its peculiar characteristics. High temporal resolution (2 images per day), moderate spatial resolution (250m), and the availability of a time series since 2000 make it suitable for monitoring vegetation variability at the national/regional scale. Furthermore, MODIS data are widely used to analyze vegetation conditions in the context of land degradation studies [53-56].
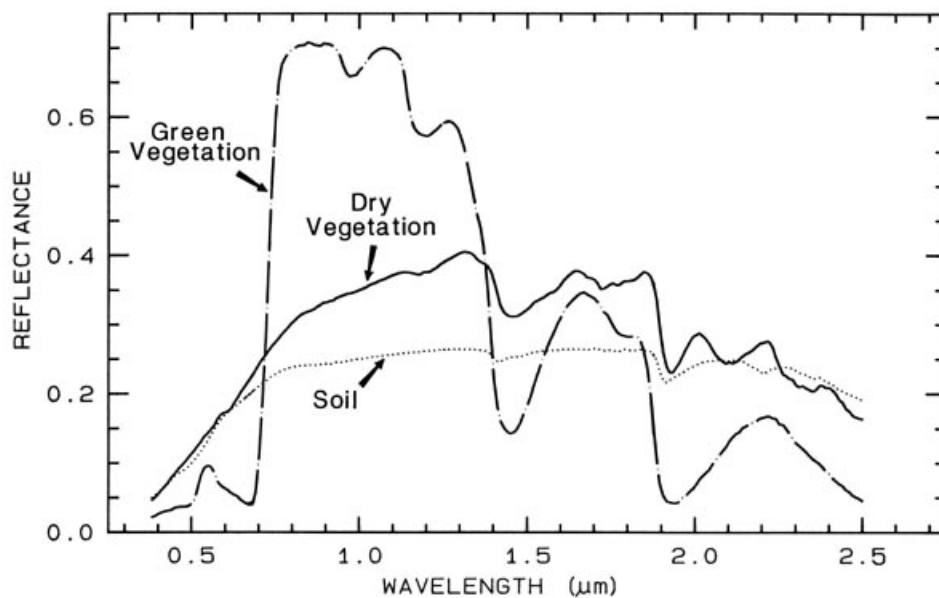
Figure 2. Spectral reflectance of natural surfaces (see http://bluemarble.ch/wordpress/2003/01/07/)

3.2. Census data

In order to estimate anthropic pressure indicators we extracted information from census database. The main source has been the Agricultural Census carried out by ISTAT (Italian National Institute of Statistics) for the years 1990 and 2000 (latest available census). Data are provided by municipality (i.e., the minimum administrative level) for the Basilicata region.
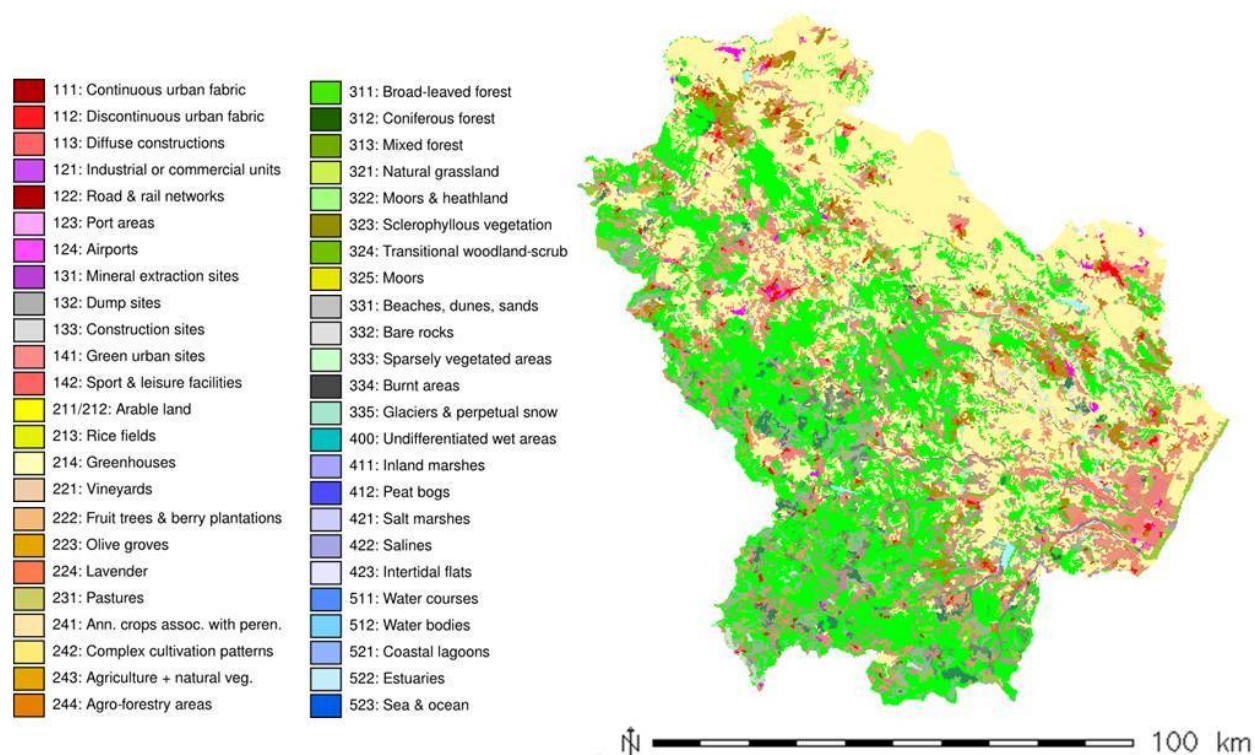
In particular, we gathered data on:

• Utilized Agricultural Area (UAA, years 1990 and 2000);

- Permanent grass and Pasture areas (PP, year 2000);

- Number of heads of cattle (bovines, buffalos, sheep, goats and equines, year 2000).
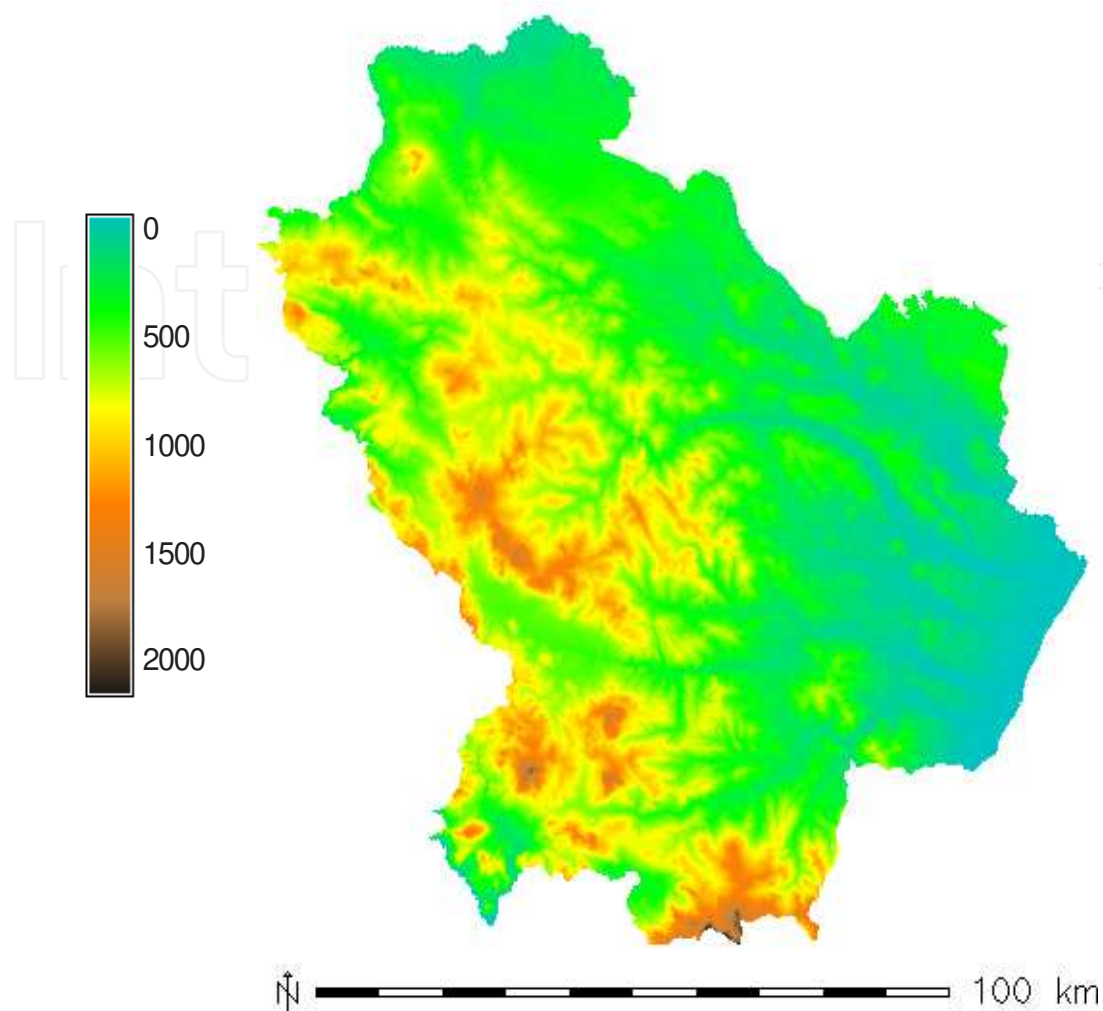
3.3. Ancillary data

For the elaboration of the Mechanization Level Index (MLI), we used the following ancillary data:

- level-3 Corine Land Cover (CLC) 2000 map (Fig. 3), downloaded from the High Institute for Environment Protection and Research (ISPRA - former APAT, see http://www.eea.europa.eu/data-and-maps/data/corine-land-cover-2000-clc2000-seamless-vector-database-4);

- number of machinery passes per cultivation type (source ENAMA – Italian National Agency of Agricultural Mechanization);

- 20m resolution DEM (Digital Elevation Model, Fig. 4) of the Basilicata provided by the Basin Authority of the Region.

111: Continuous urban fabric	311: Broad-leaved forest
112: Discontinuous urban fabric	312: Coniferous forest
113: Diffuse constructions	313: Mixed forest
121: Industrial or commercial units	321: Natural grassland
122: Road & rail networks	322: Moors & heathland
123: Port areas	323: Sclerophyllous vegetation
124: Airports	324: Transitional woodland-scrub
131: Mineral extraction sites	325: Moors
132: Dump sites	331: Beaches, dunes, sands
133: Construction sites	332: Bare rocks
141: Green urban sites	333: Sparsely vegetated areas
142: Sport & leisure facilities	334: Burnt areas
211/212: Arable land	335: Glaciers & perpetual snow
213: Rice fields	400: Undifferentiated wet areas
214: Greenhouses	411: Inland marshes
221: Vineyards	412: Peat bogs
222: Fruit trees & berry plantations	421: Salt marshes
223: Olive groves	422: Salines
224: Lavender	423: Intertidal flats
231: Pastures	511: Water courses
241: Ann. crops assoc. with peren.	512: Water bodies
242: Complex cultivation patterns	521: Coastal lagoons
243: Agriculture + natural veg.	522: Estuaries
244: Agro-forestry areas	523: Sea & ocean

100 km

Figure 3. CLC map for Basilicata region

Figure 4. Digital Elevation Model for Basilicata region

4. Methodological procedure

4.1. Estimation of the vulnerability due to anthropic factors

In the last years, despite scientists have paid much attention to anthropogenic factors as potential land degradation drivers [57,34], the socio-economic component still remains difficult to explore. The main problems are related to the qualitative character, the strong spatial aggregation, and the infrequent update of the information [58]. Our approach takes into account the so called "agricultural impact" hypothesis [59] as potential explanation for the most part of the land degradation processes, by focusing on crop intensification/land abandonment and overgrazing in Southern Italy. Among the indicators already adopted in similar studies [60-62], we selected the following ones: variation of cultivated surfaces, percentage of permanent grass and pasture on the total agricultural area, grazing intensity

and mechanization level. The first three indicators are based on census data, the last is calculated combining information on land cover and the other ancillary data.

According to the ESA model, in order to make the used indicators comparable, we classified them in a common range of vulnerability levels starting from 1 (the lowest vulnerability to land degradation) up to 2 (the highest vulnerability to land degradation).

4.1.1. Census based indicators

The first indicator calculates the percentage variation of the cultivated surfaces (UAA_VAR) referred to a time horizon of ten years, as follows:

$$UAA\_VAR = \left| \frac{UAA_{t_2} - UAA_{t_1}}{UAA_{t_1}} \cdot 100 \right| \qquad (2)$$

where UAA_{t_1} and UAA_{t_2} are the Utilized Agricultural Area (arable land, permanent grassland, permanent crops and other agricultural land such as kitchen gardens, see http://epp.eurostat.ec.europa.eu/statistics_explained/index.php/Category:Agriculture_glossary) at the start and at the end of the investigated period (t_1=1990 and t_2=2000 in this study). The absolute value makes this indicator a good proxy both for agricultural intensification and land abandonment (Table 1).

Vulnerability class	UAA_VAR Values	
	Decreases	Increases
(2) high	< - 50	> 50
medium - high	-50 : -20	20 : 50
medium	-20 : -10	10 : 20
medium - low	-10 : -5	5 : 10
(1) low	-5 : 5	-5 : 5

Table 1. Distribution of vulnerability classes for the index of agricultural area variations (UAA_VAR)

In fact, both these processes are considered potential land degradation drivers: the increase in cultivated surfaces means a reduction in natural lands and requires additional inputs (water resources, fertilizers, tilling, etc.) that strongly impact on the environment; on the other hand, the decrease in cultivated areas is associated to the abandonment of marginal lands (lack of maintenance of drainage network, terracing, etc.) causing acceleration of deg-

radation [63,64], or urbanization/industrialization phenomena with consequent soil sealing and pollution.

The second indicator estimates the percentage of Permanent grass and Pasture surfaces (*Sur_PP*) with respect to the total Utilized Agricultural Area (UAA) according to this formula:

$$PP\_UAA = \frac{Sur\_PP}{UAA} \cdot 100 \tag{3}$$

The rationale behind this indicator is the basic assumption that grass and pasture can be considered low-impact covers because they do not require considerable amount of external input (fertilizers, herbicides, mechanization and irrigation scheme), accomplishing an important protection function against erosional processes [61]. Therefore, the higher the indicator value, the lower the vulnerability level (Table 2).

Vulnerability class	PP_UAA Values
(2) high	< 5
medium - high	5 : 10
medium	10 : 30
medium - low	30 : 50
(1) low	50 : 100

Table 2. Distribution of vulnerability classes for the percentage of permanent grass and pasture on the Utilized Agricultural Area (PP_UAA)

The third indicator is used to estimate the Grazing Intensity (GI), by evaluating the amount of Adult Bovine Unit (ABU) on the total area of permanent grass and pasture (expressed in hectares), as follows:

$$GI = \frac{ABU}{Sur\_PP} \tag{4}$$

where ABU is computed accounting for the unit number of various livestock types (referred to the 2000 year), homogenizing them to the size of adult bovine [60]:

$$ABU = n.\text{bovines} + n.\text{ buffalos} + n.\text{ equines} + \frac{n.\text{ goats}}{10} + \frac{n.\text{ sheep}}{10} \tag{5}$$

Overgrazing remains a typical driver of degradation in many areas of Southern Italy, resulting from the inappropriate practice of grazing too many livestock for too long periods exceeding the productive capacity of the considered areas. Livestock hooves remove vegetation cover, exposing soil to be washed away and reducing its capacity of water storage, previously facilitated by vegetation [65]. As additional effects, soil compaction arises and runoff increases. On this basis, the highest vulnerability scores are associated to the highest values of the indicator (Table 3).

Vulnerability class	GI Values
(2) high	> 100
medium - high	30 : 100
medium	10 : 30
medium - low	3 : 10
(1) low	0 : 3

Table 3. Distribution of vulnerability classes for grazing intensity (GI)

4.1.2. Land cover based indicator

The index of mechanization level is a proxy for soil compaction due to heavy equipments used in agriculture. Multiple passes of machinery on the same lanes facilitate the formation of a compacted layer of soil (ploughsole) with a severe deterioration of many soil properties, such as porosity, hydraulic conductivity and root penetration [66-68]. The plant roots often spread out horizontally exhibiting stunted growth because of the insufficient access to soil water and nutrients [69]. Altogether, mechanization can increase risk of runoff [70], flood events and loss of nutrients by leaching [71].

The mechanization level index adopted in this work follows a new formulation based on land cover and morphological data [36], so as to obtain information more flexible for resolution, update frequency, and quality compared to census data, which are normally used to calculate this indicator [72,73]. Our indicator estimates soil compaction due to heavy vehicle traffic by taking into account the variable number of passes for each cultivation type (extracted from the land cover map and ancillary information) and the different impact on soil produced by using tyres or tracks (evaluated thanks to morphological data).

As a first step, starting from level-3 CLC we separated cultivable from natural or anthropized classes. Then we associated an average number of passes, obtained from the aggregation of ENAMA data (Table 4), for each agricultural CLC class.

Cultivation type and corresponding CLC2000 level3 code	Number of average passes
Arable land (cereals, legumes, crops, vegetables, etc.) - 2.1.1/2.1.2	7,5
Permanent crops (vineyards, fruit trees, olive groves) - 2.2.1/2.2.2/2.2.3	7
Pastures - 2.3.1	3
Annual crops associated with permanent crops - 2.4.1	5
Complex cultivation patterns - 2.4.2	4
Land principally occupied by agriculture, with natural areas - 2.4.3	3
Agroforestry areas - 2.4.4	1
Other classes	0

Table 4. Number of average passes for CLC2000 class, obtained aggregating ENAMA data for cultivation type.

In order to take into account the different equipments of the agricultural machinery, consisting in tyres or tracks, we applied a threshold (20%) on the slope map derived from the 20m resolution DEM since land on steep slope can be managed only by tracked vehicles, whereas tyres are adopted in all the other cases. Soil compaction induced by tracks is limited to the topsoil, that can be rather easily restored, whereas tyres mostly damage subsoil layers that are more difficult to restore [74,75]. Neglecting such a variable means to estimate equal vulnerability levels in very different conditions of soil tillage. According to this evaluation, we introduced a correction factor (f) associating a lower vulnerability to areas where tracked vehicles are used (f =1) with respect to those managed with tyred vehicles (f =1.5). The final formulation of the index (MLI) is the following:

$$MLI = N_p \cdot f \tag{6}$$

where Np is the number of average passes for each CLC class, and f represents the correction factor accounting for track or tyre use. The indicator was classified within the ESA range (1-2) to provide values comparable with the values of other land management indicators (Table 5).

Vulnerability class	MLI Values
(2) high	>9
medium - high	7 : 9
medium	5 : 7
medium - low	3 : 5
(1) low	<3

Table 5. Distribution of vulnerability classes for mechanization level indicator at pixel scale (MLI)

4.1.3. Land management index

The overall land management index (LMI) is calculated for each pixel as the geometric mean of the scores of the four indicators previously described:

$$LMI = (MLI \times UAA\_VAR \times PP\_UAA \times GI)^{1/4} \qquad (7)$$

4.2. Estimation of the vulnerability due to vegetation component

The ESA model is devised to assess only the structural (potential) vulnerability to land degradation, which is connected, in the specific case of vegetation, to the different sensitivity of the different land cover classes. Nevertheless, it is frequent to detect areas showing similar vulnerability levels from a structural point of view and exhibiting, on the contrary, very different actual signs of degradation. In addition, vegetation conditions change in time and this temporal evolution can be very interesting for singling out degradation processes. Thus, moving from the assumption that land degradation should not be regarded as something static but as a dynamic process [76], multitemporal investigations using satellite time series can be profitably used for estimating not only the current state of vegetation but also the changes occurred over time. At this aim, in this chapter, we used NDVI_PV, already adopted by APAT [77], as a reliable indicator to carry out a multitemporal analysis of the vegetation activity [78].

4.2.1. NDVI_PV indicator

NDVI_PV provides the spatial variability of the changes in the study area at the satellite resolution and is based on the estimation of NDVI interannual variations compared with the starting conditions. It is calculated as follows:

$$NDVI - PV = \left[\frac{Y\sum_{i=1}^{Y} MVC_{p,i} \cdot y_i - \sum_{i=1}^{Y} MVC_{p,i} \sum_{i=1}^{Y} y_i}{Y\sum_{i=1}^{Y} y_i^2 - \left(\sum_{i=1}^{Y} y_i\right)^2} \right]^Y \frac{}{MVC_{p,in}} \qquad (8)$$

where Y = the number of years (11 in this work); y_i = given year; $MVC_{p,i}$ = Maximum Value Composite for the given pixel and year i; $MVC_{p,in}$ = Maximum Value Composite for the given pixel at the first year of the investigated time series.

The normalization to the initial value reported in the formula takes into consideration that the vulnerability of an area is strongly linked to the starting value and to the type of vegetation cover corresponding to different typical values of NDVI. This aspect is particularly important, because the same change (trend magnitudo and direction) has a different weight if the examined cover is a densely or sparsely vegetated. Therefore, the percentage

variation rather than the absolute values allows for better estimating degradation levels. This indicator is able to enhance increase/decrease of vegetation activity and to identify slow variations, long-term processes (e.g., decline of forest areas), and sudden changes (e.g., fire events).

Finally, the NDVI_PV indicator has been classified within the ESA range 1-2 (Table 6).

Vulnerability class	NDVI_PV values
high	< -20
medium- high	-10 : -20
medium	-5 : -10
medium -low	0 : -5
low	>0

Table 6. Distribution of vulnerability classes for NDVI_PV indicator.

4.3. Integration of the anthropic and vegetation components

In order to take into account the information provided by the evaluation of the anthropogenic and vegetation components (LMI and NDVI_PV), we integrated them through the geometric mean. We defined a modified index based on the ESA final index [32]:

$$ESA_{mod} = (NDVI\_PV \times LMI)^{1/2}$$
(9)

4.4. Main contributing factor

Once defined the different vulnerability levels of a composite index, it is possible to identify spatial patterns of the main contributing factor (MCF) so as to point out the prevalent driving forces acting at pixel scale on the ongoing degradation processes. This is strategic to address ad hoc measures of conservation/mitigation/rehabilitation towards the specific involved factors. In GIS environment such an analysis is carried out by means of a simple maximizing algorithm applied on the comparable layers (rasters) representing each land management indicator:

$$OUTPUT = MAX(RASTER\,1, RASTER\,2, RASTER\,3, ... RASTER\,N)$$
(10)

The output raster shows the spatial dominance of one factor with respect to the other ones.

# 5. Results

5.1. Analysis of the land management indicators

Among the anthropic indicators, the highest vulnerability values were found for the UAA_VAR indicator (Fig. 5). Most of the vulnerable municipalities seem to be equally distributed in the study area, confirming that the abandonment of marginal lands (especially in inland areas), and the agriculture intensification (in lowlands and along the Ionian coast) represent important human-induced causes of degradation for Basilicata region [79-81].
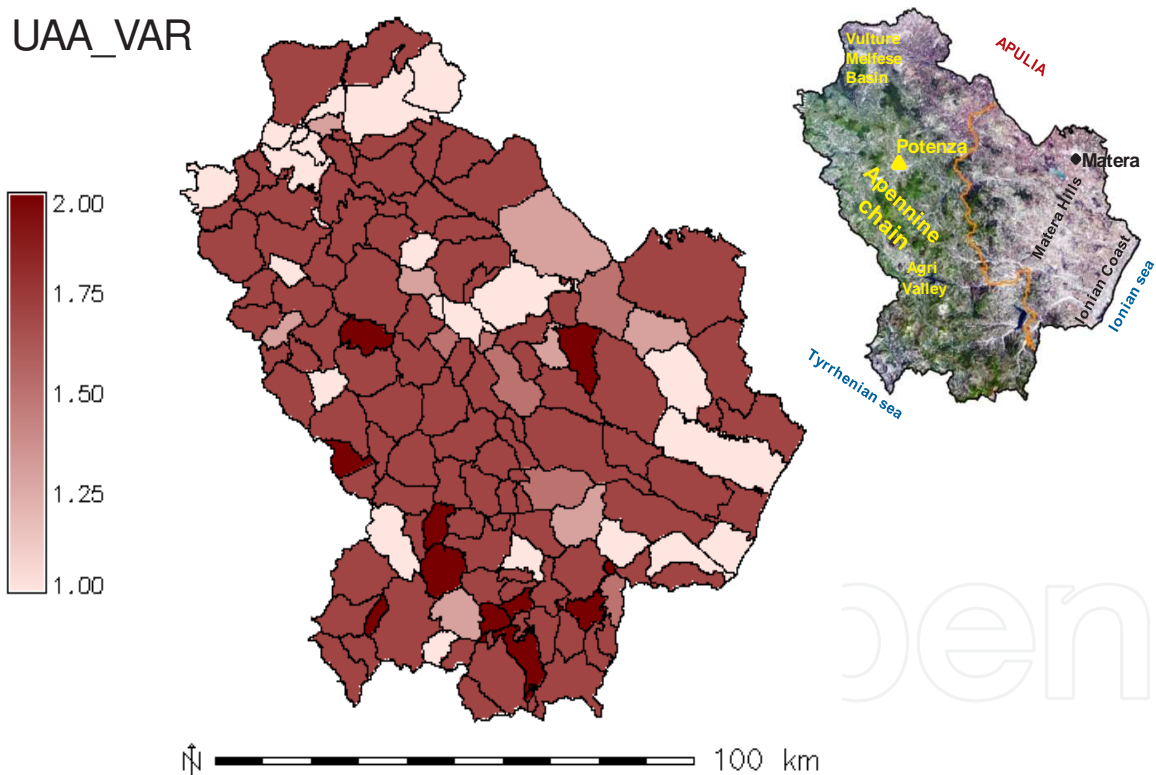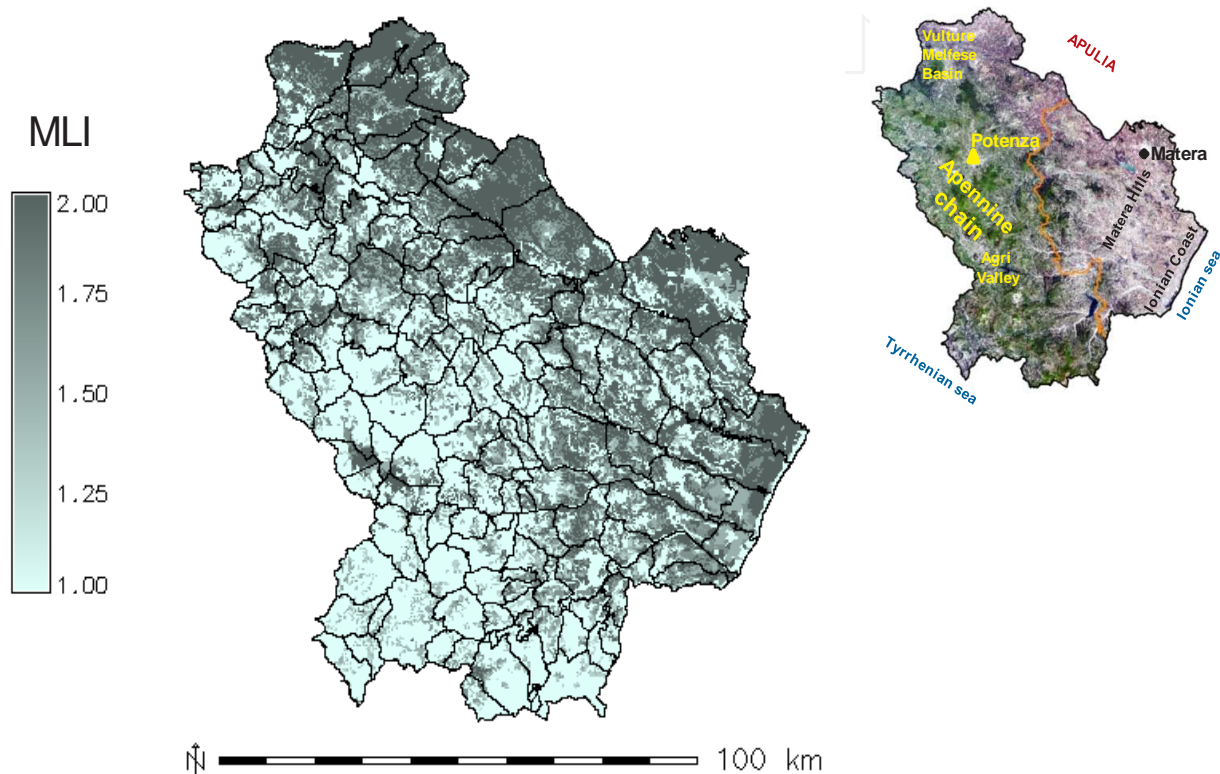

Figure 5. Classification of UAA_VAR in vulnerability classes. In the upper right corner it is shown the geographical reference map

As far as PP_UAA is concerned (Fig. 6), this is an important vulnerability factor only for a limited number of municipalities. In these areas, UAA is prevalently devoted to intensive farming activities (permanent crops, arable lands and heterogeneous agricultural areas) rather than to less-impacting practices that are normally carried out in grass, pasture and agroforestry areas; conversely, the Apennine and sub-Apennine zones show medium-low or low values of vulnerability, because the municipal UAA encompasses a fairly considerable proportion of grass and pasture (see http://censagr.istat.it/basilicata.pdf).
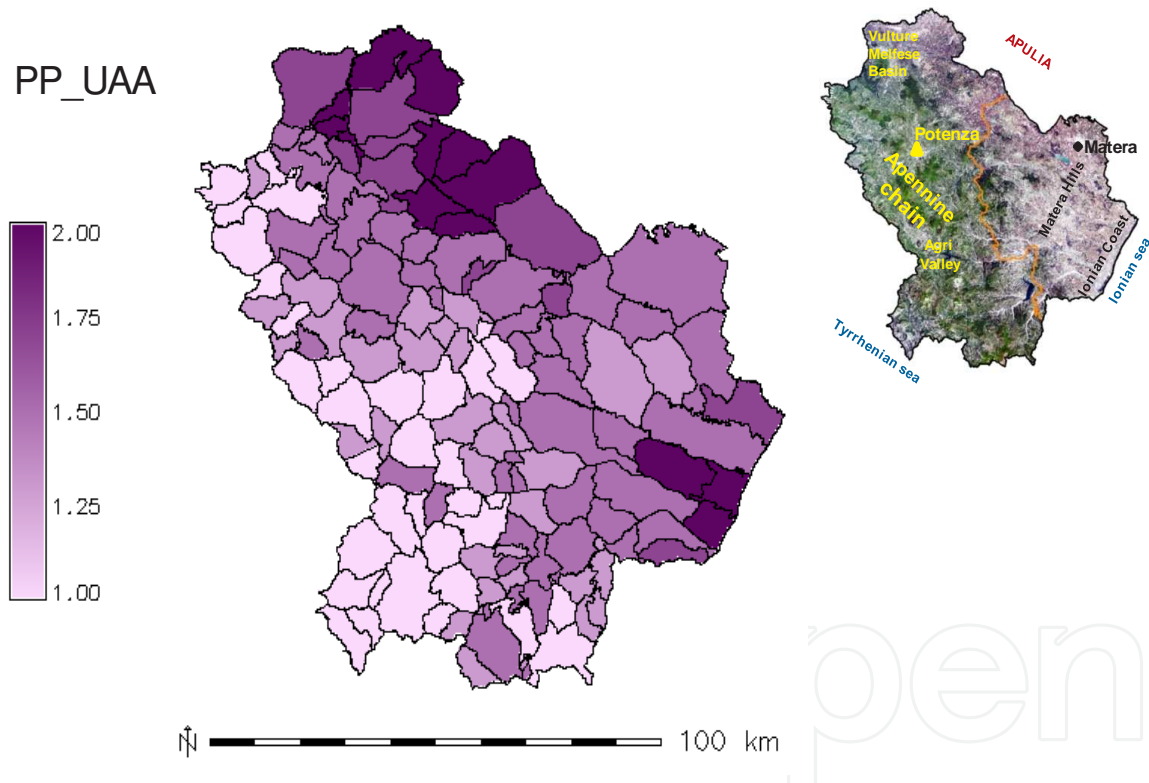
Figure 6. Classification of PP_UAA in vulnerability classes. In the upper right corner it is shown the geographical reference map

The vulnerability map of Grazing Intensity (GI - Fig. 7) reveals at a glance that the least im-
pacting degradation factor in Basilicata region is overgrazing, because we found high vul-
nerability values only in a very few municipalities, whereas the rest of the examined areas
shows prevalently low vulnerability values.
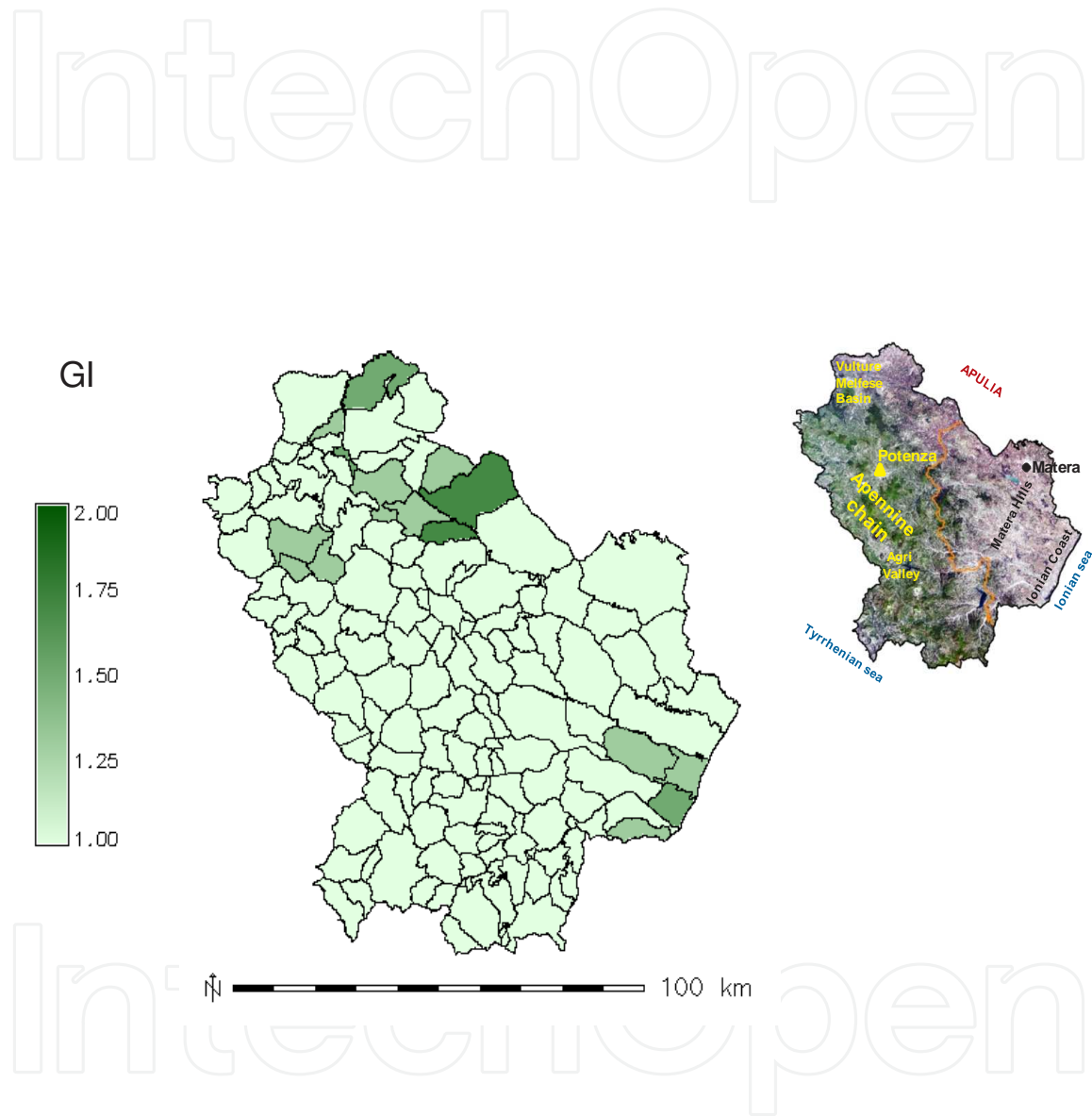
Figure 7. Classification of GI in vulnerability classes. In the upper right corner it is shown the geographical reference
map

This agrees with the indications inferred from the previous indicators: even though live-stock husbandry is a well-established economic platform comprising a large number of small to medium size enterprises in Basilicata (also in mountainous areas), the fairly even abundance of pastures and grasses allows to graze without exceeding the regeneration capacity of vegetation. As illustrated in Fig. 8, the mechanization level indicator (MLI), which is displayed with the spatial resolution of the pixel (20m as the original DEM), allows a quick discrimination of different vulnerability values also inside the municipal areas.
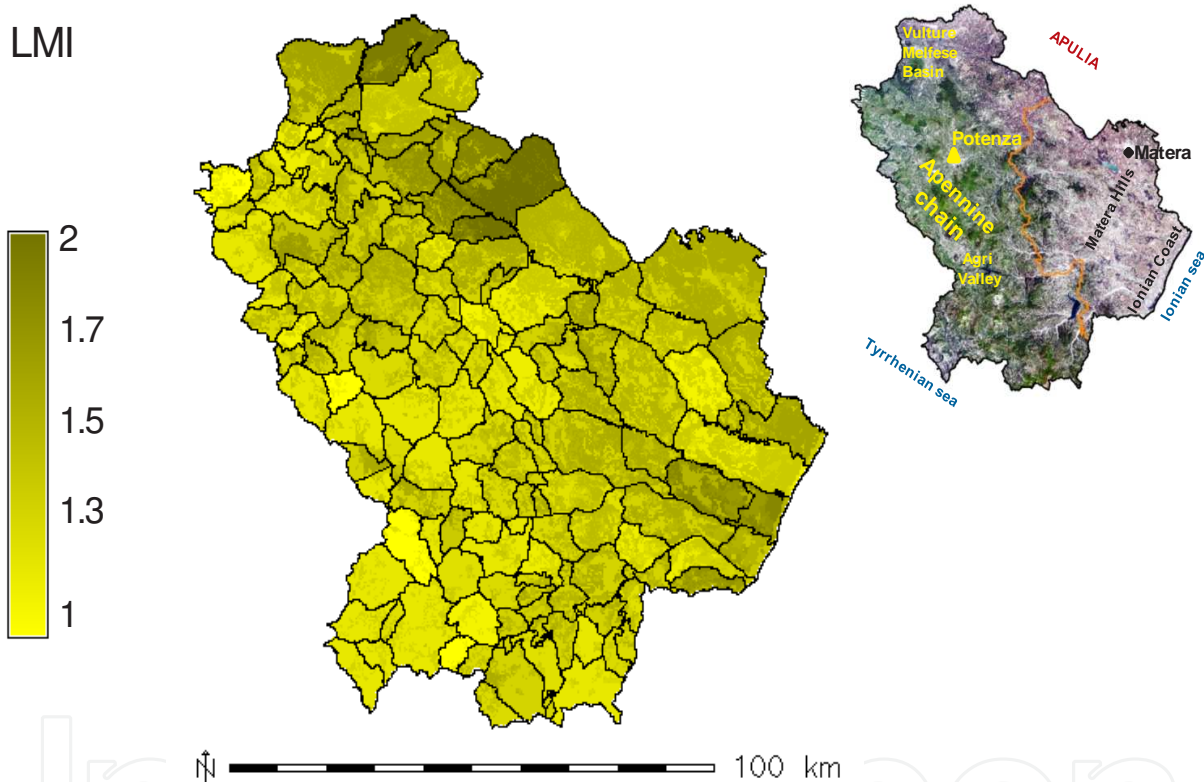

Figure 8. Classification of MLI in vulnerability classes. In the upper right corner it is shown the geographical reference map

This is a first improvement with respect to previous analyses made at the municipal level, enabling a better identification of the local critical aspects in terms of induced environmental impacts. In particular, the arrangement of the vulnerable areas reflects the agricultural productivity patterns of Basilicata, providing a picture of the actual conditions of the investigated region which is more realistic of that provided by census-based indicators [82].

We found high and medium-high vulnerability for areas located in lowlands (wide stripe in the Northeastern part of the region) and along the coast as well as in a large part of the hilly landscape (e.g., medium and low hills surrounding the city of Matera), which is particularly devoted to (intensive) farming practices; low vulnerability levels are found instead in mountain areas, less suitable to be exploited for agricultural purposes.

Finally, the Land Management Index (LMI), exhibiting the same resolution of the MLI indicator, is shown in Fig. 9. It is evident that the most severe management problems related to agriculture/grazing activities are concentrated in the cluster in the Northeastern part of the region and in some of the coastal areas along the Ionian sea. The rest of the seaboards are characterized by medium/medium-high levels of vulnerability as well as hilly areas in the Matera province and some areas surrounding the city of Potenza. The management state for the Western side of the region, dominated by natural areas, is quite satisfactory, even if there are patches having medium vulnerability values (Vulture-Melfese and Agri valley).

Figure 9. Classification of LMI in vulnerability classes. In the upper right corner it is shown the geographical reference map

5.2. Spatial pattern of Main Contributing Factors (MCF) related to anthropic pressure

We performed a preliminary analysis consisting in area-weighted average calculations of the adopted indicators (see radar chart, Fig. 10). According to our results, UAA_VAR shows the highest average value (1,57). Also MLI and PP_UAA are not negligible (respectively 1,45 and 1,42) whereas the role of GI seems to be nonessential (1,05).
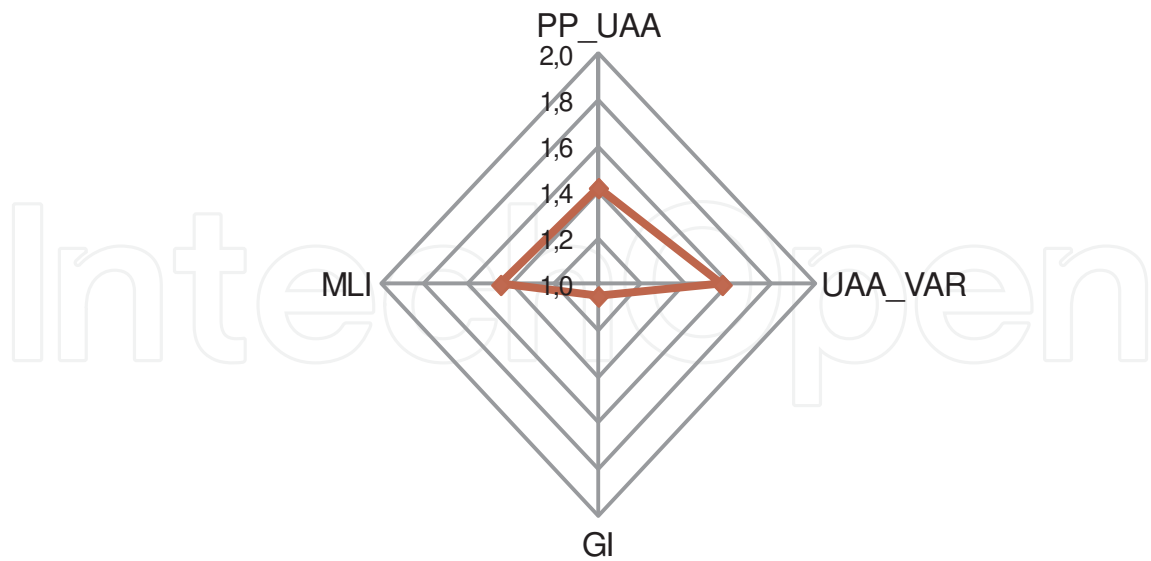
Figure 10. Radar chart showing the comparison among the area-weighted average values of land management indicators for the whole investigated region

In order to investigate the role of each indicator we applied the MCF algorithm (see section 4.4) at the pixel scale. It should be remarked that (see Fig. 11) 70% of the regional surface shows a unique MFC, while the remaining part of the investigated areas is characterized by two (about 24% of the total surface), three indicators (about 4% of the total surface), or no prevailing indicator (about 2% of the total surface). In the last case all the four indicators reach the maximum vulnerability value.
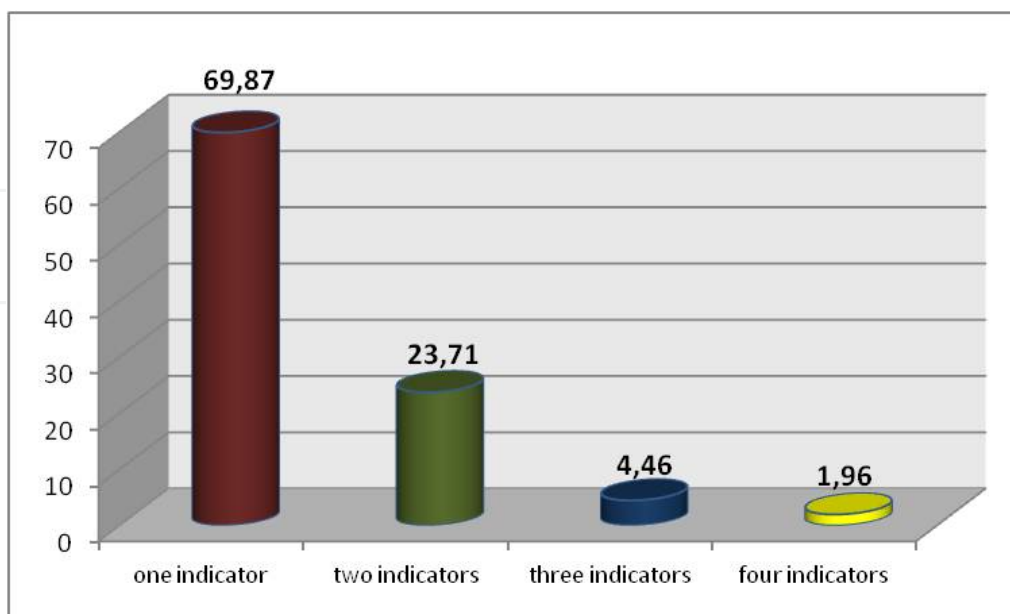
Figure 11. Frequency distribution of the number of prevalent indicators on the investigated area

The analysis of the areas in which just one indicator is dominant (Fig. 12) brings out the importance of the UAA_VAR as the most significant driver of degradation (about 58% of the considered area). In these areas the degradation mainly comes from the decrease in cultivated surfaces.

Apart from the appreciable contribution of the mechanization indicator (MLI, about 29% of the examined area), neither the scarce presence of grass and pasture (PP_UAA, about 13% of the examined area) nor the overgrazing (GI, no area involved) contribute meaningfully to degradation.
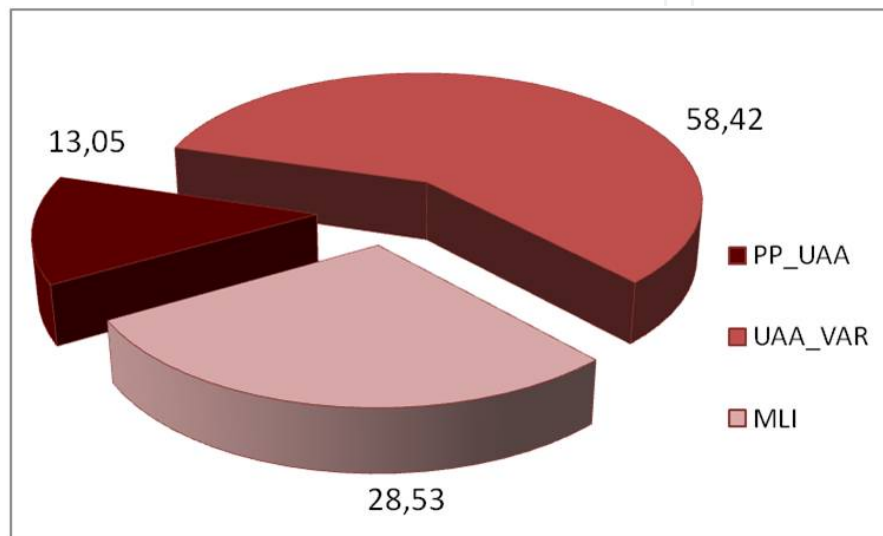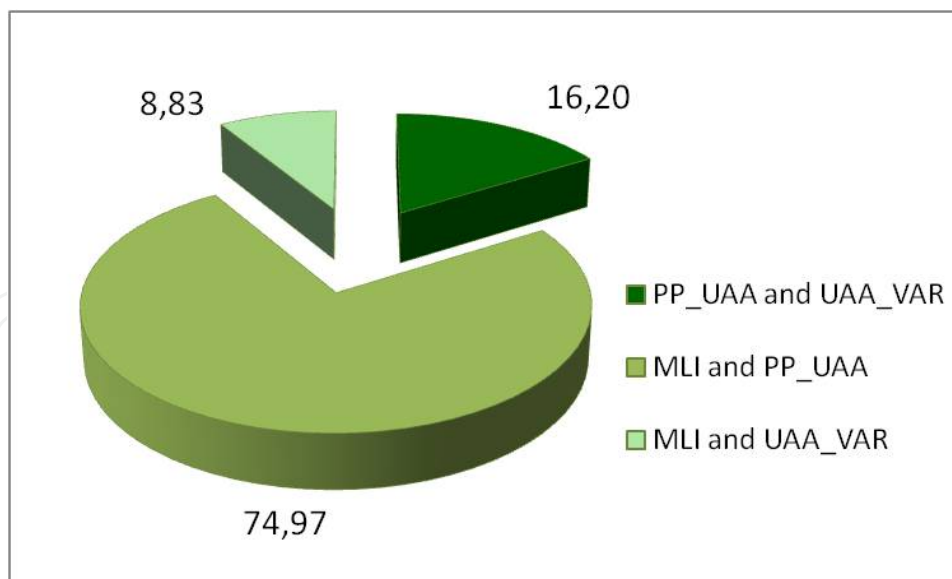

Figure 12. Frequency distribution of the prevalent indicators (areas having just one indicator prevalent)

The analysis of the pixels having two dominant indicators (Fig. 13) shows a large prevalence of the synergy between MLI and PP_SAU (about 75%). On the contrary, the variation of cultivated lands (UAA_VAR) jointly with PP_UAA or MLI (respectively about 17% and 9% of analyzed areas) seems not to be particularly diffused as a degradation driver. Owing to the negligible role of grazing, areas exhibiting simultaneously three dominant indicators are always characterized by the values of MLI, PP_UAA, and UAA_VAR.

On the whole, the analysis aimed at identifying the MCF for the anthropic component indicates that UAA_VAR plays the main role in inducing degradation followed by excessive mechanization (MLI), whereas PP_UAA and particularly GI seem not to play an important role in promoting environmental degradation. This last result is due to the positive effects generated by the widespread presence of grass and pasture, also in non mountainous areas. These covers represent a mainstay of the local agricultural structure enabling a sustainable management because, on the one hand, they counterbalance the man-induced impact caused by intensive agricultural practices (resulting in lower values of the PP_UAA indicator), on the other, they allow a suitable form of grazing (resulting in very low values of the GI indicator).

The spatial patterns of the MCF (Fig. 14) show two opposite paths in the Basilicata region: marginalization of inland rural areas and further intensification of low-sustainable agriculture in lowland areas.

The first phenomenon, arising from complex socio-economic dynamics, involves the inland districts located in the core of the region (prevalently near Potenza town) that were mainly devoted to poor agricultural practices in the recent past. Today, these areas experience de-population (for further details see http://www.istat.it/it/basilicata) as a consequence of the present economic crisis generating low profitability of agricultural products. This reduction in profit margin, in turn, can be accelerated by natural factors such as growing aridity and natural disasters (flood, landslide, fire, etc.) which induce an increase in agricultural man-agement costs (e.g., irrigation, agrochemicals products, land rehabilitation, etc.) exacerbating land abandonment and culminating in a downward spiral of land degradation [83]. This fact, supported by provisional data of the Sixth National Agricultural Census (indicating a reduction of farm and cultivated areas, see section 2), stresses one of the most critical aspect of the local economic-productive system having serious repercussions on environmental quality and promoting social imbalances between marginal and more populated areas [84]. However, in this case, regional/national policies should be undertaken to strengthen infra-structural facilities and promote the redevelopment of marginal lands.

Figure 13. Frequency distribution of the prevalent indicators (areas having two indicators prevalent)

The second phenomenon focuses on the long-term sustainability of intensive farming. Especially in areas where the natural conditions are optimal (e.g., slope) and technologies and infrastructure are easily available, we notice a tendency to increase agricultural production. This occurs at the expense of future land fertility, because enlarging cultivated areas, increasing the use of mechanization and fertilizers and overexploiting water resources contributes to exacerbate land degradation processes. In these places, we observe the reverse problem affecting marginal areas and thus appropriate strategies are required to locally encourage farmers towards sustainable soil management practices and technical skill improvement.
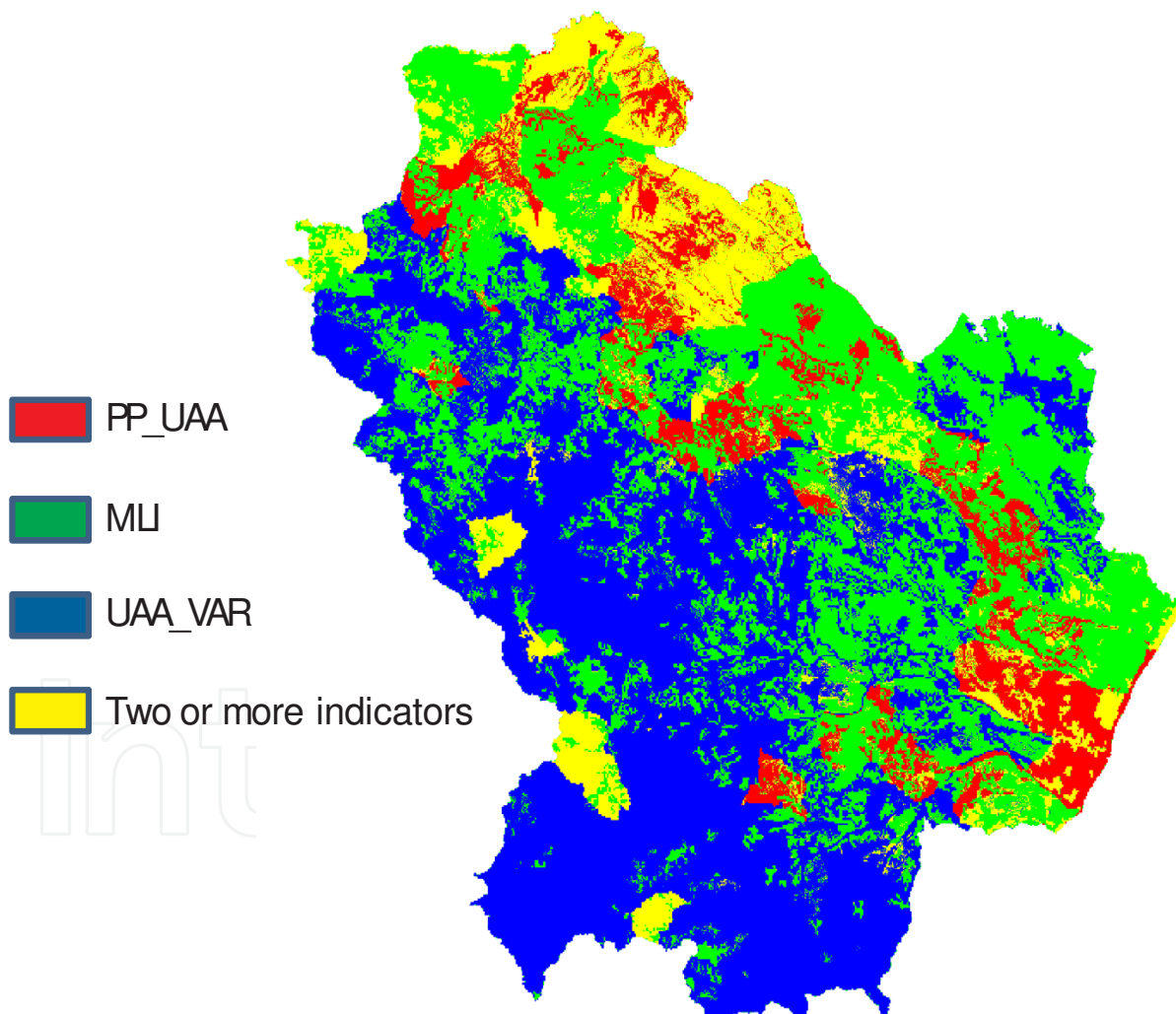

Figure 14. Map of the Main Contributing Factor (MCF) computed for the anthropic component

5.3. Analysis of trends in photosynthetic activity (NDVI_PV)

In Fig. 15 absolute values of NDVI_PV are displayed. Positive values of the indicator (generally fairly high) are visible especially in areas located south of Matera city and they mainly are estimated for permanent crops (fruit trees and olive groves) and, in some cases, for arable lands. Areas mostly characterized by dense vegetation (coniferous and broad-leaved forests) reveal stability or a slight increase in photosynthetic activity. Negative values are detected in correspondence with arable lands (the narrow stripe bordering Apulia region) and industrial districts (geographically concentrated in Tito Scalo, near Potenza and in S. Nicola di Melfi at the northern of Basilicata, where we find one of the most recent FIAT plant, see Fig. 15).

By aggregating the NDVI_PV values in 7 ranges (see Fig. 16) we observe a considerable coverage of stable areas (more than 50%) and a limited extent of areas characterized by low negative values (10%). Areas affected by a strong decrease in vegetation activity are only 1% of the investigated territory; on the contrary, areas marked by positive trends (slight and appreciable increases in photosynthetic activity) altogether amount to 30% of the examined surfaces.
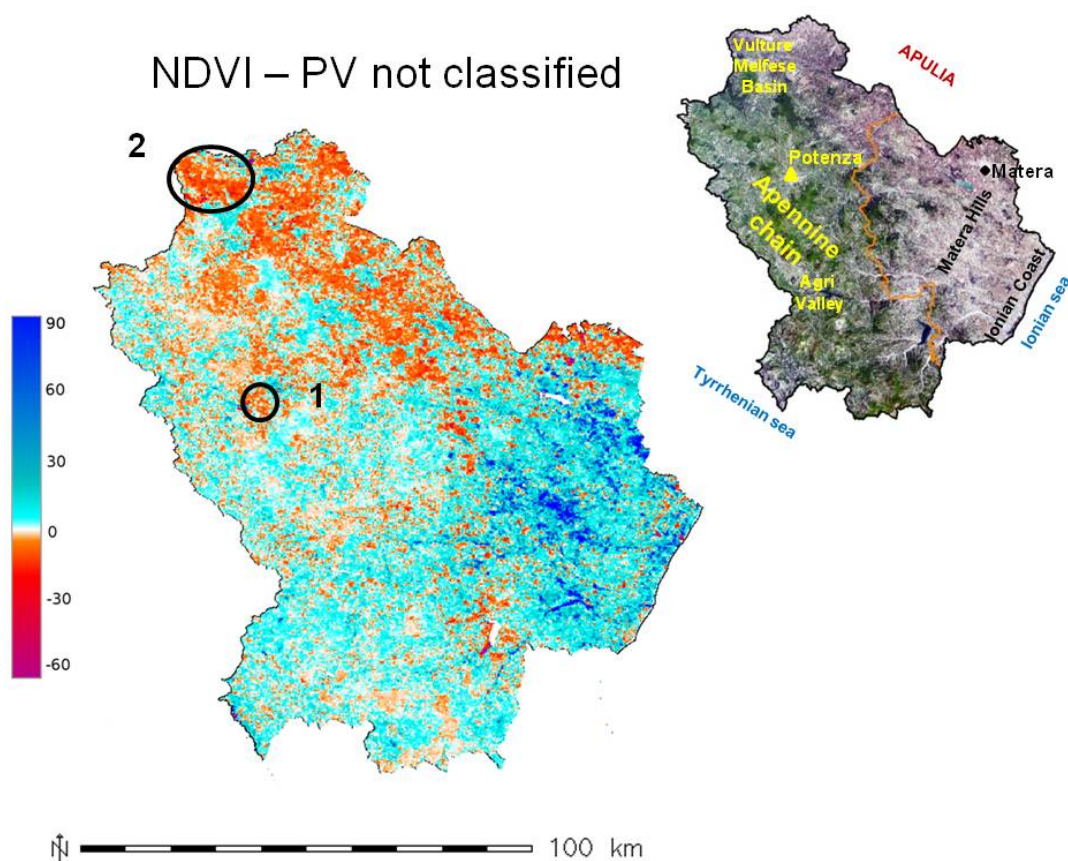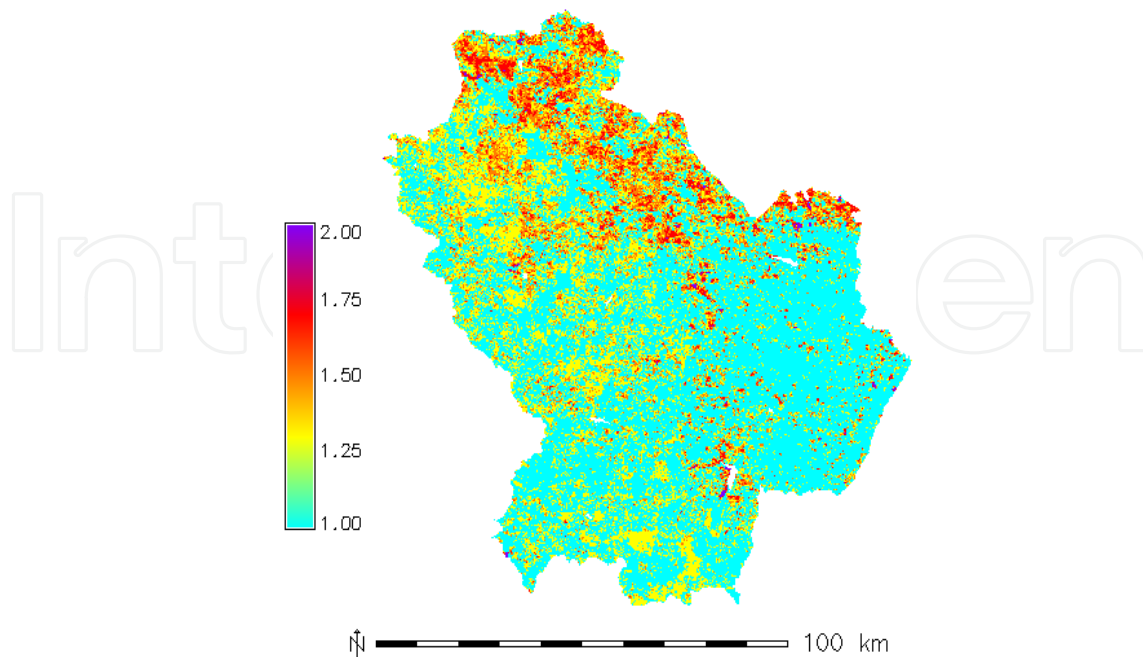

Figure 15. Map of the indicator NDVI_PV (not classified). Areas within the circles 1 and 2 belong to the Tito Scalo and San Nicola di Melfi locations respectively. In the upper right corner it is shown the geographical reference map
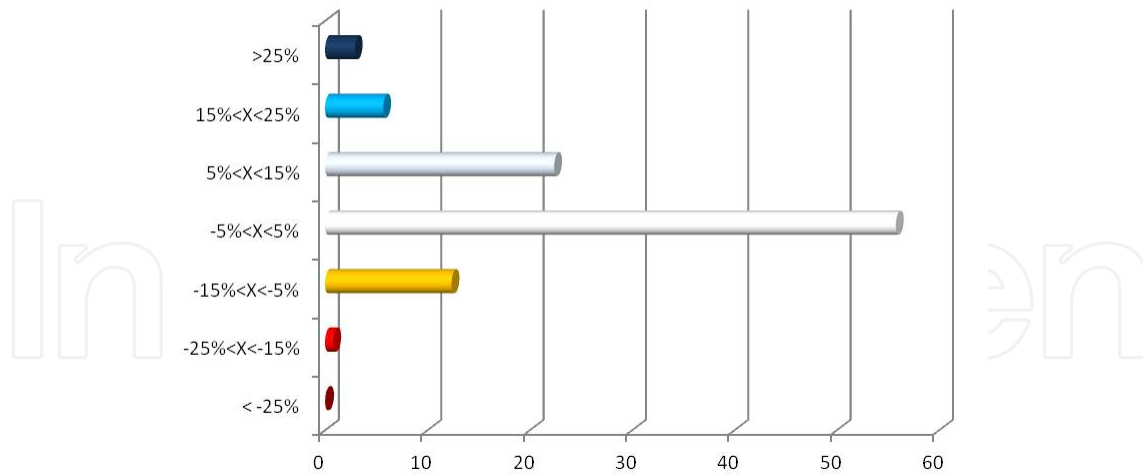
Figure 16. Frequency distribution of the prevalent indicators (values in abscissa represent the percentage of areas included in the given ranges)

By classifying the obtained values of NDVI_PV in the ESA range (1-2), we can extract some further information: highly vulnerable areas (medium-high and high) reach about 5% of the Basilicata surface; there are few medium vulnerability areas (about 10%), whereas the extent of areas with medium-low/low vulnerability is very significant (about 85%, see Fig. 17).

NDVI – PV classified

Figure 17. Map of the indicator NDVI_PV, classified in the ESA range (1-2)

5.4. Analysis of the integrated vulnerability map (ESA_{mod})

As we can see from the map in Fig. 18, the combined analysis of the anthropic component and the vegetation one, does not show a particularly critical picture of the Basilicata region. The most vulnerable areas ($ESA_{mod}>1.5$) are located, as expected, in the Northeastern sector of the region, including the agriculture-oriented lands bordering Apulia region, a part of the Ionian coast and some areas belonging to the hilly zone in the surrounding of Matera city. More densely vegetated areas, but also a large part of grasses, pastures and semi-natural areas, where the anthropic influence is clearly lower, seem to show good health conditions and thus a rather negligible vulnerability.

As established by the ESA methodology, the arrangement of the examined areas in different risk classes points out that about 23% of the region is included in the critical areas ($ESA_{mod} > 1.38$) and nearly the 30% in the fragile ($1.23<ESA_{mod}<1.37$); the rest of the investigated territory is characterized by potential or non-threatened areas ($ESA_{mod}<1.22$; 50% of the regional surface) according with results from independent studies [85]. The composite picture emerging from all these investigations suggests that for areas falling within the first two categories (critical and fragile) several measures should be put in place to prevent more severe degradation processes by promoting mitigation/restoration actions. As for the third category (potential and non-threatened areas), a periodic monitoring can be a great (and sometimes cost-effective) solution.
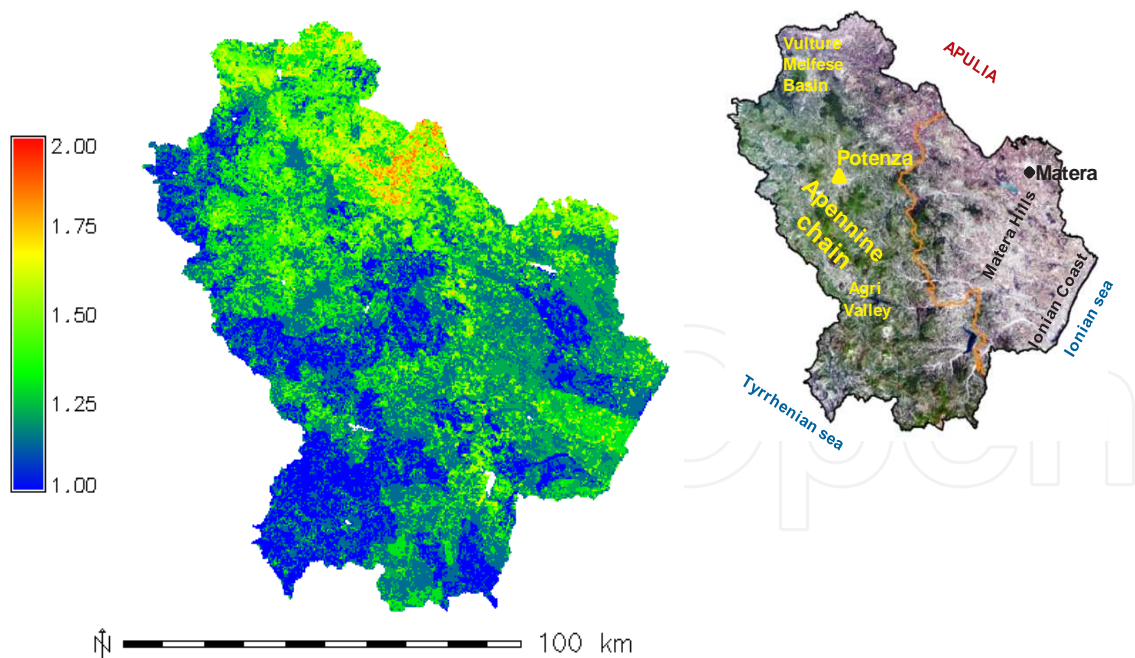
Figure 18. Map depicting the integration of the analyzed components (ESA_{mod}). In the upper right corner it is shown the geographical reference map

Finally, Fig.19 shows the ESA_{mod} map segmented according to four different levels of influence of MLI and NDVI_PV.

The extent of areas having both the anthropogenic component (LMI) and the biophysical one (NDVI_PV) not exceeding the value of 1.4 (vulnerability threshold) is very considerable (blue pixels). These pixels are principally concentrated in the Western side of the region and belong to various type of land cover including mainly forested and seminatural areas and some human-influenced covers such as arable lands. These last dominate, instead, in two of the four classes: areas showing both negative vegetation trends and inappropriate land management (red pixels), and areas affected by substantial decreases of photosynthetic activity (yellow pixels) but where management is quite satisfactory. Finally, a lot of permanent crops occupy largely those areas experiencing positive trends of vegetation activity but unsuitable agricultural practices (green pixels).
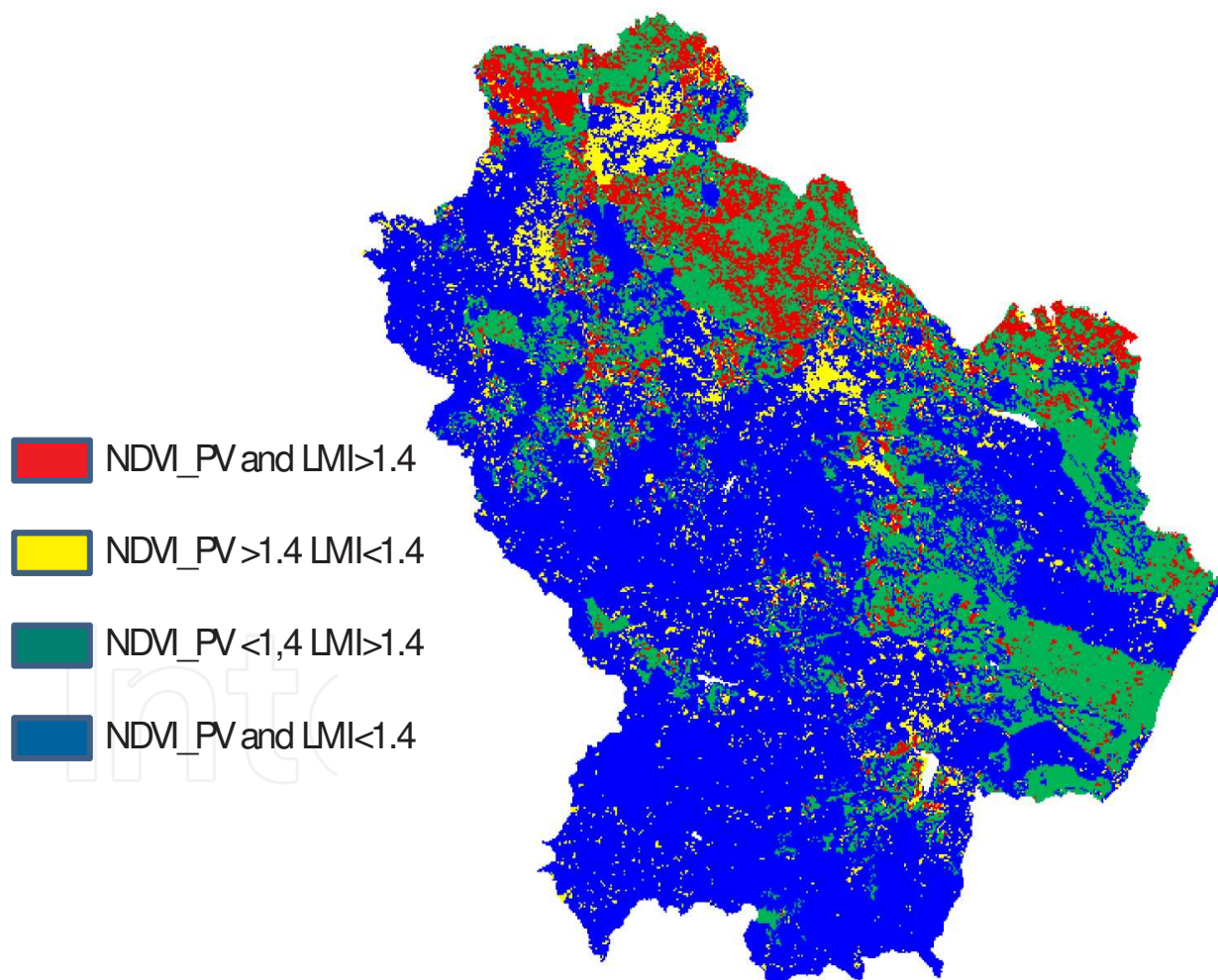
Figure 19. Zones of influence resulting from the partition of the ESA$_{mod}$ map

6. Conclusions

In order to estimate the vulnerability to land degradation of a typical Mediterranean region (Basilicata) we have jointly considered the impact of the anthropic component and the vegetation conditions, using socio-economic indicators related to agriculture/grazing activities and analyzing trends of photosynthetic activity. As regards anthropic pressure we have used census-based indicators (UAA_VAR, PP_UAA and GI computed at municipal scale) and the mechanization indicator (MLI) based on land cover map and morphological information (DEM). Thanks to its formulation, the new indicator we elaborated is independent from census data, enabling a faster rate of update and providing a better discrimination of the vulnerability values because the adopted spatial resolution is connected to the used land cover map or DEM in state of the municipal level. It allows friendly exportability to different monitoring scales, which can be obtained by selecting the most opportune land cover map, and high adaptability, thanks to the possibility of selecting the number of classes for the satellite data classification.

We have combined all the socio-economic indicators to define the Land Management Index (LMI) and have carried out an analysis aimed at identifying the dominant factors driving human-induced degradation processes.

In order to estimate trends of vegetation activity we have calculated the NDVI_PV indicator using a time series (2000-2010) of the MODIS sensor observations. This indicator is able to compute interannual variations of NDVI compared with the starting conditions, so that it is possible to detect also slow variations and long-term processes of increase/decrease of the photosynthetic activity in the analyzed period.

The final map of the ESA_{mod} index, taking into account the vulnerability due to the anthropic and vegetation components, depicts a very complex picture characterized by a wide range of vulnerability values and by many combinations of degradation causes.

The adopted procedure, which integrates remote sensing data (synoptic view, multi-temporal availability) and socio-economic indicators, is a valuable tool for estimating vulnerability to land degradation in large anthropized areas, which are highly complex in terms of land cover type and economic vocation (intensive agriculture, grazing, industrial activities).

Our methodology allows the early detection of the most vulnerable areas and the identification of the local prevailing stress factors, providing key information for the setting up of sustainable development strategies.

Acknowledgments

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