MEDALUS Model Evolutions and Prospects Case Study Sicily

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Abstract. Desertification is defined as land degradation in arid, semi-arid, and dry sub-humid areas resulting from various factors, including climatic variations and human activities. The desertification process in the world affects around 200 countries and 2 billion people. It has become a growing threat in the EU due to prolonged drought periods and increasing aridity. The Mediterranean Desertification and Land Use (MEDALUS) method, identify the environmentally sensitive areas (ESAs) through the application of biophysical and socio – economic indicators and relative index (ESAI). The MEDALUS has some limitations, namely the impossibility of reconducting the ESAI results to a single and comparable value, and the need to recalibrate the indices when moving from a regional scale to a local scale. The Environmentally Sensitive Index Patch (ESPI) has been developed to overcome the aforementioned barriers. The ESPI index assigns numerical values to ESAI results on a scale of 0−100. In the present paper, we discuss an experimental application of the MEDALUS method on a local scale and the outcome of the experimentation of the ESPI calculated at different territorial scales. The study was carried out in the Sicily Region. Preliminary results indicate that the ESPI index can be used at all scales on the ESAI and its four constituent qualities. Also, the authors started a critical review of the thematic layers to be adopted for the basin scales.

Keywords: Applied mathematics · Index Sensitive Desertification · MEDALUS · ESA · Ecology · Geological problems · G.I.S. · Spatial analyses

1 Introduction

Land consumption and fertility loss are global issues with serious impacts on the environment, the economy and society. Around 200 countries and 2 billion people are affected by the desertification process in the world [1–3]. 44.44% of EU Member States suffer from soil degradation; the Mediterranean Region is among the most affected by intrinsic

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predisposing factors [4]. The Italian territory is at high risk of desertification, with the most affected territories located in the regions of Basilicata, Calabria, Puglia, Sardinia, and Sicily [5]. Sicily represents the hotspot region of desertification [6]; it is the Italian Region with the greatest risk of desertification [7–14].

The Environmental Sensitive Areas Index (ESAI) is a popular indicator-based methodology that identifies environmentally sensitive areas (ESAs) prone to desertification [15–21]. In Italy, numerous study groups have analyzed desertification processes on a national and regional scale [8, 11, 22–29], producing desertification maps based on only thirty years of climatic data, from 1961 to 1990. These studies did not analyze the situation before and after this period. Also, Sicily's territory has been studied, since the 2000s, with the Mediterranean Desertification and Land Use (MEDALUS) protocol, also known as the ESAI methodology [15–20]. This work aims to share the results of over 20 years of studies dedicated to desertification processes in Sicily, including prospects and opportunities.

This work is organized as follows: first, we describe the study area and the methodology adopted to understand Sicily's susceptibility to desertification. Then, we share the most important results of the last twenty years of study of desertification processes in Sicily, also a local scale, applying the ESAI and the Environmentally Sensitive Patch Index (ESPI). In particular: a) the results of the analyses of the evolution by means of bi-temporal and tri-temporal analysis on the regional and municipal scale; b) the regional Desertification Risk of three periods: 1931–60; 1961–90; 1991–2015; c) the correlation of Desertification Risk with Climate Quality; d) the limits of the ESAI when moving from a regional to a local scale and the possible actions to overcome them, as well as prospects for the study of desertification process; e) the results of a calculation procedure of ESPI, his extension procedure to the four ESAI's qualities and his potential; (f) the regional Desertification Risk of the three periods ESPI-ESAI e ESPI-CQI for the analysis of the trend of Climate Quality. Finally, we describe the conclusions and share the prospects for the study of desertification processes on a local scale.

2 Materials and Methods

2.1 Study Area

The study area of this work is the insular region of Sicily, which is the largest of the Italian and Mediterranean islands, the seventh in Europe [30]. The climate of Sicily is generally dry Mediterranean, with hot and very long summers, mild and rainy winters, and very changeable intermediate seasons. On the coasts, especially the southwestern and south-eastern ones, the climate is more affected by the African currents which cause torrid summers. During the winter season, in inland areas, temperatures are slightly colder, resulting in a Mediterranean climate but with characteristics like those of the continental climate [31].

2.2 Methodology

The original mapping method, ESAI, is applied for the identification and mapping of ESAs exclusively at the regional scale and with a static climate period in regions at risk, allowing the classification of critical, fragile, potentially affected, and non-affected areas [15–20]. The estimation of the soil's ability to resist degradation processes takes place through the combination of the four indices: Vegetation Quality (VQI), Management Quality (MQI), Soil Quality (SQI), and Climate Quality (CQI) using the following formula:

$$ESAI = \sqrt[4]{(SQI \cdot CQI \cdot VQI \cdot MQI)} \quad (1)$$

ESAI is distinguished in four classes of ESAs (see Table 1):

Table 1. ESAs Classification. [https://esdac.jrc.ec.europa.eu/public_path/shared_folder/projects/DIS4ME/esi_jan_05/method.htm].

Sensitivity class	Subclass	Land description
NON-AFFECTED	N	Areas not threatened.
POTENTIAL	P	Areas threatened under significant climate change, if a particular combination of land use is implemented or where off-site impact will produce severe problems elsewhere.
FRAGILE	F1	Areas in which any changes in the delicate balance of natural and human activities are likely to bring. As an example, the impact of predicted climate change could affect vegetation cover, intensify soil erosion and, finally, shift the level of sensitivity of the area to the "critical" class. A land use change (e.g., a shift towards cereal cultivation on sensitive soils) might produce immediate increase in runoff and soil erosion, and perhaps pesticide and fertilizer pollution down-stream.
	F2	
	F3	
CRITICAL	C1	Areas already degraded through past misuse, showing a treat to the environment of the surrounding land (e.g., badly eroded areas subjected to severe runoff and sediment loss).
	C2	
	C3	

In previous studies [9, 12–14, 32–41], some authors introduced innovations in the application of the canonical ESAI method, including:

- Regional and municipal studies of trends and evolutions of territorial susceptibility to desertification processes through dynamic temporal analysis: bi-temporal, tri-temporal (first and second half of the century, studies using three thirty years of data). Multi-temporal analysis of ESAs allows: a) to detect changes in land use; b) to identify which factors are more predisposing than others in a specific area or period; c) have an information base for spatial planning and the recovery or restoration of areas [9, 14];
- Desertification Sensitivity maps at the municipal scale [12, 13, 32–37]. They are also useful in the perspective of using results for surveys as a basis for spatial planning and land use management procedures.
- The development of the geospatial database that enables the bi-temporal comparison of municipal territories between two ESAI climate periods. The database contains

the following information on all 390 municipalities in the region: municipal limits, ESAI elaborated for two climate periods, 1931–1960 and 1961–1990 [14].

Also, the ESAI method does not allow comparing with a single numerical value the areas. To overcome this limit, some of the authors have developed the ESPI [12, 38–41]. The ESPI provides an estimate a degree of environmental sensitivity and an easy comparison of different plots of land (country, region, province, municipality, river basin, etc.) and periods with a unique value. The ESPI provides a global sensitivity value to desertification on a scale of 0 to 100 for a given territorial context [38–41]. The formula is [38]:

$$ESPI = \frac{\left(\sum I + \sum F\right) \cdot (min + max)}{8} \tag{2}$$

3 Results

In this work, we share the results of previous investigations on desertification processes in the study area: the evolution over time by means of bi-temporal analysis on regional and municipal scale [9, 12, 14, 33, 38–41], and on Regional Parks areas [32, 34–36] (see Fig. 1, 2), the development of a geospatial database that enable the bi-temporal comparison of municipal territories between two ESAI climate periods [14] (see Fig. 3).

From the tri-temporal comparison (see Fig. 4 a, b, c), it has emerged that the characterization of the risk of desertification in the 390 municipalities of the island has the undisputed merit of having equipped the Sicilian Region with an implementation of the knowledge on the course of the phenomenon. In fact, compared to the 17 contributions published in the bulletin of the Accademia Gioenia [14], which gave the bi-temporal comparison of the trend of the risk of desertification (first half of the last century compared to the second half), with the twenty-two IRSSAT notebooks [37, 42] the time comparison is extended to three periods (1931–60, 1961–90, 1991–2015).

The regional Desertification Risk of the three periods (see Fig. 4 a, b, c) [9, 38–41, 43] shows that:

- the Non-Affected Class recorded an increase of 8% in territories from the first to the second period and a loss of about 3.5% in the comparison between the second and third periods [43];
- the Fragile Class suffers a slight increase - about 2% of territories - in the transition between the first and second period, while it increases by almost 10% in the transition from the second to the third period [43];
- the Critical Class improved by 13.6% of territories between the first and second periods, while the increase between the second and third periods was only 1.5% [43].

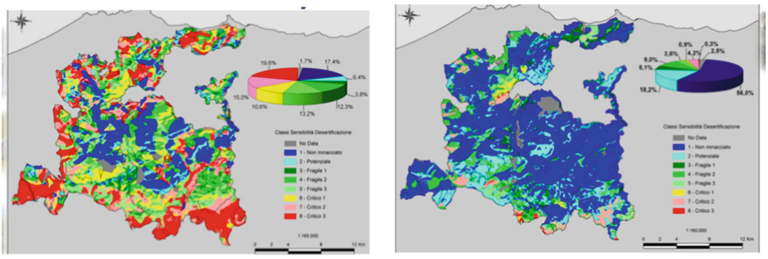


Fig. 1. Result of the comparison between the first and the second half of the century of the ESAs in the territory of the Madonie Regional Park [35]. For the colors of the ESAI classes, see Table 1.

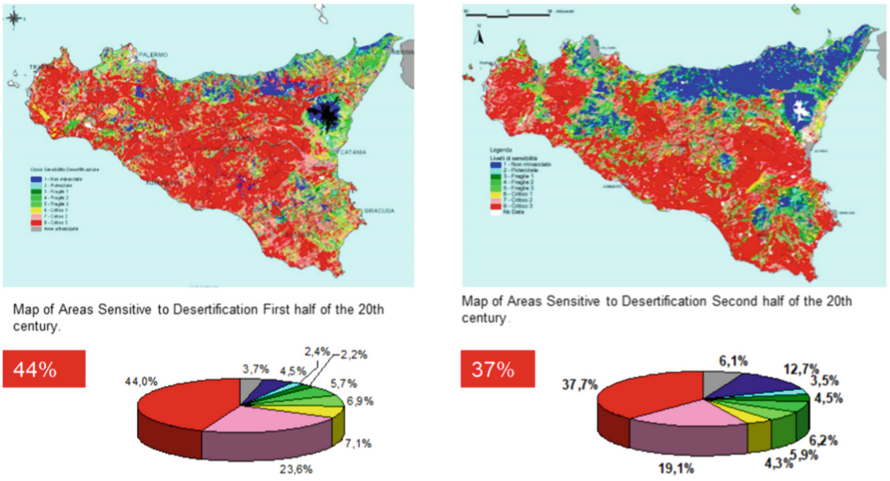


Fig. 2. Sicilian Region ESAs, comparison between first and second half of the 20th century [13].

For the purpose of determining Climate Quality (see Fig. 5 a, b, c) it emerges that [43]:

- High Quality recorded a loss of 6.5% of territories from the first to the second period and a recovery of 4.5% from the second to the third period.
- Average quality is almost constant with a maximum difference between periods of no more than 3% of territories.
- Low Quality shows almost a 9% increase in territories from the first to the second period that are reabsorbed from the second to the third.

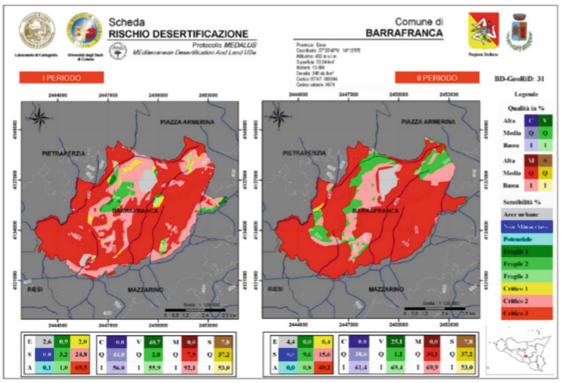
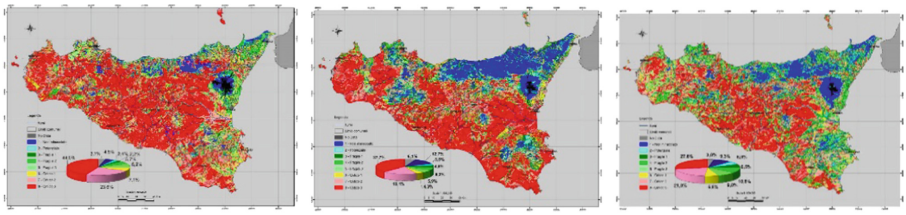


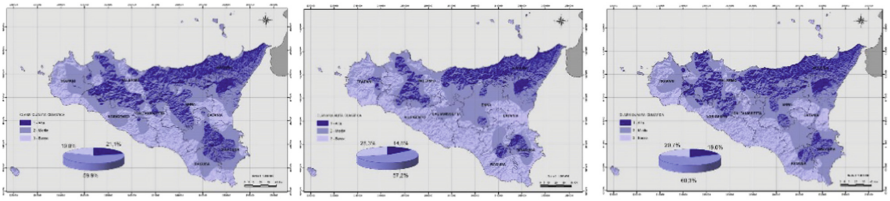
Fig. 3. Example of Georeferenced Database output (Italian language). Project Desertification Risk in Sicily. Bi-temporal characterization of municipal territories in the 9 Sicilian's province [14]. The image shows the comparison between the results of the calculation of the ESA Index on a municipal scale in the first and second half of the twentieth century in the municipality of Barrafranca (EN). The comparison highlights a worsening of the territorial situation. For the colors of the ESAI classes, see Table 1.

The correlation of Desertification Risk with Climate Quality shows that the latter does not seem to have significantly affected the overall trend. The improvement can be attributed to several factors in the second period, such as: reforestation, recovery of degraded environments, establishment of protected areas, reduction of overgrazing, etc. These actions in the second period, compensated for the loss of Climate Quality [43].



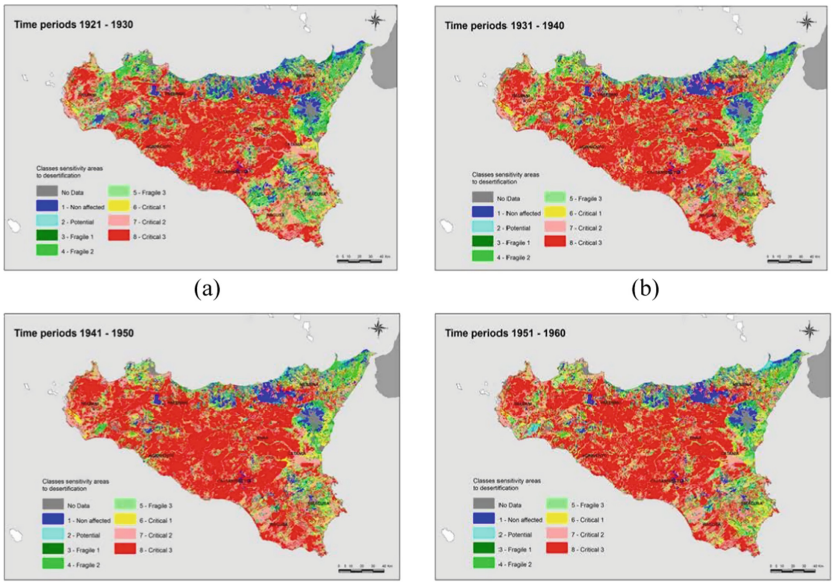
(a) (b) (c)

Fig. 4. a, b, c. Tri-temporal ESAI analysis, sensitive areas to desertification period: a) 1931–60, ESAI Critical 3 value 44%; b) 1961–90, ESAI Critical 3 value 37,7%; c) 1991–2015, ESAI Critical 3 value 27,6% [43].



(a) (b) (c)

Fig. 5. a, b, c. Tri-temporal Climatic quality (*sensu* ESAI) relative to the period: a) 1931–1960, CQI high-value 21,1%; b) 1961–1990, CQI high-value 14,6%; c) 1991–2015, CQI high-value19,0% [43].

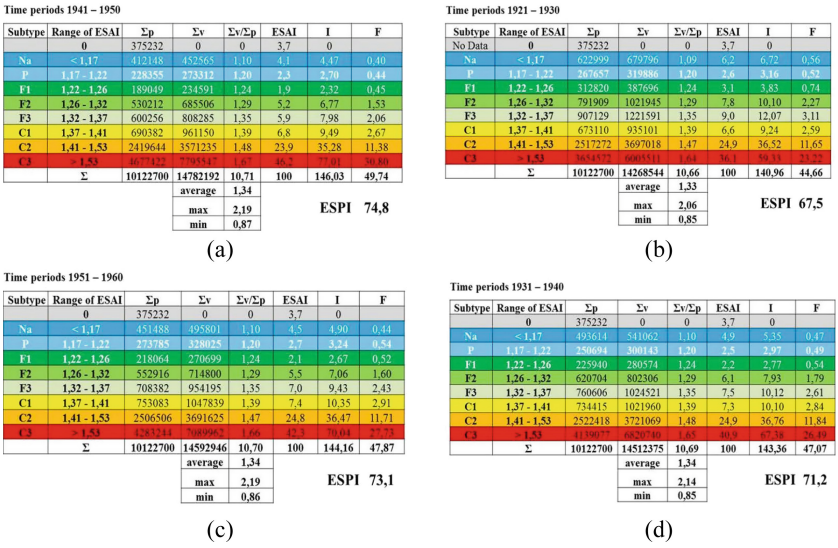


(a) (b)

(c) (d)

Fig. 6. a, b, c, d. The validation of the ESPI at the regional scale was obtained by comparing the data and trends with the results of the MEDALUS database developed for the Region of Sicily [12, 13, 38, 43], derived from two scenarios: first half of the 20th century and climate data of four decades 1921–30, 1931–40, 1941–50, 1951–60. The images show the result of querying.

The ESPI was applied, tested, and validated at the municipal scale in districts, provincial, watersheds, and protected areas, comparing the values with the ESAI analysis results (see Fig. 6, 7, 8, 9) [38]. It has also been tested for monitoring the temporal evolution of desertification risk. The ESPI application to the ESAs of the Sicily Region was performed using eight decades of Investigation (1921–2000). By analyzing the annual Desertification Risk of the three periods (see Fig. 10, 11, 12), it is possible to see the substantial difference between the period 1931–1960 and 1961–1990. In the first period, the risk of desertification for all years is in the range of 60–70. In the second period, the risk of desertification fluctuates between 50 and 65 maximum, and in the third, the trend of the previous thirty years is preserved [43].



Time periods 1941 – 1950

Subtype	Range of ESAI	Σp	Σv	Σv/Σp	ESAI	I	F
	0	375232	0	0	3,7	0	
Na	< 1,17	412148	452565	1,10	4,1	4,47	0,40
P	1,17 - 1,22	228355	273312	1,20	2,3	2,70	0,44
F1	1,22 - 1,26	189049	234591	1,24	1,9	2,32	0,45
F2	1,26 - 1,32	530212	685506	1,29	5,2	6,77	1,53
F3	1,32 - 1,37	600256	808285	1,35	5,9	7,98	2,06
C1	1,37 - 1,41	690382	961150	1,39	6,8	9,49	2,67
C2	1,41 - 1,53	2419644	3571235	1,48	23,9	35,28	11,38
C3	> 1,53	4677422	7795547	1,67	46,2	77,01	30,80
	Σ	10122700	14782192	10,71	100	146,03	49,74
			average	1,34			
			max	2,19		ESPI	74,8
			min	0,87			

(a)

Time periods 1921 – 1930

Subtype	Range of ESAI	Σp	Σv	Σv/Σp	ESAI	I	F
No Data	0	375232	0	0	3,7	0	
Na	< 1,17	622999	679796	1,09	6,2	6,72	0,56
P	1,17 - 1,22	267657	319886	1,20	2,6	3,16	0,52
F1	1,22 - 1,26	312820	387696	1,24	3,1	3,83	0,74
F2	1,26 - 1,32	791909	1021945	1,29	7,8	10,10	2,27
F3	1,32 - 1,37	907129	1221591	1,35	9,0	12,07	3,11
C1	1,37 - 1,41	673110	935101	1,39	6,6	9,24	2,59
C2	1,41 - 1,53	2517272	3697018	1,47	24,9	36,52	11,65
C3	> 1,53	3654577	6005511	1,64	36,1	59,33	23,22
	Σ	10122700	14268544	10,66	100	140,96	44,66
			average	1,33			
			max	2,06		ESPI	67,5
			min	0,85			

(b)

Time periods 1951 – 1960

Subtype	Range of ESAI	Σp	Σv	Σv/Σp	ESAI	I	F
	0	375232	0	0	3,7	0	
Na	< 1,17	451488	495801	1,10	4,5	4,90	0,44
P	1,17 - 1,22	273785	328025	1,20	2,7	3,24	0,54
F1	1,22 - 1,26	218064	270699	1,24	2,1	2,67	0,52
F2	1,26 - 1,32	552916	714800	1,29	5,5	7,06	1,60
F3	1,32 - 1,37	708382	954195	1,35	7,0	9,43	2,43
C1	1,37 - 1,41	753083	1047839	1,39	7,4	10,35	2,91
C2	1,41 - 1,53	2506506	3691625	1,47	24,8	36,47	11,71
C3	> 1,53	4582247	7800068	1,66	45,3	77,03	31,73
	Σ	10122700	14592946	10,70	100	144,16	47,87
			average	1,34			
			max	2,19		ESPI	73,1
			min	0,86			

(c)

Time periods 1931 – 1940

Subtype	Range of ESAI	Σp	Σv	Σv/Σp	ESAI	I	F
	0	375232	0	0	3,7	0	
Na	< 1,17	493614	541062	1,10	4,9	5,35	0,47
P	1,17 - 1,22	250694	300143	1,20	2,5	2,97	0,49
F1	1,22 - 1,26	225940	280574	1,24	2,2	2,77	0,54
F2	1,26 - 1,32	620704	802306	1,29	6,1	7,93	1,79
F3	1,32 - 1,37	760606	1024521	1,35	7,5	10,12	2,61
C1	1,37 - 1,41	734415	1021960	1,39	7,3	10,10	2,84
C2	1,41 - 1,53	2522418	3721069	1,48	24,9	36,76	11,84
C3	> 1,53	4119057	6820710	1,65	40,9	67,38	26,49
	Σ	10122700	14512375	10,69	100	143,36	47,07
			average	1,34			
			max	2,14		ESPI	71,2
			min	0,85			

(d)

Fig. 7. a, b, c, d. The ESPI procedure in Sicilian ESAs was applied in the first half of the 20th century in the periods 1921–30, 1931–40, 1941–50, 1951–60 [38]. The images show the results of the application of the ESPI on a regional scale.

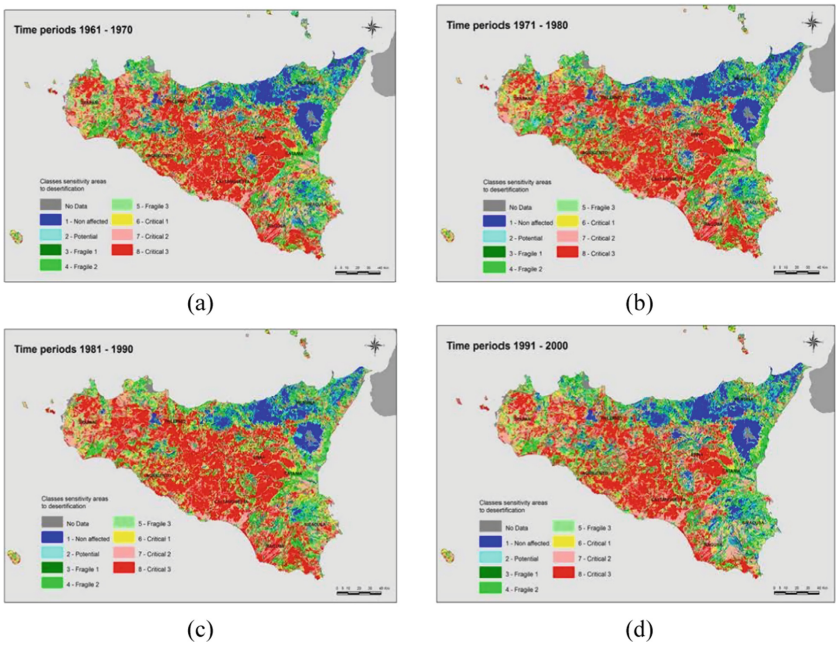


Fig. 8. a, b, c, d. The validation of the ESPI at regional scale was obtained by comparing the data and trends with the results of the MEDALUS database developed for the Region of Sicily [12, 13, 38, 43], derived from two scenarios: first half of the 20th century and climate data of four decades 1961–70, 1971–80, 1981–90, 1991–00. The images show the result of querying.

For the analysis of the trend of Climate Quality (see Fig. 13, 14, 15) emerges [43]:

- in the first period a climatic constant of 60 with ESPI values ranging from 50 to 80;
- in the second, a marked deterioration in the climate from 1961 to 1990, from 60 to 70;
- in the third period, from 1991 to 2015, a condition which seems to be stabilizing, with a range of 60–80 and a single exception in 1996.

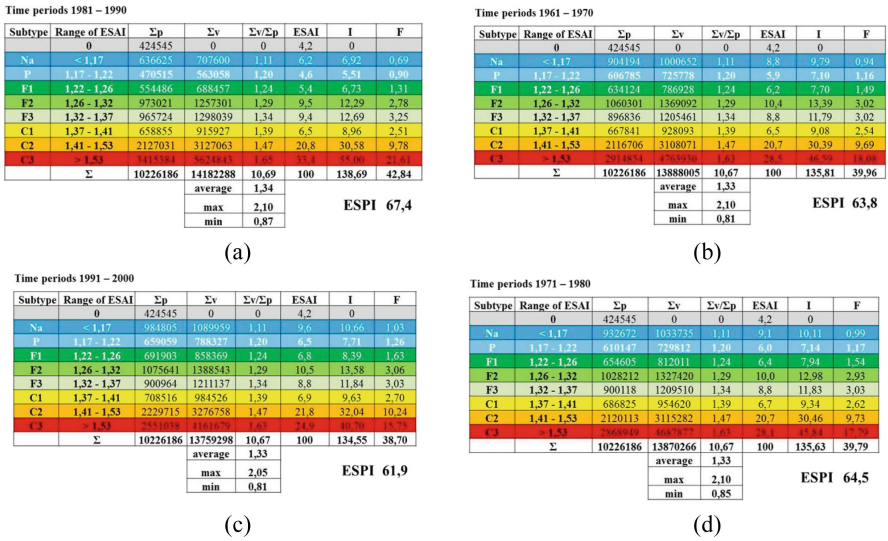


Fig. 9. a, b, c, d. The ESPI procedure in Sicilian ESAs was applied in the first half of the 20th century in the periods 1961–70, 1971–80, 1981–90, 1991–00 [38]. The images show the results of the application of the ESPI on a regional scale.

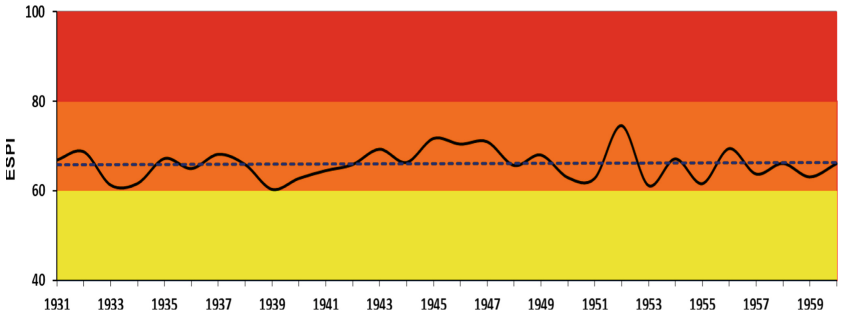


Fig. 10. Annual trend (from 1931 to 1960) of Sensitivity to Desertification sensu ESAI. The abscissa axis shows the time expressed in years. The ordinate axis shows the ESPI ESAI value on a scale from 1 to 100 [43].

4 Conclusions

In areas with a high risk of desertification, such as arid, semi-arid and sub-humid, priority should be given to risk mitigating and enhancing resilient [38]. A first step in planning mitigation actions is the knowledge of the territories, even on a detailed scale. The characterization of desertification risk in the 390 municipal areas of the island has the undisputed merit of having provided the Sicilian Region with an implementation of knowledge on the trend of the phenomenon. However, limitations emerge in the straightforward adoption of the ESAI methodology [12, 33, 37].

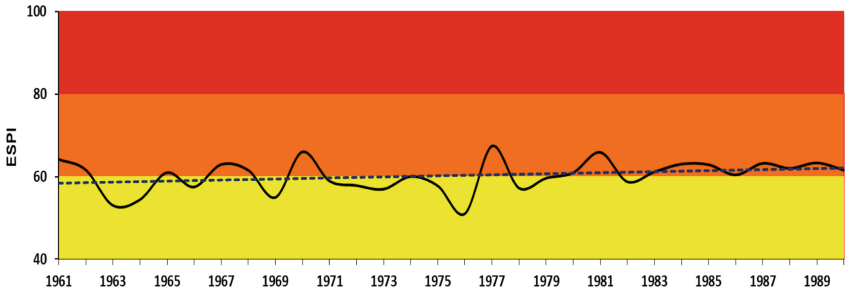


Fig. 11. Annual trend (from 1961 to 1990) of Sensitivity to Desertification sensu ESAI. The abscissa axis shows the time expressed in years. The ordinate axis shows the ESPI ESAI value on a scale from 1 to 100 [43].

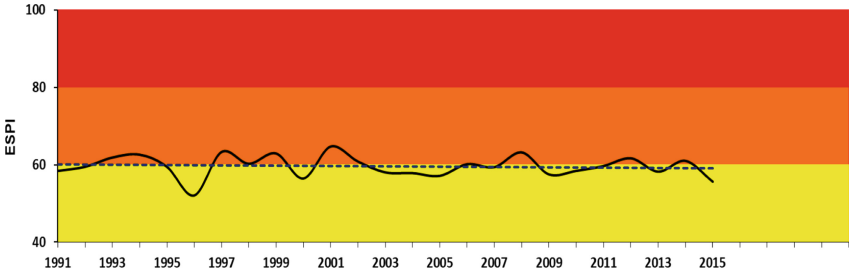


Fig. 12. Annual trend (from 1991 to 2015) of Sensitivity to Desertification sensu ESAI. The abscissa axis shows the time expressed in years. The ordinate axis shows the ESPI ESAI value on a scale from 1 to 100 [43].

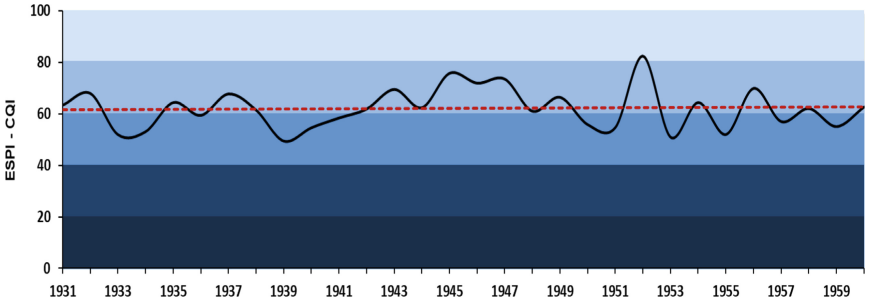


Fig. 13. Annual trend (from 1931 to 1960) of Climatic Quality sensu MEDALUS. The abscissa axis shows the time expressed in years. The ordinate axis shows the ESPI CQI value on a scale from 1 to 100 [43].

The results of the analysis of the new ESPI index tested in Sicily (reference period 1921–2000) are promising for the qualitative and quantitative study of the processes of desertification in space and time. The ESPI applied to ESAI results allows you to produce classifications and comparisons between areas at different scales and periods, and this is advantageous. For example, it can allow stakeholders to control the effectiveness of

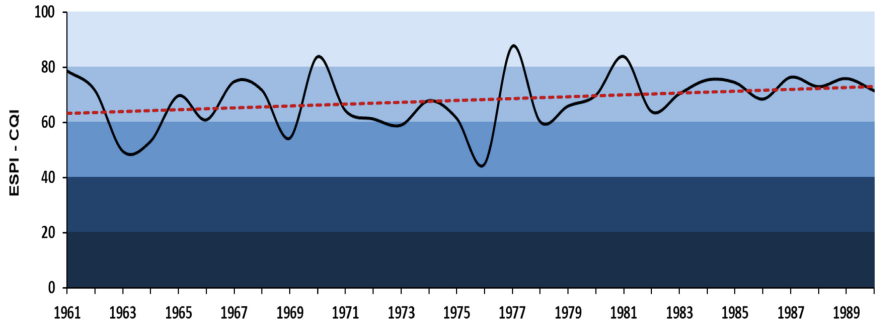


Fig. 14. Annual trend (from 1961 to 1990) of Climatic Quality sensu ESAI. The abscissa axis shows the time expressed in years. The ordinate axis shows the ESPI CQI value on a scale from 1 to 100 [43].

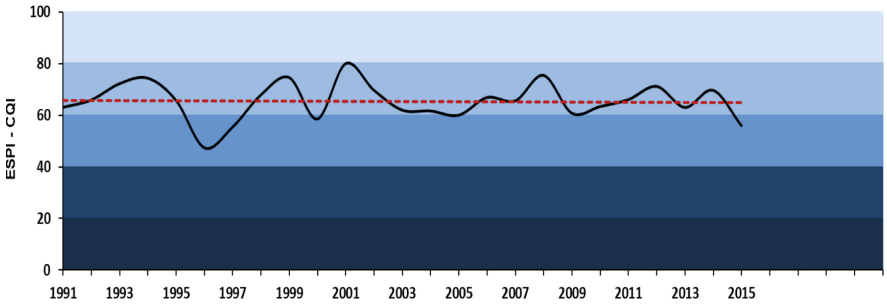


Fig. 15. Annual trend (from 1991 to 2015) of Climatic Quality sensu ESAI. The abscissa axis shows the time expressed in years. The ordinate axis shows the ESPI CQI value on a scale from 1 to 100 [43].

recovery or restoration interventions in a particular territory both from a qualitative and quantitative point of view, with the possibility of developing projections of the evolution of the phenomenon (see Fig. 16, 17, 18). It is very important to monitor the evolution of the risk of desertification in space and time, which is why the ESPI index could be a new environmental standard adopted by public authorities [13, 38].

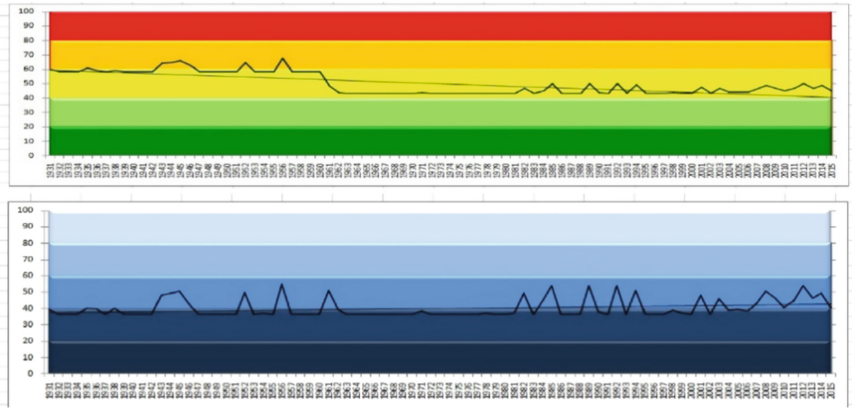


Fig. 16. Annual trend (from 1931 to 2015) Municipality of Sant'Agata di Militello, Messina [42]. The ESPI ESAI and ESPI CQI values indicate a situation of low desertification risk. The abscissa axis shows the time expressed in years. The ordinate axis shows the ESPI ESAI and ESPI CQI value on a scale from 1 to 100.

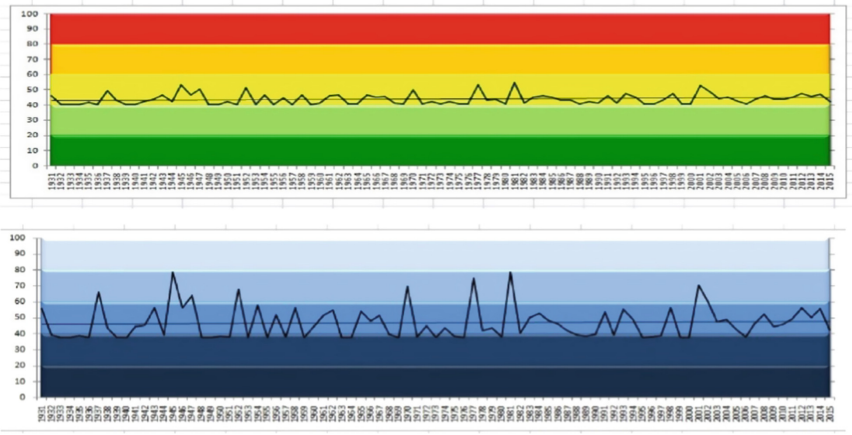


Fig. 17. Annual trend (from 1931 to 2015) Municipality of Castiglione, Catania. The ESPI ESAI and ESPI CQI values indicate potentially stationary situation. The abscissa axis shows the time expressed in years. The ordinate axis shows the ESPI ESAI and ESPI CQI value on a scale from 1 to 100 [42].

ESPI also makes it possible to translate the risk of desertification into opportunities by developing a protocol approach to identify areas irreversibly compromised for soil loss and, therefore, suitable for constructing plants. By doing so, it is possible to valorize those sites which proven the presence of irreversible degradation processes avoiding land take in non-threatened or fragile areas [44].

As part of the investigations carried out, the authors found that some thematic layers of the ESAI methodology need to be revised if we want to study the desertification process at an interregional and local scale. For the study of desertification processes

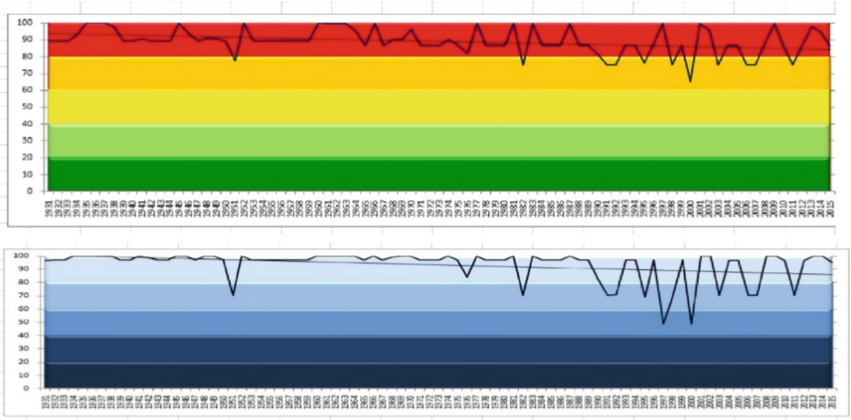


Fig. 18. Annual trend (from 1931 to 2015) Municipality of Portopalo, Siracusa. The ESPI ESAI and ESPI CQI values indicate potentially critical situation. The abscissa axis shows the time expressed in years. The ordinate axis shows the ESPI ESAI and ESPI CQI value on a scale from 1 to 100 [42]. Figures 16, 17 and 18 – ESPI applied on a municipal scale to both ESAI and CQI. Comparison of 3 municipalities with three very different trends [8].

on a local scale, it is necessary [43]: a) to identify new indicators suitable for the local representation scale (1:250,000 - 1:100,000 - 1:50,000) and to establish the relevant criteria, including dedicated guidelines; b) deepening knowledge of the macro indicators that contribute to the characterization of the bioclimatic vulnerability of the territories and the management of the territories also in terms of reducing climate and environmental risks; c) provide the region with detailed classifications of the levels of desertification risk at the municipal administrative level of the extent of the predisposing factors.

Regarding prospects, the authors consider the line of research dedicated to modifying some indices within the MEDALUS procedure to study the territory promising. They also consider integrating machine learning techniques and mathematical models to predict areas at risk of desertification useful for studies. Finally, in the logic of contrasting desertification processes as a participatory process, it is important to evaluate the creation of freely consultable and accessible tools [45–48] that make the research results usable by all the stakeholders [49].

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