Universidade de Aveiro	Universita' degli Studi di Cagliari	University of Pushchino

Ecole Nationale de l'Industrie Minerale

International Ph. D. Program in Environmental Science and Engineering

(Academic Year 2007/2008)

- XXI Cycle -

A LANDSCAPE APPROACH FOR DETECTING AND ASSESSING CHANGES IN AREAS PRONE TO DESERTIFICATION BY MEANS OF REMOTE SENSING AND GIS

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Settore disciplinare: ing ind 24

ACKNOWLEDGEMENTS

I would like to thank my research advisor, Prof. Alberto Marini, head of TELEGIS laboratory of the University of Cagliari (Italy), who contributed in stimulating my interest in remote sensing techniques for environmental monitoring.

I would also like to thank G. Loj of ERSAT (Ente Regionale di Sviluppo e Assistenza Tecnica in Agricoltura), who provided the data on the sensitivity to desertification in Sardinia and G. Pace of ACS (Advanced Computer Systems ACS SpA) who provided the validation points of the DESERTWATCH Project.

Very special thanks to many colleagues from the Institute for Environmental Protection and Research (ISPRA, Rome), to many friends and my relatives who constantly encouraged me to keep at my research and offered their time to give me all their technical and moral support: A. Morandotti, A. Poerio, A. Troccoli, A. Cemmi, A. Capriolo, A. Alvazzi Delfrate, A. Luise, A. Saso, A. Sambati, A. Cutugno, B. Capra, C. Noli, C. Jacomini, C. Caria, C. Maricchiolo, C. Sibilio, C. Pagnini, C. Di Stefano, D. Frigeri, D. Di Meo, D. Romano, D. Gaudioso, D. Zuccaro, E. Piccione, E. Rossi, F. Baffo, F. Baiocco, F. Delli Quadri, F. Rossi, F. D'Ascola, F. Rizzitiello, F. Desiato, G. Antolini, G. Cervetto, J. Ambrosi, I. Leoni, I. Delbono, L. Naitza, L. Giordano, M. Di Leginio, M. Tomaino, M. Boccone, M. Sciortino, M. Silvestri, M. Alfieri, M. Maschi, M. Munafò, M. Torre, my Mum, N. Bonora, N. De Stefano, N. Della Luna, P. Lamano, P. De Luca, R. Guarini, R. Condor, R. Mascolo, R. Cinquegrani, S. Cervi, S. Cuneo, my Sister, S. Minestrini, S. Viti, S. Loffredi, T. Melis, V. Bernardini and V. Sambucini.

Thank you all
Francesca

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LIST OF ACRONYMS

Acronyms	Meaning
AREA_MN	Mean Patch Area
AVHRR	Advanced Very High Resolution Radiometer
BA	Barren areas
C (C1, C2, C3)	Critical ESAs
CLC90	CORINE Land Cover 1990
CLC00	CORINE Land Cover 2000
COHESION	Patch Cohesion Index
CORINE	COoRdination of INformation on the Environment
CP	Croplands
CVA	Change Vector Analysis
DIS4ME	Desertification Information System for the Mediterranean
ED	Edge Density
EEA	European Environment Agency
EM	Expectation-Maximization
ENN_MN	Mean Euclidean Nearest-Neighbor Distance
ESAs	Environmentally Sensitive Areas
F (F1, F2, F3)	Fragile ESAs
FS	Forestlands
GCPs	Ground Control Points
GIS	Geographic Information System
IJI	Interspersion and Juxtaposition Index
LPI	Largest Patch Index
LSI	Landscape Shape Index
LULC	Land Use and Land Cover
MEDALUS	MEditerranean Desertification And Land USe
MPI	Mean Proximity Index
MSS	Landsat MultiSpectral Scanner
N	Non-threatened areas
NP	Number of Patches
P	Potential ESAs
PCA	Principal Component Analysis
PD	Patch Density
PLAND	Percentage of Landscape
RMS	Root Mean Square
SAR	Synthetic Aperture Radar
SHDI	SHannon’s Diversity Index
SPAs	Special Protection Areas
SPOT	Satellite Pour l’Observation de la Terre
TM	Landsat Thematic Mapper
UA	Urban areas
UAA	Utilized Agricultural Area
UNCCD	United Nations Convention to Combat Desertification
UNEP	United Nations Environment Programme
UTM	Universal Transverse Mercator
WB	Water bodies
WL	Wetlands

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INTRODUCTION

Key concept: *up to now landscape ecology has been rarely combined with the issue of desertification, in particular in the Mediterranean region.*

Desertification - *land degradation*[1] *in arid, semi-arid and dry sub-humid areas resulting from various factors, including climatic variations and human activities* (UNCCD, 1994) – is becoming one of the world's most serious environmental problems and its assessment represents an instrumental component in developing global and regional action plans aimed at preventing and/or eradicating this environmental threat.

Before the presence of man, natural processes shaped the landscape, but after man came to Earth, the face of the planet has changed. In the last two centuries, the impact of human agricultural, industrial and extractive activities on the land has grown enormously, altering entire landscapes with important ecological consequences such as loss of biodiversity, deforestation, soil erosion and desertification.

In Italy about 21,3% of the land is at risk of desertification, as a consequence of both natural and anthropic occurrences. In particular, 4,3% shows functional sterility, 4,7% is sensitive to desertification and 12,3% is vulnerable to desertification[2]. Sicily, Sardinia, Apulia, Calabria, Basilicata and Campania, which are located in the Southern part of the country, show the highest risk of desertification in the country (Costantini et al., 2007).

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[1] The United Nations Convention to Combat Desertification (UNCCD) defines land degradation as a reduction or loss in arid, semi-arid and dry sub-humid areas of the biological or economic productivity and complexity of rainfed cropland, irrigated cropland, or range, pasture, forest and woodlands resulting from land uses or from a process or combination of processes, including those arising from human activities and habitation patterns, such as: (i) soil erosion caused by wind and/or water; (ii) deterioration of the physical, chemical and biological or economic properties of soil; and (iii) long-term loss of natural vegetation.

[2] Functional sterility characterize areas in which agriculture and forestry are currently no longer economically or ecologically sustainable. An area with functional sterility could be cultivated, but the economic and social input needed would be so high that only rarely could it be put into practice.

A sensitive land is a surface where the process leading to desertification is active, although the land does not yet have functional sterility.

In a vulnerable land, environmental characteristics, like soil for instance, are close to that of a desertified area, but some factors, e. g. vegetation cover or irrigation, successfully mitigate the process of desertification.

Due to its particular geographical position and its extreme climatic events, such as droughts and floods, Sardinia can be considered a representative area of the typical environmental problems of the Mediterranean Basin. In fact, the landscape morphology and the climate make the soil very fragile and sensitive to activities which do not consider soil suitability and its limitations. In the last decades, urban sprawl[3] along the coastal areas has strongly increased due to new tourist settlements and urban infrastructures. Not only urban sprawl, but also loss of fertile soil, massive water exploitation, overgrazing and fires represent other important causes of the environmental problems on the island (Giordano and Marini, 2008).

Due to these environmental conditions, land degradation and desertification problems are of great concern to the island and the subject has been widely investigated over the last decades within the framework of national and international researches and projects (Motta et al., 1999; Kosmas et al., 1999; Bandinelli et al., 2000; Zucca et al., 2003; Pittalis, 2003; Motroni et al., 2004; RIADE, 2002-2005; DesertNet, 2002-2004; DesertNet II, 2005 - 2008, Desertwatch, 2004-2006, Ceccarelli et al. 2006).

Research studies are ongoing in order to further investigate where desertification represents a problem, to assess how critical the problem is and finally to better understand the processes of desertification. Desertification indicators[4] have been identified as potentially useful tools for both management and monitoring, and the Mediterranean countries are searching for a common methodology for identifying and using such indicators (Desertlinks, 2005).

From this perspective, a change in land cover and landscape represents an important and sensitive indicator that echoes the interactions between human activity and the natural environment (Zhou et al., 2008 a). In semi-arid and arid environments, in

[3] Urban sprawl is commonly used to describe physically expanding urban areas. The European Environment Agency (EEA) has described sprawl as the physical patterns of low-density expansion of large urban areas, under market conditions, mainly into the surrounding agricultural areas.

[4] The European Environment Agency (EEA) defines an indicator as a parameter or value derived from parameters, which provides information about a phenomenon. Indicators are quantified information that helps to explain how things are changing over time and how they vary spatially. Indicators generally simplify the reality in order to make complex phenomena quantifiable, so that information can be communicated.
Desertification indicators should help to identify where desertification is a current or potential problem and to monitor changes over time.

particular, where fragile ecosystems are dominant, land cover and landscape change often reflects the most significant impact on the environment due to excessive human activity (Zhou et al., 2008 b).

Most landscapes of the Mediterranean Basin have been shaped by human-nature interactions over large periods of time. In such cultural landscapes the main driving factor of changes is human impact, especially in terms of land-use and demography. These, in turn, are connected to regional, national and international policies. Land-use and population change usually leads to landscape changes with consequences in terms of habitat fragmentation and alteration. As a consequence, a comprehensive assessment of the causes and the extent of landscape change is needed in order to gain a better understanding of the possible ecological consequences such as biodiversity loss, soil erosion and reduced productivity, and as a baseline for setting appropriate management and restoration strategies (Plieninger, 2006).

The role spatial pattern plays in ecological processes has made the development of landscape assessment approaches possible for regional environmental quality assessment and for monitoring land use and land cover types.

Studying the landscape, its current state (structure) and its future changes (dynamics) enables understanding of the ecological mechanisms and processes that drive changes in the landscapes. Thus, the spatio-temporal analysis of landscape is a necessary basis for a mechanistic linkage between particular species or human being and the changing characteristics of the landscape.

Desertification assessment, in particular, has made increasing use of landscape ecology principles but still few examples of landscape metrics, derived from land use and land cover maps and used to quantify environmental change in arid and semi-arid regions, are found in literature (Sun et al., 2007; Sun et al., 2008).

Since information on land cover and landscape is critical to understanding environmental issues and changes in arid and semi-arid regions, the integration of remote sensing with Geographic Information System (GIS) techniques is increasingly important for the assessment of environmental problems such as land desertification (Zhang et al., 2008).

Objectives of the research

In this scientific context, and based on the assumption that many processes of desertification are typically related to the spatial structure of the landscape and its temporal variation, we drawn up the following **general objective** of the present research: **to explicitly explore the concepts and methodology of a landscape approach for the monitoring of desertification**.

Up to now, the key research topics in landscape ecology have focused on ecological flows and processes in landscape mosaics, but landscape ecology has been rarely combined with the issue of desertification, in particular in the Mediterranean region.

The specific objective of the following research was therefore twofold.

The **first specific objective** being to set up both a conceptual framework and a methodological implementation for land cover and landscape spatio-temporal detection, characterization and assessment based on remote sensing, GIS and landscape analysis. The integration of such instruments was drawn up in order to provide quantitative data of interest for the monitoring of desertification: location, magnitude, direction and spatial structure of changes.

The **second specific objective** was to enhance the understanding of patterns of desertification processes:

- by performing fresh landscape analysis in a Mediterranean environment, where this kind of investigation has not been performed up to now;
- by setting up appropriate synthetic landscape indexes related to specific spatial patterns which have not been deeply investigated up to now within the framework of the most common methodologies for the monitoring of desertification.

OUTLINE OF THESIS

Chapter 1 contains some theoretical background about remote sensing and change detection techniques mainly used for land cover and landscape change assessment.

Chapter 2 provides the basic principles of landscape ecology and describes the most important aspects of desertification, thus linking the science of landscape ecology with the monitoring of this phenomenon.

Chapter 3 describes the study area selected for the purpose of the research.

Chapter 4 illustrates the materials used in order to implement the analysis and the method set up.

Chapter 5 provides a description of the results in terms of land cover and landscape change derived from the implementation of the method for the years 1972, 1990 and 2000 and for each municipality.

Chapter 6 contains the discussion of the results and, finally, reports the concluding remarks.

1. REMOTE SENSING AND CHANGE DETECTION FOR LAND COVER AND LANDSCAPE: THEORETICAL BACKGROUND

Key concept: *identifying, delineating and mapping land cover and landscape and their change is important for global monitoring studies, resource management and planning activities.*

1.1 Definitions and basic physical principles of remote sensing

Remote sensing can be defined as the collection of data about an object from a distance. Humans and many other types of animals accomplish this task with aid of eyes or by the sense of smell or hearing. In practice we do not usually think of our bodily senses as remote sensors in the way that term is applied in technical usage (Pidwirny, 2006).

As it is customarily considered, a formal and comprehensive definition of applied remote sensing is "*the science and art of obtaining and interpreting information about an object, area, or phenomenon through the analysis of data acquired by a sensor that is not in contact with an object, area, or phenomenon being observed*".

While the definition of remote sensing describes a very wide array of technologies and types of research, all remote sensing technologies are based on certain common concepts, and all remote sensing systems consist of the same basic components. These four basic components of a remote sensing system include: a target, an electromagnetic energy source, a transmission path and a sensor (figure 1).

Figure 1 - The basic components of a remote sensing system. Source: Remote Sensing Tutorial.

The target could be a particular object, an area or phenomenon (e.g. city, forest cover, forest fire or a combination thereof).

The Sun is a common source of electromagnetic energy. It radiates solar energy in all directions. Earth reflects the energy from the Sun and emits some energy in the form of heat. Based on the energy source, remote sensing systems can be grouped into two types: passive and active systems. Passive remote sensing systems detect radiation

that is reflected and/or emitted from the surface features of Earth (e.g. Landsat, SPOT). Active remote sensing systems provide their own energy source (e.g. SAR).
The transmission path is the space between the electromagnetic energy source and the target, and back to the sensor. In the case of Earth observation, the transmission path is usually the atmosphere of Earth.

While passing through Earth's atmosphere, the electromagnetic energy that hits a target interacts with matter or the target in several ways: the energy could be scattered by minute particles, absorbed by gases such that its strength and spectral characteristics are modified before being detected by the sensor or transmitted (Remote Sensing, 2003).
Much of the sun's high-energy radiation is absorbed by the atmosphere, preventing it from reaching the Earth's surface. This absorption of energy in the upper atmosphere is an important factor in allowing life to flourish on the Earth.
Atmospheric particles such as dust, sea salt, ash and water droplets will reflect energy back into space. Visible light can be scattered by particles in the atmosphere, allowing only selected wavelengths to penetrate to the surface.
A portion of the energy is able to penetrate the atmosphere and to reach the Earth's surface. Radiation that is able to penetrate the material and pass through it is said to be transmitted. Most wavelengths of visible light energy from the sun are transmitted through the atmosphere, allowing it to come into contact with the Earth's surface. Once this radiation reaches the surface, it interacts with the surface materials through electron or molecular reactions within the material. A portion of this energy is then emitted by the material that absorbed it, usually at longer wavelengths, while some of it remains and heats the target.

The sensor is a device that detects reflected and/or emitted energy. Passive remote sensing systems carry optical sensors that detect energy in the visible, infrared and thermal infrared regions of the electromagnetic spectrum. In active remote sensing systems, the same antenna that sends out energy pulses detects the return pulse (Remote Sensing, 2003).

Electromagnetic radiation is energy that travels in waves. Waves have measurable properties that help us in describing radiation, including wavelength, frequency, velocity and amplitude.

The point of maximum upward displacement of a wave is called its crest, and the area of maximum downward displacement is called a trough. The wavelength of a wave is defined as the distance between two successive crests (or between two successive troughs).

Frequency is a measure of how many waves pass a fixed point in a given unit of time, and is therefore dependent on the velocity at which the wave is travelling. Since all electromagnetic energy travels at a constant speed (the speed of light), the wavelength and frequency of different energy types are inversely related. In other words, for electromagnetic energy, a general rule states that the longer the wave, the lower the frequency, and the shorter the wave the higher the frequency.

A wave's amplitude is defined as the magnitude (or distance) of the vertical displacement caused by the wave. In more general terms, amplitude can be thought of as the height of the wave.

The difference in energy wave characteristics allows us to classify electromagnetic energy into groups that exhibit similar wave property characteristics.

When all the possible forms of radiation are classified and arranged according to wavelength or frequency, the result is the electromagnetic spectrum.

The electromagnetic spectrum includes types of radiation that range from extremely low energy, long wavelength, low frequency energy like radio energy to extremely high energy, short wavelength, high frequency energy types such as X-rays and gamma ray radiation.

The electromagnetic spectrum is traditionally divided into regions of radio waves, microwaves, infrared radiation, visible light, ultraviolet rays, X-rays and gamma rays.

1.2 Remote sensing for land cover and landscape change detection: general concepts

Current applications of remote sensing are numerous and varied. They include, among others, the assessment of land use and land cover (LULC) change (Zhou , 2008 b; Munoz-Villers and Lopez Blanco, 2008; Alrababah and Alhamad, 2006; Dwivedi et al., 2005), forest or vegetation change (Cakir et al., 2008; Gobron et al., 2005; Fensham et al., 2005; De Barros Ferraz et al., 2005), landscape change

(Zha et al., 2008; Groom et al., 2006; Lu et al., 2003; Wu and Ci, 2002), urban change (Geymen and Baz, 2008; Kurucu and Chiristina, 2008; Sudhira et al., 2004).

Land cover and landscape change detection applications using remote sensing technologies are among the most important applications in environmental monitoring. Land cover refers to the surface cover on the ground, whether vegetation, urban infrastructure, water, bare soil or other. A landscape[5] is a spatial configuration of patches of dimensions relevant for the phenomenon under consideration. Identifying, delineating and mapping land cover and landscape and their change is important for global monitoring studies, resource management and planning activities.

Change detection is defined as the process of identifying differences in the state of an object or phenomenon by observing it at different times (Singh, 1989). Its objective is, therefore, to compare spatial representation of two points in time by controlling all variances caused by differences in variables that are not of interest and to measure changes caused by differences in the variables of interest (Green et al., 1994).

The basic premise in using remotely sensed data for change detection is that changes in the objects of interest will result in changes in reflectance values or local textures that are separable from changes caused by other factors such as differences in atmospheric conditions, illumination and viewing angles and soil moistures.

Timely and accurate change detection of Earth’s surface features provides the foundation for better understanding relationships and interactions between human and natural phenomena in order to better manage and use resources.

In general, change detection involves the application of multi-temporal datasets to quantitatively analyse the temporal effects of the phenomenon. Because of the advantages of repetitive data acquisition, its synoptic view and digital format suitable for computer processing, remotely sensed data, such as Thematic Mapper (TM), Satellite Probatoire d’Observation de la Terre (SPOT), Radar and Advanced Very High Resolution Radiometer (AVHRR), have become the major data sources for different change detection applications during the past decades.

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[5] See Chapter II for a further description of landscape.

A variety of change detection techniques have been developed up to now and new techniques are constantly developed.

Four important aspects of change detection for the monitoring of natural resources are: i) detecting if a change has occurred; ii) identifying the nature of change; iii) measuring the areal extent of the change and iv) assessing the spatial pattern of the change.

When implementing a change detection project, three major steps are involved: i) image preprocessing including geometrical rectification and image registration, radiometric and atmospheric correction; ii) selection of suitable techniques to implement change detection analyses and iii) accuracy assessment. Controversial conclusions about which change detection techniques are most effective suggest that it is not easy to select a suitable algorithm for a specific change detection project. Hence, identifying a suitable change detection technique becomes of great significance in producing good quality change detection results.

Successfully implementing a change detection analysis using remotely sensed data requires careful considerations of the remote sensor system, the environmental characteristics and the image processing methods. The temporal, spatial, spectral and radiometric resolutions of remotely sensed data have a significant impact on the success of a remote sensing change detection project.

Of the various requirements of preprocessing for change detection, multitemporal image registration, radiometric and atmospheric corrections are the most important. The importance of accurate spatial registration of multi-temporal imagery is obvious because largely spurious results of change detection will be produced if there is misregistration.

When selecting remote sensing data for change detection applications, it is important to use the same sensor, same radiometric and spatial resolution data with anniversary or very near anniversary acquisition dates in order to minimize the effects of external sources such as sun angle, seasonal and phenological differences.

For a given research purpose, when the remotely sensed data and study areas are identified, selection of an appropriate change detection method has considerable significance in producing a high-quality change detection product (Lu et al., 2004).

1.3 Change detection techniques for land cover and landscape: a brief review of the methods

Due to the importance of monitoring change of Earth's surface features, research of change detection techniques is an active topic and a variety of new techniques are constantly developed.

It is not easy to select a suitable algorithm for a specific change detection project but in general a good change detection research should provide information like the area change and change rate, the spatial distribution of changed types, the change trajectories of land cover types and the accuracy assessment of change detection results.

Hence, a review of change detection techniques used in previous research is useful to understand how these techniques can be best used to help address specific problems and to produce good quality change detection results.

The change detection methods for land cover and landscape can be grouped into the following categories: i) algebra; ii) transformation; iii) classification; iv) advanced models; v) GIS approaches; vi) visual analysis and vii) other approaches[6].

For the first six categories, the main characteristics, advantages and disadvantages are provided in this context.

Algebra

The algebra category techniques mainly used for land cover and landscape change includes image differencing, image ratioing and change vector analysis (CVA). These algorithms have a common characteristic, i.e. selecting thresholds to determine the changed areas. These methods are relatively simple, straightforward, easy to implement and interpret, but these cannot provide complete matrices of change information. One disadvantage of the algebra category is the difficulty in selecting suitable thresholds to identify the changed areas.

[6] The seventh category "other approaches" includes those change detection techniques that are not suitable to group into any one of the six categories and are not yet extensively used in practice. Hence, this category is not discussed in detail.

Transformation

The transformation category techniques mainly used for land cover and landscape include principal component analysis (PCA), tasselled cap and chi-square. These techniques have the advantage of reducing data redundancy between bands and emphasizing different information in derived components. However, they cannot provide detailed change matrices and require selection of thresholds to identify changed areas. Another disadvantage is the difficulty in interpreting and labelling the change information on the transformed images.

Classification

The classification techniques for land cover and landscape change detection include post-classification comparison, spectral temporal combined analysis, EM (expectation-maximization) detection, unsupervised change detection, hybrid change detection and artificial neural networks. These methods are based on the classified images, in which the quality and quantity of training sample data are crucial to produce good quality classification results. The major advantage of these methods is the capability of providing a matrix of change information and reducing external impact from atmospheric and environmental differences between the multi-temporal images. However, selecting high-quality and sufficiently numerous training sample sets for image classification is often difficult, in particular for historical image data classification. The time-consuming and difficult task of producing highly accurate classifications often leads to unsatisfactory change detection results, especially when high-quality training sample data are not available.

Advanced models

Among the advanced models, the spectral mixture model and the biophysical parameter method are the most used in land cover and landscape change detection. In these methods, the image reflectance values are often converted to physically based parameters or fractions through linear or non-linear models. The transformed parameters are more intuitive to interpret and better to extract vegetation information than are spectral signatures. The disadvantage of these methods is the time-consuming and difficult process of developing suitable models for conversion of image reflectance values to biophysical parameters.

GIS

The GIS-based change detection category includes the integrated GIS and remote sensing method and the pure GIS method. The advantage of using GIS is the ability to incorporate different source data into change detection applications. Thus, the powerful GIS functions provide convenient tools for the multi-source data processing and are effective in handling the change detection analysis using multi-source data.

However, different source data associated with different data accuracies and formats often affect the change detection results.

Visual analysis

The visual analysis category includes visual interpretation of multi-temporal image composite and on-screen digitizing of changed areas. This method can make full use of an analyst's experience and knowledge. Texture, shape, size and patterns of the images are key elements useful for identification of LULC change through visual interpretation. These elements are not often used in the digital change detection analysis because of the difficulty in extraction of these elements. However, in visual interpretation, a skilled analyst can incorporate all these elements in helping make decisions about LULC change. The disadvantage of this method is the time consumed for a large-area change detection application and it is difficult to timely update the change detection results. It is also difficult to provide detailed change trajectories (Lu et al., 2004).

2. LANDSCAPE ECOLOGY AND DESERTIFICATION MONITORING

Key concept: *studying the landscape, its current state (structure) and its future changes (dynamics) enables understanding of the ecological mechanisms and processes that drive changes in the landscapes*.

2.1 Basic principles of landscape ecology

Landscape ecology is largely founded on the notion that environmental patterns strongly influence ecological processes (Turner, 1989). The development of landscape ecology is directly related to the discussion over the concept of landscape. This goes back a long way and was chiefly initially shaped in Europe (Germany, The Netherlands and Denmark).

In contrast to the classical approaches of German-language landscape ecology, the approach of quantitative landscape ecology emerged in the 1980s and 1990s, which was in particular developed by the North American landscape ecologists Forman & Godron (1986), Urban et al. (1987), Turner (1989), Turner & Gardner (1991 a, b), Hansen & Castri (1992), O'Neill (1995) and Hansson et al. (1995).

These approaches were based on the definition of landscape ecology put forward by Forman & Godron (1986), which states: "*Landscape ecology explores how a heterogeneous combination of ecosystems – such as woods, meadows, marshes, corridors and villages – is structured, functions and changes. From wilderness to urban landscapes, our focus is on:*

a) the distribution patterns of landscape elements or ecosystems;

b) the flows of animals, plants, energy, mineral nutrients and water among these elements;

c) *the ecological changes in the landscape mosaic over time.*"

It could be stated that landscape ecology was born as a consequence of the need to identify significative units to manage on the territory.

Landscape ecology, hence, investigates three essential features of the landscape:

i) structure, which refers to the spatially related properties of elements of the ecosystem and their spatial interrelationship within the landscape. They are used to describe the distribution of energy, material and type with respect to the size, shape, number, type and configuration of ecosystems in a landscape;

ii) function, which describes the existing interaction between the spatial elements of the ecosystem, which is expressed in exchange processes of energy, material and substances;

iii) dynamics, which is exhibited by the change of structures, functions of the landscape structure and the landscape mosaic over time.

The view that "*environmental problems are nothing more than the result of disturbed interrelations between different processes and structures*" (Tischendorf, 1995) shows that for the sake of future environmental protection, a landscape-based approach is necessary which enables landscape structures, functions and their dynamics to be quantitatively determined.

There are many different interpretations of the term "landscape"[7]. In the present study we refer to the definition by Forman and Godron (1986): "*landscape is a heterogeneous land area composed of cluster of interacting elements that is repeated in similar form throughout*".

From a spatial point of view landscapes can be differentiated in terms of their composition and their configuration.

In particular, landscape composition refers to the number, proportional frequency and diversity of landscape elements within the landscape, with the concrete spatial relations being neglected.

The configuration of landscape elements covers all the spatially related characteristics and primarily describes the spatial position and distribution of the elements within a landscape. According to Forman and Godron (1986), the composition and configuration of landscape elements, biotopes and the entire landscape represent key aspects of landscape ecology.

The smallest individual, largely homogeneous element of a landscape is named patch. Patches represent discrete areas with independent characteristics

[7] Definitions of landscape invariably include an area of land containing a mosaic of patches or landscape elements. The concept differs from the traditional ecosystem concept in focusing on groups of ecosystems and the interactions among them. There are many variants of the definition depending on the research or management context. It is therefore incumbent upon the investigator or manager to define landscape in an appropriate manner.

qualitatively described depending on the scale of surveying and observation. In terrestrial environments an example of patch could be a vegetation patch. Using remote sensing methods, a patch is formed by the pixels belonging together to one land cover class of the classified satellite picture. A patch is therefore an isolated structure with respect to the surrounding context and is characterised by dimension, shape and perimeter.

The total number of patches of the same type form a class (Lausch and Thulke, 2001).

Of the several types of landscape elements, the matrix is the most extensive and most connected landscape element type and therefore plays the dominant role in the functioning of the landscape.

In order to quantify spatial characteristics of patches, classes of patches or entire landscape mosaics a plethora of landscape metrics, which are specific algorithms, has been developed. These metrics fall into the two categories: those that quantify the composition of the landscape without reference to spatial attributes and those that quantify the spatial configuration of the landscape, requiring spatial information for their calculation.

Composition is easily quantified and refers to features associated with the variety and abundance of patch types within the landscape, but without considering the spatial character, placement or location of patches within the mosaic.

Configuration is much more difficult to quantify and refers to the spatial character and arrangement, position or orientation of patches within the class or landscape. Some aspects of configuration are measures of the placement of patch types relative to other patches, other patch types, or other features of interest. Other aspects of configuration are measures of the spatial character of the patches (McGarigal et al., 2002).

2.2 Desertification: definition, causes, consequences and indicators

Desertification, defined as land degradation in arid, semi-arid and dry sub-humid areas[8] resulting from various factors, including climatic variations and human activities, is becoming one of the world's most serious environmental problems. Desertification does not refer to the expansion of existing deserts, but it occurs because dryland ecosystems are extremely vulnerable to overexploitation and inappropriate land use. Over 250 million people in the world are directly affected by desertification. In addition, some one thousand million (or one billion) people in over one hundred countries are at risk. These people include many of the world's poorest, most marginalized and politically weak citizens (UNCCD, 1994).

In Italy about the 21,3% of the land is at risk of desertification, as a consequence of both natural and anthropic causes. In particular, 4,3% shows functional sterility, 4,7% is sensitive to desertification and 12,3% is vulnerable to desertification. Sicily, Sardinia, Apulia, Calabria, Basilicata and Campania, which are located in the Southern part of the country, show the highest risk of desertification in the country (Costantini et al., 2007).

Desertification is induced by several factors, such as overgrazing, urban sprawl, overcultivation, fires, deforestation, overexploitation of groundwater, unsustainable irrigation practices and increased soil salinity, global climate change. Increasing human population and poverty contributes to desertification, as poor people may be forced to overuse their environment in the short term, without the ability to plan for the long term effects of their actions. Desertification reduces the ability of land to support life, affecting wild species, domestic animals, agricultural crops and people. The reduction in plant cover that accompanies desertification leads to accelerated soil erosion by wind and water. As vegetation cover and soil layer are reduced, rain drop impacts and run-off increase. Water is lost off the land instead of soaking into the soil to provide moisture for plants. Even long-lived plants that would normally survive droughts, die. A reduction in plant cover also results in a

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[8] The United Nations Environment Programme (UNEP) has adopted the following Aridity Index (AI): $AI = P / PET$, where PET is the potential evapotranspiration (mm) and P is the average annual precipitation (mm). On the basis of this definition, the boundaries that define various degrees of aridity are as follows: Hyperarid ($AI < 0,05$); Arid ($0,05 < AI < 0,20$); Semiarid ($0,20 < AI < 0,50$); Dry subhumid ($0,50 < AI < 0,65$).

reduction in the quantity of humus and plant nutrients in the soil, and plant production drops further. As protective plant cover disappears, floods become more severe. In some way desertification is self-reinforcing, i.e. once the process has started, conditions are set for continual deterioration.

Desertification reduces the land's resilience and its resources, such as soil, vegetation, freshwater supplies, to natural climate variability. Soil becomes less productive, as its physical structure and bio-chemical composition can change for the worse, thus reducing soil's ability to support plant growth and to hold moisture. The loss of vegetation cover is both a consequence and a cause of land degradation. Desertification is considered a major global environmental issue largely because of the link between dryland degradation and food production. The relationship between soil degradation and crop yields, however, is seldom straightforward. Productivity is affected by many different factors, such as the weather, disease and pests, farming methods, and external markets and other economic forces (UNCCD, 1994).

Indicators of desertification may demonstrate that desertification has already proceeded to its end point of irreversibly infertile soils. The most useful indicators, however, are those which indicate the potential risk of desertification while there is still time and scope for remedial action.

In the Mediterranean environments indicators systems were developed in order to characterise and identify desertification processes (Enne and Zucca, 2000).

One of the most used indicators systems to identify areas sensitive to desertification is represented by the key indicators set developed in the framework of the MEDALUS (MEditerranean Desertification And Land USe) Project.

The aim of this methodology is the identification of Environmentally Sensitive Areas (ESAs) at local scale through a multifactor approach based on both a general and a local knowledge of the environmental processes acting. At this scale it is appropriate and possible to pay attention to detailed soil and vegetation properties and to local topographic factors. The various types of ESAs to desertification can be distinguished and mapped by using certain indicators for assessing the land capability to withstand further degradation, or the land suitability for supporting specific types of land use. The different types of ESAs to desertification can be analysed in relation to various parameters such as landforms, soil, geology, vegetation, climate and human action. Each of these parameters is grouped into various uniform classes with respect to its behaviour on desertification and weighting factors are assigned in each class. Then the following four qualities are evaluated: soil quality, climate quality, vegetation quality and management quality. After the computation of the four indices for each quality, the ESAs to desertification are defined by combining them by means of a geometric mean. Three general types of ESAs to desertification are distinguished based on the stage of land degradation:

i) type C (C1, C2, C3) - critical ESAs. Areas already highly degraded through past misuse, presenting a threat to the environment of the surrounding places.
ii) type F (F1, F2, F3) - fragile ESAs. Areas in which any change in the delicate balance of natural and human activity is likely to bring about desertification.
iii) type P - potential ESAs. Areas threatened by desertification under significant climate change, if a particular combination of land use is implemented or where offsite impacts will produce severe problems elsewhere. This is a less severe form of type F, for which nevertheless planning is necessary.
iv) type N - non-threatened by desertification. Areas with deep to very deep, nearly flat, well drained, coarse-textured or finer soils, under semi-arid or wetter climatic conditions, independently of vegetation are considered non-threatened (Kosmas et al., 1999).

2.3 Landscape approach for desertification monitoring

Up to now, the key research topics in landscape ecology have focused on ecological flows and processes in landscape mosaics, but landscape ecology has been rarely combined with the issue of desertification, in particular in the Mediterranean region (Giordano, 2007). Using a landscape approach allows for relatively quick assessment of desertification that can be used in developing practicable application plans at the regional level in desertification prevention planning and decision-making (Sun et al., 2007). Landscape metrics derived from land use and land cover maps have been used to quantify environmental change specifically in arid and semi-arid regions (Kepner et al., 2000; Seixas, 2000; Fu and Chen, 2000; Li et al., 2004; Sun et al., 2005; Zhang et al., 2008).

The table 1 reports some examples of landscape metrics used to analyse and to characterize desertification spatial patterns[9].

Landscape metric	Reference
Class area	Li et al., 2004, Kepner et al., 2000
Percentage of landscape	Li et al., 2004
Number of patches	Li et al., 2004, Kepner et al., 2000
Patch Density	Sun et al., 2005, Sun et al., 2007
Landscape Shape Index	Sun et al., 2005, Sun et al., 2007
Largest Patch Index	Li et al., 2004, Sun et al., 2005, Kepner et al., 2000
Mean Patch Size	Li et al., 2004, Kepner et al., 2000
Mean Nearest Neighbor distance	Li et al., 2004
Fractal Dimension Index	Sun et al., 2005, Sun et al., 2007
Contagion	Li et al., 2004, Sun et al., 2005
Interspersion and Juxtaposition Index	Li et al., 2004
Shannon's Diversity Index	Li et al., 2004, Sun et al., 2005
Shannon's Evenness Index	Li et al., 2004
Landscape connectivity	Sun et al., 2007, Sun et al., 2008, Kepner et al., 2000
Heterogeneity	Seixas, 2000

Table 1 – Examples of landscape metrics used for the monitoring of desertification.

In the Mediterranean region the landscape approach has been rarely combined with the monitoring of desertification.

In recent years the Desertlinks project developed a Desertification Indicator System for Mediterranean Europe (DIS4ME), including 148 indicators of relevance to Mediterranean desertification, in order to better understand and monitor the processes leading to desertification. Among these indicators some landscape indicators were identified, both in the physical-ecological category and in the economic one: forest fragmentation, land use evolution, land use type, Shannon's diversity index, urban sprawl (Desertlinks, 2005).

Another recent project, Desertwatch (Desertwatch, 2004-2006) aiming at the development of an information system for assessing and monitoring desertification using earth observation technologies, set up a series of desertification indicators.

[9] See Chapter IV for a further description of landscape metrics used in the present research.

Among these indicators, some were indicators related to land cover such as forested areas and soil sealing, while others were assessed through specific spatial analyses like forest fragmentation, in terms of forest density and forest continuity (Pace et al., 2007).

In scientific researches set of landscape metrics were developed and set up in order to enhance the comprehension of the dynamics of ecosystems and the landscape structure. In the table 2 examples of set of metrics used in literature are described.

Set of landscape metric	Landscape pattern	Reference
Class Level		
NP + AREA_MN + LPI	*Fragmentation*	Baskent and Kadiogullari, 2007
SHEI + PD + AREA_MN	*Urbanization*	Weng, 2007
PD + ED + AREA_MN	*Urbanization*	Bianchin and Bravin, 2004
Landscape Level		
NP + AREA_MN	*Grain*	Li et al., 2004
IJI + CONTAG	*Clumpiness and connectivity*	Li et al., 2004
NP + AREA_MN + MPI + IJI	*Clumpiness*	Li et al., 2004
MPI + IJI	*Uniformity*	Li et al., 2004
SHDI + SHEI	*Heterogeneity and evenness*	Li et al., 2004

Table 2 - Set of landscape metrics used in desertification researches. NP = Number of Patches; AREA_MN = Mean Patch Area; LPI = Largest Patch Index; SHEI = SHannon Evenness Index; PD = Patch Density; ED = Edge Density; IJI = Interspersion and Juxtaposition Index; CONTAG = Contagion; SHDI = SHannon's Diversity Index.

By using specific combinations of landscape metrics to examine and quantify landscape patterns through time, it is possible therefore to determine and quantify the long-term changes due to prior land use and management.

3. THE STUDY AREA

Key concept: *Sardinia can be considered as a representative area of the typical environmental problems of the whole Mediterranean Basin.*

3.1 Environmental characterisation

Sardinia, due to its particular geographical position and extreme climatic events such as droughts and floods, is characterized by having a lack of water and can be considered as a representative area of the typical environmental problems of the whole Mediterranean Basin (RIADE, 2002-2005).

The study area (40° 43’ N, 8° 34’ E) selected for the present research is located in the north-western part of Sardinia and includes the municipalities of Alghero, Stintino, Porto Torres and Sassari, comprising approximately 88400 ha (figure 2).

Figure 2 - Location of the study area.

The area was selected as representative of various land degradation and desertification processes such as urban sprawl, massive water exploitation, overgrazing and fire. Furthermore, it offers a wide availability of data, information and studies derived from many national and international projects (Motta et al., 1999; Kosmas et al., 1999; Bandinelli et al., 2000; Zucca et al., 2003; Pittalis, 2003;

Motroni et al., 2004; RIADE, 2002-2005; DesertNet, 2002-2004; DesertNet II, 2005 - 2008, Desertwatch, 2004-2006; Ceccarelli et al., 2006).

The area is characterized by a high geological and morphological complexity and is entirely volcanic. Human activity has increased the variability of the landscape, by modifying in particular the original structure of vegetation.

The climate is typically Mediterranean dry-subhumid with an abundant amount of rainfall during the autumn-winter period and a small amount of rainfall with very high temperatures during the summer period. Mean annual precipitation values vary between 490 mm and 870 mm. During the climatological period 1961-1990 a mean annual temperature of 16°C was registered. The mean hottest temperature was registered during august with a value equal to 29,7°C. Due to these climatic characteristics the soil suffers from low water quantities and, as a consequence, in this area sclerophyllous vegetation, surviving in water scarce conditions, is widespread.

The study area belongs to the phytoclimatic region of *Lauretum*[10]. Vegetation is characterised by Mediterranean scrub such as sclerophyllous evergreen forests (*Cistus*, *Oleaster*, *Pistacia Lentiscus*, *Quercus suber*, *Quercus ilex*) and other typical Mediterranean species (*Calycotome*). From a vegetational point of view the most interesting locations are Capo Caccia, plenty of endemic and rare species, Porto Conte with Mediterranean scrub and the Calich pond characterized by typical lake vegetation. In some locations, small flaps of *Quercus ilex* evolved to *Arbustus unedo* and *Erica arborea* and other kinds of scrub, such as that of *Myrtus* and *Calycotome*, the Mediterranean thermoxerophile scrub (*Pistacia lentiscus*) and the garrigue. The landscape is also characterised by artificial pinewoods of *Pinus pinea* and *Pinus halepensis*.

The halophile groups[11] characterise the first parts of rocky coasts and are constituted by *Crithmo-Staticetum acutifoliae* which form a belt along the coast and *Thymaeleo-Helichrysetum* and *Centauretum horridae* in the part lying behind.

[10] *Lauretum* is the hottest phytoclimatic zone as defined by Mayr-Pavari, based on rainfall regimes and temperatures.
[11] Salt-tolerant vegetation.

The endemic species distributed in the study area represent 4% of the Sardinia's flora and can be found in particular along the coast between Capo Caccia and Cala del Turco (Primo Rapporto sullo Stato dell'Ambiente - Città di Alghero, 2003).

In the study area water resources availability is an important issue. Here, groundwater and surface water suffer from an overexploitation coming from various sectors such as civil, industrial, agricultural and zootechnical ones. The proximity of mountain reliefs to the coast prevents the formation of watercourses of some importance.

Within the study location the only natural lake is the Baratz lake, which is close to Porto Ferro, in the municipality of Sassari. It is located 30 km from the city of Sassari and 20 km from the city of Alghero, it can receive about 2-2,5 million cubic meters of freshwater and the altitude is about 30 meters above sea level. The lake has a naturalistic value for its flora and fauna and is surrounded by a lush pine forest made of Mediterranean scrub (*Arbutus unedo, Cistus, Rosmarinus officinalis, Myrtus communis, Lavandula officinalis*). One of the most important dunal system of Sardinia, which is covered by pine forest and by a typical vegetation of these rare natural systems, is located between the lake and Porto Ferro.

During time the depth of the lake has considerably changed, varying from the maximum value during the sixties (14 m) to the minimum value during the seventies (5 m), as a consequence of the water abstraction for agricultural purposes. The level is currently 6,5 meters which is somehow worrying because of the lack of rain in the last years, with likely consequences for the surrounding fragile ecosystems. The lake, in fact, is located 1,5 km away from the sea and the water cycle is only based on evaporation and filtration, with a possible risk of lake extinction in the future.

Two ponds close to the municipality of Stintino are found: the pond of Pilo and the pond of Cesaraccio, located 15 km and 3 km respectively from the town. They both represent important reproductive reserves for avifauna (*Phoenicopterus, Circus aeruginosus, Egretta garzetta, Ardea, Phalacrocorax carbo*).

The pond of Pilo had a singular origin: about 100,000 years ago the sea level was higher and the current shores of the lake represented the coastline. The pond was formed after the sea level withdrawal. Currently it is mainly fed by the Chirigu Corsu stream together with rainfall. The shape is quite irregular, the length is equal to 2,000 meters and the width is about 1,300 meters.

The pond of Cesaraccio is located in the north-western part of the island, with a length equal to 1,700 meters and a width equal to 900 meters.

Both ponds are formed by salty water, with many salt deposits derived by the decrease of water level during the driest periods. Here the vegetation is mainly represented by halophyle vegetation (*Juncus acutus, Juncus maritimus*, *Triglochin laxiflorum*). Flora and fauna are characterized by endemic and rare species.

The brackish pond of Calich is located very close to Alghero, in the area of Fertilia. In Sardinia very few urban areas have a wetland like this one. For this reason, the pond of Calich has been declared a Special Protection Area (SPA)[12] in the framework of The Birds Directive as a natural resource of scenic and a high economic value to be protected. It is a coastal pond of about 70 hectares fed by Rio Fangal in the south, Rio Barca in the east and Oruni canal in the north, in which large quantities of water are gathered. The pond shape resembles a goblet with the stem penetrating into the inner part of the Nurra region. Here the freshwater slowly becomes brackish and finally salty in the Calich. Flora and fauna are of high interest, in particular the fish species.

3.2 Socio-economic context

In the study area four main urban areas are found: Sassari, Alghero, Porto Torres and Stintino. Sassari is the second city of Sardinia, with about 130.000 inhabitants in 2008. The economy is based on the advanced tertiary, the administrative management of the north of Sardinia and some small-to-medium enterprises. Olive-groves range all around the city and traditional productions of oil, wine, fruit and vegetables, cheese and fabric are found. Alghero is the second city of the study area, with its 40.802 inhabitants in 2008. The main economic activities concern agriculture, with important productions of wine and oil, handicraft, small industrial poles and tourism.

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[12] Special Protection Areas (SPAs) are designated under the European Commission Directive on the Conservation of Wild Birds (The Birds Directive). All European Community Member States are required to identify internationally important areas for breeding, over-wintering and migrating birds and designate them as SPAs.

Porto Torres is located in a strategic position, in the middle of the Asinara Gulf and represents the third urban pole of the study area with 22.081 inhabitants. The economy of the area is mainly based on industrial activities, even if this sector is declining since many years, while fishery and agriculture persist. Finally, Stintino is located in the last edge of Sardinia, from the Nurra plain toward the Asinara island. With its 1.285 inhabitants in 2008 it represents a small village with many tourist interesting places such as the beaches and the ponds.

In the inner part of the study area, the Nurra plain dominates the landscape, with its wide cultivated surfaces and areas mainly devoted to cattle and ovine breeding (ISTAT, 2008). The area has a consolidated vine-growing and wine-producing, olive-growing and vegetable tradition and is mostly covered by arable land.

Over the previous decades in the area of Sassari, as in the whole region, high demographic changes occurred, with consequent effects on the environmental dynamic of the territory. In the table 3 population data from the census close to the three periods investigated (1971, 1991 and 2001) are indicated in a temporal series going from 1961 to 2001 in order to better characterise the demographic evolution occurred in the municipalities of the study area.

	1961	**1971**	**1981**	**1991**	**2001**
Sassari	89.311	106.261	118.631	122.339	120.729
Alghero	26.688	32.187	36.508	39.026	38.404
Porto Torres	11.199	16.230	20.990	21.264	21.064
Stintino	726	864	965	1.114	1.127
Study area	**127.924**	**155.497**	**177.094**	**183.743**	**181.324**
SARDINIA	**1.419.000**	**1.473.800**	**1.594.174**	**1.648.248**	**1.631.880**

Table 3 - Population in each municipality and in the study area in 1961, 1971, 1981, 1991 and 2001. Source: ISTAT, 1961, 1971, 1981, 1991, 2001.

The table 4 indicates the variation, percentage wise, in the population occurred in each municipality between the periods 1961-1971, 1971-1981, 1981-1991 and 1991-2001.

Population increased in all the municipalities, in particular between 1961 and 1981. Between 1991 and 2001, population started to show a slight decrease, except for the municipality of Stintino where the population showed a continuous slight growth. Over the overall period analysed the largest increase in population was registered in the municipality of Porto Torres, in particular in the periods 1961-1971 and 1971-1981.

	VAR % 61-71	VAR % 71-81	VAR % 81-91	VAR % 91-01	VAR % 1961-2001
Sassari	19,0	11,6	3,1	-1,3	35,2
Alghero	20,6	13,4	6,9	-1,6	43,9
Porto Torres	44,9	29,3	1,3	-0,9	88,1
Stintino	19,0	11,7	15,4	1,2	55,2
Study area	**21,6**	**13,9**	**3,8**	**-1,3**	**41,7**
SARDINIA	**3,9**	**8,2**	**3,4**	**- 1,0**	**15,0**

Table 4 – Percentage variation in the population in each municipality and in the study area between the periods 1961-1971, 1971-1981, 1981-1991 and 1991-2001. Source: ISTAT, 1961, 1971, 1981, 1991, 2001.

In the last decades a considerable population shift occurred from the inner parts of the island to the coastal urban centers, especially with regard to young generations. This process is still ongoing resulting in a strong increase in demographic pressure on these areas and their natural resources. The abandonment of inner areas can be somehow considered a limiting factor to the development of the rural economy.

Given the evolution described in terms of population, in the present study the socio-economic context was depicted for the period around 2000 which represents the last temporal reference for our analysis.

The table 5 shows the population density recorded in the last population census of 2001. The higher values of population density were recorded in the municipality of Sassari and Porto Torres and were significantly higher than the population density of Sardinia. Very low values were recorded in the municipality of Stintino. The population structure by gender was characterized by a predominant number of females over males.

	Population density (Persons/km^2)	Males	Females
Sassari	221	57.784	62.945
Alghero	171	18.454	19.950
Porto Torres	205	10.425	10.639
Stintino	19	554	573
Study area	205	87.217	94.107
SARDINIA	68	799.238	832.642

Table 5 – Population density, males and females in each municipality and in the study area. Source: ISTAT, 2001.

The table 6 illustrates the number of farms, the utilized agricultural area and the ratio between the utilized agricultural area (UAA) and the total surface in each municipality and in the overall region of Sardinia. The largest number of farms within the study area was located in the area of Sassari and Alghero, where the largest values of UAA were concentrated. Agriculture and sheep-farming traditionally were very relevant activities in the area investigated and represented the most important source of income since many decades.

	N. of farms	UAA	UAA / Total surface
Sassari	5.469	29.949	0,5
Alghero	1.715	7.567	0,3
P. Torres	35	1.739	0,2
Stintino	52	2.442	0,4
Study area	7.271	41.697	0,5
SARDINIA	112.689	1.020.411	0,4

Table 6 – Number of farms, utilized agricultural area (UAA) and ratio UAA / Total surface. Source: ISTAT, 2000.

The table 7 illustrates the number of enterprises for secondary and tertiary sectors. Industry developed since the sixties – seventies and the municipality of Porto Torres represented one of the most important petrochemical pole in Italy. The tertiary activities were well developed in particular in the municipalities of Sassari and Alghero where commerce, tourism and other services predominated.

	Industry (N. of enterprises)	**Tertiary** (N. of enterprises)
Sassari	1.605	4.495
Alghero	535	1.307
Porto Torres	262	492
Stintino	27	79
Study area	2.429	6.373
SARDINIA	22.992	51.140

Table 7 – Number of enterprises for secondary and tertiary sectors.

Only in the recent decades the income coming from the secondary and tertiary sectors have equalized the income deriving from the primary sector, thus demonstrating how the economy in the study area still depends on traditional productions.

During the last decade a reduction in agricultural areas was registered as a consequence of the progressive rural abandonment and the strengthening of productive processes in agriculture. This phenomenon reflected a wider process which occurred in the overall national territory.

3.3 Environmental degradation and sensitivity to desertification

Many environmental problems such as urban sprawl, overgrazing, agricultural soil consumption, massive exploitation of groundwater, land degradation and desertification can be identified in the study area.

Since the sixties, urban sprawl has affected in particular the coastal areas, where new tourist settlements and urban infrastructure have developed, resulting in the destruction of dunal and retrodunal areas and wide coastal erosion effects. Here, resident and seasonal population needs, combined with the agricultural use of these areas, have caused increasing water demands, often exceeding the available quantities (ISTAT, 2001).

In the hilly area of the Nurra region overgrazing represents a degradation system, in areas with elevated slopes and scarce vegetation cover, with environmental consequences like soil compaction, vegetation cover reduction and soil erosion processes.

The central part of the area is represented by flat territories, intensively cultivated with vineyards and olive trees. In this area environmental problems are caused by massive groundwater exploitation, resulting in a higher risk of saltwater intrusion up to many kilometers from the coast and salinization of surface groundwater. Here environmental systems are furthermore threatened by arson, leading to the consequent destruction of vegetation and erosion processes (RIADE, 2002-2005).

The agropastoral activity progressively changed the territory configuration, as land use caused deep changes in the landscape.

All these problems, together with a strong increase in the population in particular along the coast, caused substantial impacts on natural resources of the territory.

Climatic factors, such as a rise in temperature and a change in rainfall patterns, together with the unsustainable human pressure in terms of agropastoral and industrial activity and urbanization, therefore represent the main cause of soil degradation and desertification in the study area, as in the whole Sardinia (table 8).

Agro-pastoral activity	**Industrial activity**	**Urbanization**
overgrazing	sealing of agricultural areas	
overexploitation of coastal groundwater		
interventions to improve pasture	discharge of pollutants	
forestation with exotic species	excavation in agricultural areas	
deforestation		

Table 8 - Main degradation factors in the study area.

Many possible consequences could derive from the degradation factors described. As indicated by Aru (2002), physical, chemical and biological processes such as erosion, soil compaction, soil consumption, salinization, pollution, loss of organic matter, alteration of biological processes and many others (figure 3) could affect soil properties and its productivity, thus leading also to economic consequences.

Figure 3 - Hilly landscapes in the Nurra region. Photo: A. Marini.

Recent researches were carried out in order to identify the sensitivity to desertification in the whole Sardinia, by means of the MEDALUS methodology (Motroni et al., 2004). Figure 4 illustrates the map of sensitivity to desertification obtained for the study area.

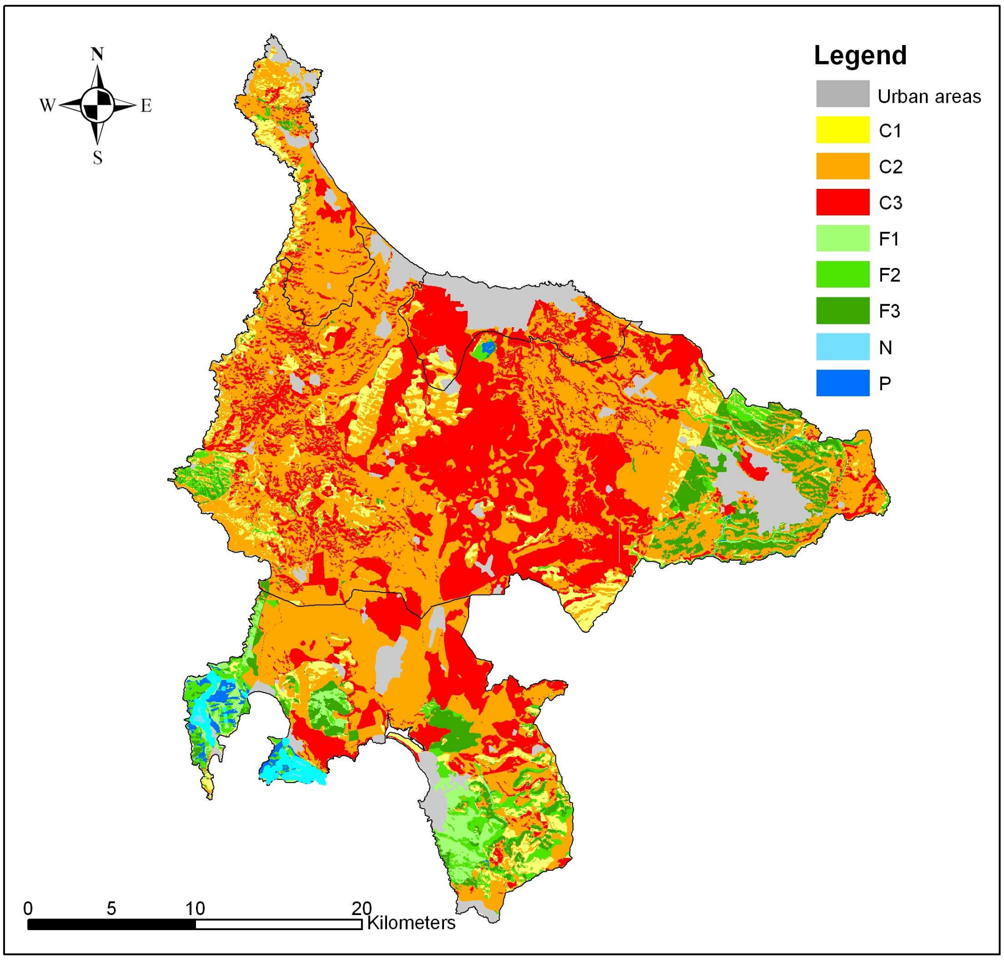

Figure 4 – Map of the sensitivity to desertification in the study area. Source: Elaboration from Motroni et al., 2004.

Sensitivity to desertification is diffused all over the territory[13]. The highest sensitive areas (C3) are concentrated in the central part of the study area, where agriculture represents the main activity and human action has misused the territory, without taking into account its real agricultural vocation. High sensitive areas are located on metamorphic reliefs of the Nurra region, where intense erosive processes are occurring because of overgrazing, fires and other human actions.

[13] Among the critical ESAs C3 represents the worst condition (ESA index > 1,53). ESA index range from 1,42 to 1,53 for C2 and from 1,38 to 1,41 for C1. Among the fragile ESAs F3 represents the worst conditions (ESA index: 1,33 – 1,37). ESA index range from 1,27 to 1,32 for F2 and from 1,23 to 1,26 for F1.

Furthermore, research studies carried out in the area demonstrated the link between the highest values of sensitivity to desertification and the presence of low quality vegetation (Pittalis, 2003).
The table 9 shows the distribution of the desertification sensitivity level among the four municipalities.

	C1	C2	C3	F1	F2	F3	N	P
Alghero	7,0	37,5	18,9	8,0	8,6	8,4	1,3	2,9
P. Torres	3,0	21,5	40,7	-	-	-	-	-
Sassari	6,5	46,8	33,6	0,5	1,9	5,2	-	0,1
Stintino	9,7	66,6	12,2	-	0,5	1,5	-	-
Study area	**6,7**	**44,3**	**28,8**	**2,3**	**3,4**	**5,5**	**0,3**	**0,8**
SARDINIA	**12**	**29**	**11**	**7**	**16**	**14**	**1**	**4**

Table 9 - Percentage of area by sensitivity to desertification in the four municipalities. Source: Elaboration from Motroni et al., 2004[14].

As indicated in the table, the municipalities of Porto Torres and Stintino can be considered the most sensitive municipalities to desertification within the study area.
In the first municipality, the non-urban areas are all classified as critical ESAs, with about 40% of the territory belonging to the worst C class (C3); in the second municipality only 2% of the non-urban areas falls within the fragile areas and almost 90% of the territory belongs to the critical ESAs.
The municipality of Alghero shows a relevant part of the territory belonging to less critical classes (F) and some small areas classified as potential or non-threatened, thus having the most well-balanced territory between more and less sensitive areas to desertification.

[14] Urban areas are not included in the elaboration of the sensitivity to desertification.

4. MATERIALS AND METHODS

Key concept: *the present research focuses on spatial patterns of interest for the monitoring of desertification, which have not been deeply investigated in the framework of the most common methodologies used up to now*.

4.1 Introduction

The present chapter describes the materials used and the methodology set up for the purposes of this research.

On the basis of the scientific literature analysed and described above, we drawn up a methodology able to perform the analysis of land cover and landscape changes and to provide quantitative data of interest for the monitoring of desertification: location, magnitude, direction and spatial structure of changes (figure 5).

Hence, we tested this approach in order to assess and to characterise the changes occurred over a period of twenty-eight years in an area prone to desertification, where this kind of investigation has not been experimented on up until now.

In particular, we focused our attention on spatial patterns of interest for the monitoring of desertification and detectable at the study scale, some of which still not deeply investigated in the framework of the MEDALUS approach commonly used up to now:

i) urban sprawl, and the related effect of soil sealing[15], which represents a direct cause of desertification and can cause indirectly the alteration and the loss of natural resources, with the result that soil is no longer able to perform the range of functions associated with it. The current urban model, in fact, generally induces a massive soil sealing with high energy consumption and environmental pollution in the surroundings areas. Sealed soil is then subtracted to other uses, like agriculture and forests, and its ecological functions, such as carbon sink and habitat, are limited or prevented. Moreover, urban areas contribute to the build up of greenhouse gases in the atmosphere.

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[15] Soil sealing refers to changing the nature of the soil such that it behaves as an impermeable medium (for example, compaction by agricultural machinery). Soil sealing is also used to describe the covering or sealing of the soil surface by impervious materials by, for example, concrete, metal, glass, tarmac and plastic (EEA, multilingual environmental glossary).

ii) loss of forestlands, which represents a key process linked to land degradation. Reduction in the perennial cover is regarded, in fact, as an important indicator of the onset of desertification. Vegetation cover plays very important role on protecting the soil surface from raindrop splashing, increasing soil organic matter, soil aggregate stability, water holding capacity, hydraulic conductivity, retarding and reducing surface water runoff, etc. (Desertlinks, 2005). Furthermore, the destruction of forests subtracts important carbon sinks from the environment thus reducing their role in mitigating climate change.

iii) forest fragmentation, which refers to a landscape-level process in which a specific habitat is progressively sub-divided into smaller, geometrically more complex and more isolated fragments, thus making the territory more sensitive to land degradation processes.

iv) expansion of croplands, which could have a dual role in relation to desertification. Among the productive activities agriculture is considered one of the most threatening activities that could cause and accelerate the process of desertification. Modern intensive practice, massive use of chemical products, overexploitation of water resources and the related problem of soil salinization, diffusion of intensive monocultures, intensive breeding and deforestation represent some examples of the most negative impacts which could derive from an agricultural land use. On the other hand, sustainable agricultural practices could assure a correct land management, thus preventing negative effects such as land degradation and desertification, soil salinization and climate change.

v) reduction in the extension of water bodies, which could be linked to the human withdrawal of water resources but also to drier climatic conditions.

vi) change in landscape structure, which is based on the assumption that many processes of desertification are typically related to the spatial structure of the landscape and to its temporal variation (Li et al., 2004).

According to the type of spatial pattern, land cover or landscape analysis was performed. In particular, loss of forestlands, expansion of urban areas and croplands and reduction in the extension of water bodies were analysed in terms of land cover change. Changes of urban sprawl patterns, forest fragmentation and landscape structure were examined by means of the landscape analysis.

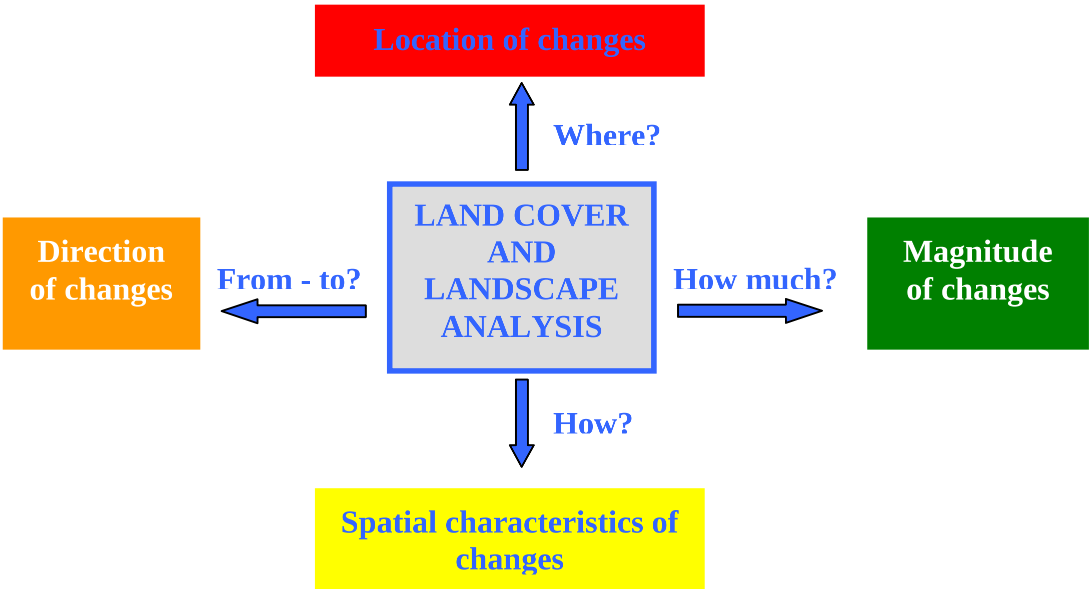

Figure 5 – Quantitative data provided by the implementation of the methodology.

We structured the methodology into a multi-step systematic procedure including nine different phases, to be performed one next to another:

i) identification of the study area[16];

ii) selection and acquisition of satellite Landsat historical dataset;

iii) selection of change detection technique;

iv) collection of the field and ancillary data; pre-processing and classification of images;

v) elaboration of land cover maps of 1972, 1990 and 2000;

vi) elaboration of land cover change maps (location and magnitude of change);

vii) evaluation of land cover change trajectories (direction of change);

viii) selection and calculation of specific landscape metrics for the landscape analysis in terms of composition and configuration at class and landscape level (spatial structure of change);

ix) analysis, comparison and discussion of results.

[16] See the previous Chapter for a further description of the study area.

In figure 6 the flow chart of the multi-step systematic procedure implemented for land cover and landscape change analysis is represented.

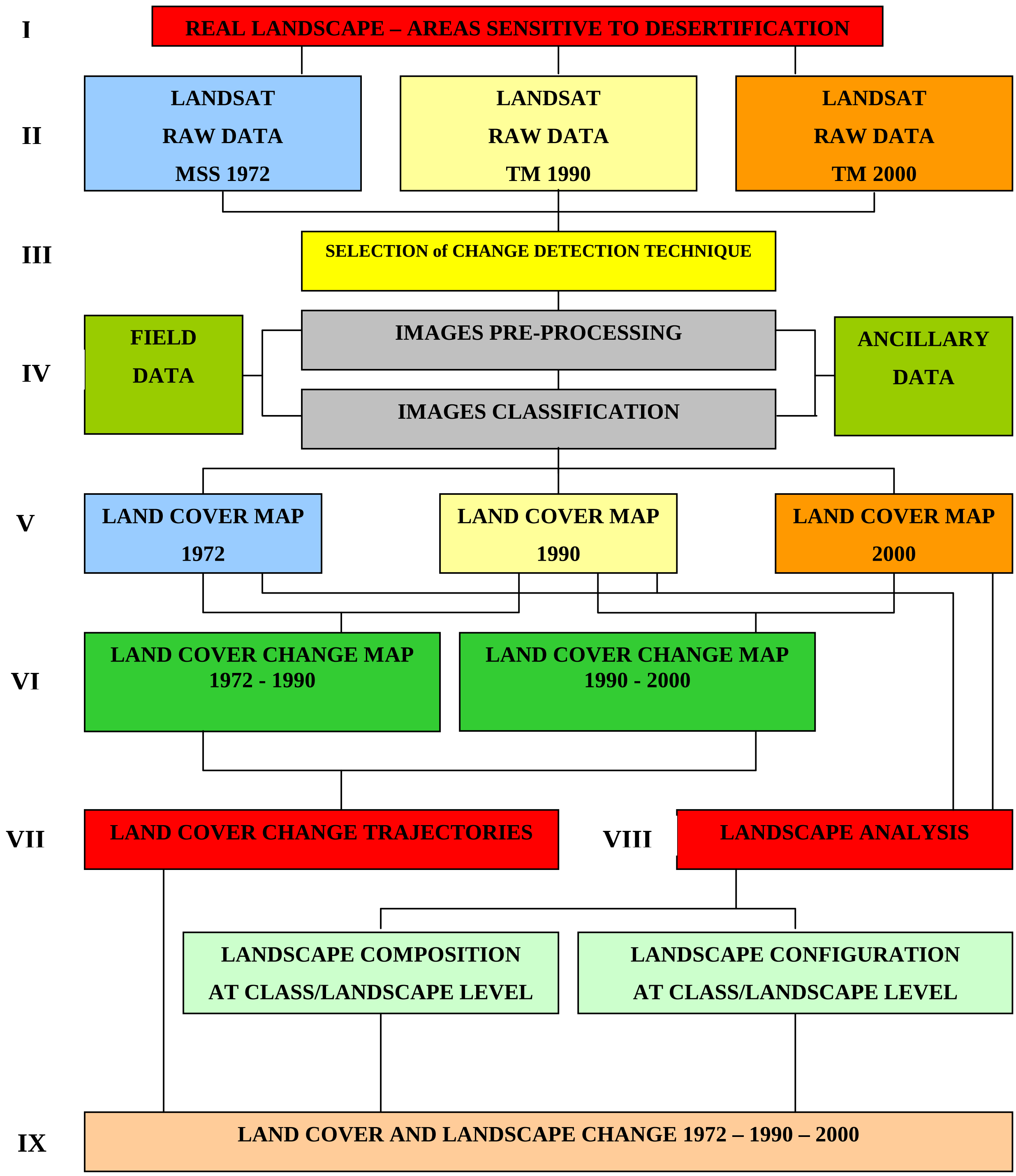

Figure 6 - Flow chart of the systematic procedure implemented.

4.2 Materials

4.2.1 Satellite data

Three Landsat images were selected over the study area: Landsat Multispectral Scanner (MSS) of August 13, 1972; Landsat Thematic Mapper (TM) of May 12, 1990 and Landsat Thematic Mapper (TM) of June 27, 2000 (table 10).
Landsat is the series of Earth observation satellites launched by the U.S. National Aeronautics and Space Administration (NASA) under the Landsat Program since 1972 to the present, as the first civilian program specializing in the acquisition of remotely sensed digital satellite data.

Image	Acquisition Date	Bands	Wavelength (µm)	Spatial Resolution (m)
Landsat 1 MSS	13/08/1972	1	0,5-0,6	56 x 79[17]
		2	0,6-0,7	
		3	0,7-0,8	
		4	0,8-1,1	
Landsat 5 TM	12/05/1990 27/06/2000	1	0,45-0,52	30
		2	0,52-0,60	
		3	0,63-0,69	
		4	0,76-0,90	
		5	1,55-1,75	
		6	10,4-12,5	120[18]
		7	2,08-2,35	30

Table 10 - Characteristics of the images used in the research.

Landsat 1 MSS recorded electromagnetic radiation in four bands:

i) Band 1 (green: 0,5-0,6 µm): scans the region between the blue and red chlorophyll absorption bands. It corresponds to the green reflectance of healthy vegetation and it is also useful for mapping water bodies;

[17] The MSS sensor images a swath 185 km wide. Each pixel in an MSS scene represents a rectangular ground area.
[18] The thermal band is resampled to 30m x 30m to match the other bands.

ii) Band 2 (red: 0,6-0,7 μm): it is the red chlorophyll absorption band of healthy green vegetation and represents one of the most important bands for vegetation discrimination;

iii) Band 3 (reflective infrared: 0,7-0,8 μm): it is responsive to the amount of vegetation biomass present in a scene. It is useful for crop identification and emphasizes soil/crop and land/water contrasts;

iv) Band 4 (reflective infrared: 0,8 – 1,1 μm): it is useful for vegetation surveys.

TM is a multispectral scanning system much like the MSS, except that the TM sensor records reflected/emitted electromagnetic energy from the visible, reflective-infrared, middle-infrared and thermal-infrared regions of the spectrum. TM has higher spatial, spectral and radiometric resolution than MSS.

Detectors record electromagnetic radiation in the following seven bands:

i) Band 1 (blue: 0,45-0,52 μm): this band is useful for mapping coastal water areas, differentiating between soil and vegetation, forest type mapping and detecting cultural features;

ii) Band 2 (green: 0,52-0,60 μm): this band corresponds to the green reflectance of healthy vegetation and is also useful for cultural feature identification;

iii) Band 3 (red: 0,63-0,69 μm): this band is useful for discriminating between many plant species and also for determining soil boundary and geological boundary delineations;

iv) Band 4 (reflective infrared: 0,76-0,90 μm): this band is responsive to the amount of vegetation biomass present in a scene and it is useful for crop identification;

v) Band 5 (mid-infrared: 1,55-1,75 μm): it is sensitive to the amount of water in plants, which is useful in crop drought studies and in plant health analyses. This is also one of the few bands that can be used to discriminate between clouds, snow and ice;

vi) Band 6 (thermal-infrared: 10,40-12,50 μm): it is useful for vegetation and crop stress detection and heat intensity;

vii) Band 7 (mid-infrared: 2,08-2,35 μm): this band is important for the discrimination of geologic rock type and soil boundaries, as well as soil and vegetation moisture content (ERDAS, 1999a).

Detailed information on Landsat history and characteristics are out of the scope of this thesis and could be easily found in Markham (2004), as well as in official web sites (http://landsat.usgs.gov/technical_details, http://www.landsat.org/, http://landsat.gsfc.nasa.gov/).

4.2.2 Orthophotos and ground truth data

Twelve orthophotos Italia 2000[19] at the scale 1:10.000 (figure 7), dating back to 2000 and covering the overall study area, were used as reference source of information required for the classification procedure of the Landsat images.

Figure 7 – Ortophoto Italia 2000.

Field data were acquired among the data provided in the framework of the DESERTWATCH Project. In particular, we acquired 1477 ground truth points covering the study area and we used them as control points for the assessment of the classification accuracies for the three land cover maps (figure 8).

[19] An ortophoto is an aerial photograph that has been geometrically corrected or orthorectified such that the scale of the photograph is uniform and the photo can be considered equivalent to a map. Unlike an uncorrected aerial photograph, an orthophoto can be used to measure true distances, because it is an accurate representation of the earth's surface, having been adjusted for topographic relief, lens distorsion and camera tilt. Terraitaly – IT2000 was carried out by Compagnia Generale Ripreseaeree SpA of Parma (Italy).

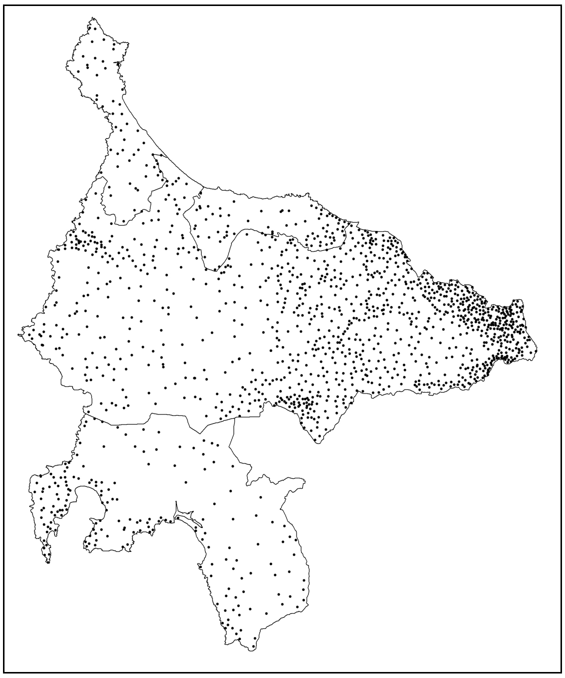

Figure 8 – Ground truth data over the study area. Source: DESERTWATCH Project.

4.2.3 Vector dataset

The vector dataset used within the present study includes the following maps:

i) CORINE Land Cover[20] 1990 (CLC90);

ii) CORINE Land Cover 2000 (CLC00);

iii) ESAs map of Sardinia.

CLC90 and CLC00 are part of the CORINE programme (COoRdination of INformation on the Environment) and are intended to provide consistent localized geographical information on the land cover of the Member States of the European Community. The scale chosen for the CORINE Maps is 1:100.000.

The nomenclature comprises three levels:

[20] On 27 June 1985 the Council, on a proposal from the Commission, adopted a decision on the CORINE programme. This Commission work programme concerns "an experimental project for gathering, coordinating and ensuring the consistency of information on the state of the environment and natural resources in the Community (Official Journal L. 176, 06.07.1985). The land cover project is part of the CORINE programme and is intended to provide consistent localized geographical information on the land cover of the 12 Member States of the European Community.
See the website http://reports.eea.europa.eu/COR0-landcover/en for further information about the project.

i) the first level contains 5 items, indicating the major categories of land cover on the planet: Artificial surfaces, Agricultural areas, Forests and semi-natural areas, Wetlands, Water bodies;

ii) the second level contains 15 more specific items;

iii) the third level contains 44 more specific items.

CLC90 and CLC00 represented relevant reference source of information for land cover in the study area.

The ESAs map represents the areas sensitive to desertification in Sardinia (Motroni et al., 2004). The scale of the map is 1:100.000. The sensitivity was computed by means of the MEDALUS methodology (Kosmas et al. 1999) and calculated as the geometrical mean of four indices: Soil Quality Index, Climate Quality Index, Vegetation Quality Index and Management Quality Index. These four indices take into account different indicators relevant to desertification, in particular:

i) Soil Quality indicators: parent material, rock fragments, soil depth, slope;

ii) Climate Quality indicators: precipitation, aridity, aspect;

iii) Vegetation Quality indicators: fire risk and ability to recover, soil erosion protection, plant drought resistance, plant cover;

iv) Management Quality and human factors: land use intensity, overgrazing, fires.

4.3 Software

4.3.1 ERDAS Imagine and ARCGIS

Remote sensing procedures were performed by means of ERDAS Imagine software[21] and GIS analysis were carried out by means ArcGIS8[22].

ERDAS Imagine is a suite of software tools specifically designed to process geospatial imagery by importing, viewing, altering and analyzing raster and vector datasets.

ERDAS Imagine has, in particular, tools for image visualization, mapping, analysis, enhancement, geocorrection and reprojection, raster and vector data handling.

[21] See the website http://www.erdas.com/default.aspx for further information about the software.
[22] See the website http://www.esri.com/ for further information about the software.

ArcGIS is a scalable system of software for geographic data creation, management, integration, analysis and dissemination. In particular, the software allows to perform basic map navigation, create interactive maps from file, database and online sources, to perform spatial analysis, to manage geographic data, tabular data and metadata, to discover information not available when working with static paper maps.

4.3.2 FRAGSTATS

Landscape analysis was performed by means of FRAGSTATS, which is a computer software program released in 1995, developed by K. McGarigal and B. Marks of Oregon University, and designed to compute a wide variety of landscape metrics for categorical map patterns.

The landscape subject to analysis is user-defined and can represent any spatial phenomenon. FRAGSTATS simply quantifies the areal extent and spatial configuration of patches within a landscape and performs a wide number of landscape metrics (McGarigal et al., 2002).

4.4 Methods

4.4.1 Images pre-processing

Pre-processing of the images was required in order to suppress unwanted distortions or enhance some image features important for further processing.

Remotely sensed image data are, in fact, representations of the irregular surface of the Earth and therefore need to be georeferenced[23]. In the present study, aiming at a change detection analysis, an accurate georeferentiation was needed, as the more accurate is the georeferentiation the more accurate will be the results obtained by change detection.

Before performing any procedure, Landsat MSS was resampled to 30m × 30m by means of the nearest neighbour technique in order to make the pixel size comparable with that of the two higher spatial resolution images.

In the present study georeferentiation was performed by means of the image-to-image method as the Landsat TM 2000, which was selected as the reference image,

[23] Georeferentiation refers to the process of assigning map coordinates to image data, which may already be projected onto the desired plane, but not yet referenced to the proper coordinate system.

was already georeferenced (table 11). By means of this technique it was possible to make the Landsat MSS 1972 and Landsat TM 1990 fit the Landsat TM 2000.

Projection	UTM[24] - zone 32
Spheroid	WGS[25] 84
Datum	WGS 84

Table 11 - Map parameters.

To perform this operation the first step was the identification of Ground Control Points (GCPs), which are specific pixels in an image for which the output map coordinates are known. GCPs consist of two X, Y pairs of coordinates:

i) source coordinates or data file coordinates in the image being rectified (Landsat MSS 1972 and Landsat TM 1990);

ii) reference coordinates, or coordinates of the reference image to which source image is being registered (Landsat TM 2000).

Accurate GCPs are essential for an accurate georeferentiation. From the GCPs, in fact, the georeferenced coordinates for all other points in the image are extrapolated.

A set of 30 GCPs was selected throughout the scenes for the georeferentiation of the images, in a dispersed way including the intersection of roads, the airport runway of Alghero, buildings and avoiding landmarks that can vary during time (figure 9).

The second step for the georeferentiation was the use of polynomial equations in order to convert source file coordinates to georeferenced map coordinates. The selection of the polynomial equation depends upon the distortion in the imagery, the number of GCPs used and their locations relative to one another. The degree of complexity of the polynomial is expressed as the order of the polynomial. The order is simply the highest exponent used in the polynomial.

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[24] Universe Transverse Mercator (UTM) is an international plane (rectangular) coordinate system developed by the US Army that extends around the world from 84°N to 80°S. The world is divided into 60 zones each covering six degrees longitude. Each zone extends three degrees eastward and three degrees westward from its central meridian. Zones are numbered consecutively west to east from the 180° meridian.

[25] The World Geodetic System (WGS) comprises a standard coordinate frame from the Earth, a standard spheroidal reference surface for raw altitude data and a gravitational equipotential surface (the geoid) that defines the nominal sea level. The latest revision is WGS84 (dating from 1984 and last revised in 2004), which will be valid up to about 2010.

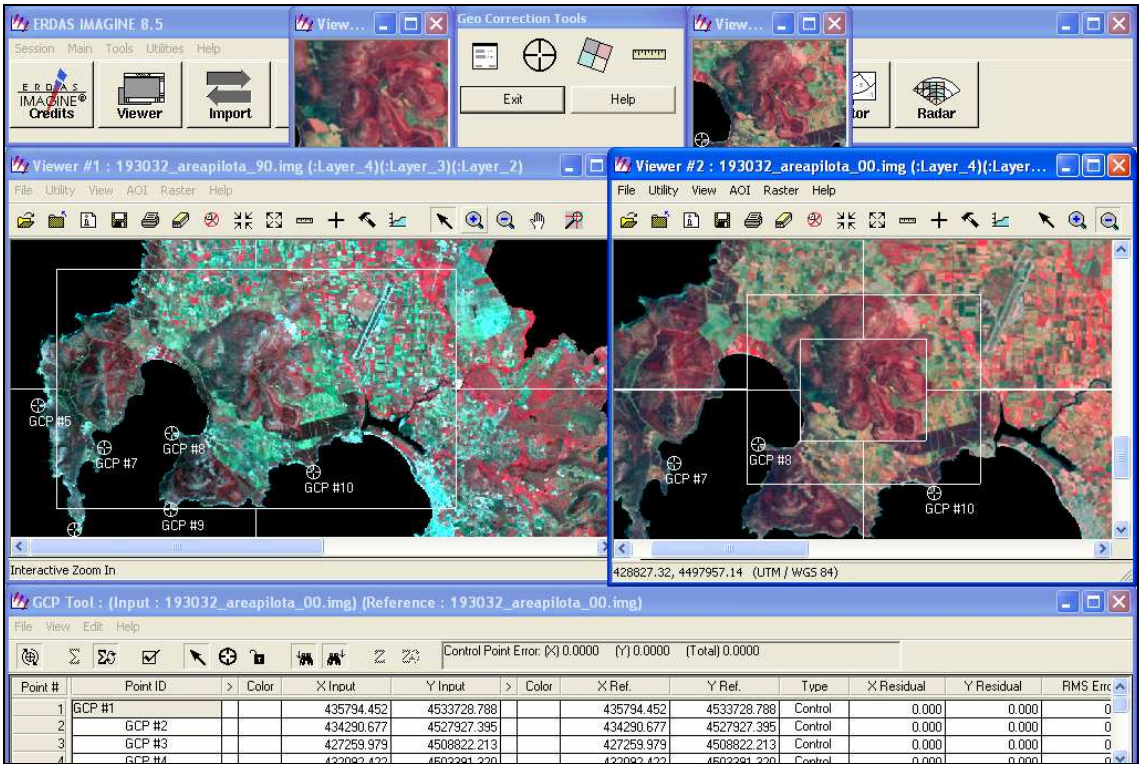

Figure 9 - Georeferentiation of Landsat 1990 to Landsat 2000.

In the present study a 1st-order transformation was used to perform georeferentiation for both the images. This transformation was a linear transformation able to change location in X and/or Y, scale in X and/or Y, skew in X and/or Y and perform rotation.

During the georeferentiation process a Root Mean Square error (RMS) was calculated, representing the distance between the input (source) location of a GCP and the retransformed location for the same GCP. In other words, the RMS error is the difference between the desired output coordinate for a GCP and the actual output coordinate for the same point, when the point is transformed with the geometric transformation.

RMS error was calculated with the following distance equation:

$$RMS\ error = \sqrt{(X_r - X_i)^2 + (Y_r - Y_i)^2}$$

where X_i and Y_i were the input source coordinates and X_r and Y_r were the retransformed coordinates.

RMS was 0,83 pixels for Landsat MSS 1972 and 0,71 pixels for Landsat TM 1990, that means that the reference pixel is 0,83 (24,9 m) and 0,71 pixel (21,3 m) away from retransformed pixel.

For Landsat images an RMS error of less than 1,0 pixel could be considered acceptable, when considering that georeferentiation is accurate within 30 meters.

After georeferentiation the data file values of rectified pixels were resampled to fit into a new grid of pixel rows and columns. Resampling is the process of extrapolating data values for the pixels on the new grid from the values of the source pixels. Although some of the algorithms for calculating these values are highly reliable, some spectral integrity of the data can be lost during rectification.

Among the resampling methods available in ERDAS Imagine, nearest neighbor was selected. With this technique, to determine an output pixel's nearest neighbor, the rectified coordinates (X_0, Y_0) of the pixel are retransformed back to the source coordinate system using the inverse of the transformation. The closest pixel to the retransformed coordinates (Xr, Yr) is the nearest neighbor. The data file values for that pixel become the data file values of the pixel in the output image.

4.4.2 Selection of change detection technique

As described in Chapter I, par. 1.3, many techniques are available in scientific literature for change detection of land cover and landscape. Selection of suitable technique is therefore very important and needs to be implemented on the basis of the results required and the available images.

For the present research we chose the post-classification comparison method among the techniques available in scientific literature.

Post-classification comparison belongs to the "Classification" category and represents a common approach used for change detection in practice. In fact, this technique offers the advantages of minimizing the impacts of atmospheric, sensor and environmental differences between multi-temporal images. It also provides a complete matrix of change information (Mas, 1999; Lu et al., 2004) and is relatively easy to perform.

Post-classification comparison method separately classifies multi-temporal images into thematic maps, then implements comparison of the classified images, pixel by pixel. The classification of each date of imagery builds a historical series that can be more easily updated and used for other applications.

Before implementing this method the main sources of uncertainty were focused.

First of all this approach requires very good accuracy in both classifications because the accuracy of the change map is the product of the accuracies of the individual classifications (Singh, 1989; Lambin and Strahler, 1994). The importance of accurate spatial registration of multi-temporal imagery is obvious because largely spurious results of change detection will be produced if there is misregistration (Townshend et al., 1992; Dai and Khorram, 1998; Stow, 1999; Verbyla and Boles, 2000; Carvalho et al., 2001; Stow and Chen, 2002).

Moreover, if the images used for each classification are from different seasons of the year, the comparison can be more difficult, especially for some legend items due to vegetation phenology.

Furthermore, misregistration of the polygon boundaries in the different classifications could lead to the presence of border pixels with false positive or negative changes.

4.4.3 Images classification

Multispectral classification is the process of sorting pixels of an image into a finite number of individual classes, or categories of data, based on their data file values. If a pixel satisfies a certain set of criteria, the pixel is assigned to the class that corresponds to that criteria.

In the present research supervised classification was employed in order to classify individual images independently, using a unified land cover classification scheme to ensure that the classifications of the multi-temporal images well-matched each other. To perform this process the computer system was trained to recognize patterns in the data. Training is the process of defining the criteria by which these patterns are recognized.

In the present study a supervised training was performed. In this process pixels representing specific land cover features were recognized with the help of ortophotos and available maps.

On the basis of the spatial patterns of interest for our research, we defined our land cover classification scheme as it follows:

i) croplands;

ii) urban areas;

iii) forestlands;

iv) barren areas;

v) wetlands;

vi) water bodies.

Table 12 describes the composition of the map legend defined.

Map legend	Description
Croplands	Arable land Permanent crops Pastures Heterogeneous agricultural areas
Urban areas	Urban fabric Industrial, commercial and transport units Mines and dumps Artificial non-agricultural vegetated areas
Forestlands	Forests Scrub and/or herbaceous vegetation associations
Barren areas	Beaches, dunes and sand Bare rocks Sparsely vegetated areas Burnt areas
Wetlands	Inland wetlands Coastal wetlands
Water bodies	Continental waters Marine waters

Table 12 - Description of the map legend.

By identifying specific patterns, the computer system was then instructed in order to identify pixels with similar characteristics.

The result of training was a set of signatures defining training samples representative of the class to be identified. For each class a set of about 50 training sample was identified.

After the signatures were defined, the pixels of the image were sorted into classes based on the signatures by use of a classification rule[26].

Parametric decision rule was trained by the parametric signatures. These signatures are defined by the mean vector and covariance matrix for the data file values of the pixels in the signatures. When a parametric decision rule is used, every pixel is assigned to a class since the parametric decision space is continuous.

Once the signatures have been created they were evaluated in order to merge or delete unwanted signatures. The alarm evaluation technique was used to compare an estimated classification of one or more signatures against the original data. According to the decision rule, the pixels that fitted the classification criteria were highlighted in the displayed image.

Training was repeated several times before the desired signatures were produced. Once a set of reliable signatures was created and evaluated, the next step was to perform a classification of the data. In this process each pixel was analysed independently.

The measurement vector for each pixel was compared to each signature, according to the decision rule. Pixels that passed the criteria that were established by the decision rule were then assigned to the class for that signature.

The maximum likelihood algorithm was here applied to parametric signatures, which are based on statistical parameters of the pixels that are in the training sample. The maximum likelihood algorithm is a common use classifier. Based on statistics (mean and variance/covariance), a probability function[27] is calculated from the inputs for classes established from training sites. Each pixel is then judged as to the class to which it most probably belongs.

After the classification was performed the accuracy of the classification was evaluated by comparing it to geographical data that were assumed to be true (ground truth). The accuracy report calculated statistics of the percentage of accuracy, based upon the results of the error matrix[28]. Determining the accuracy of the current map

[26] The decision rule is a mathematical algorithm that, using data contained in the signature, performs actual sorting of pixels into distinct class values.

[27] Bayesian function.

[28] The error matrix simply compares the reference points to the classified points in a $c \times c$ matrix, where c is the number of classes.

was a necessary step in assigning appropriate confidence in the map products. The classification accuracy obtained for each image, was respectively: 83% for Landsat 1972, 88% for Landsat 1990 and 92% for Landsat 2000. Accuracies higher than 80% are generally considered good.
The nominal scale of the maps obtained by the Landsat images was 1:100.000.

4.4.4 Land cover change maps

Following the post-classification procedure, the identification of land cover changes was performed by comparing two-by-two the land cover maps obtained.
Land cover change was here interpreted as a conversion of the area of a land cover class or its part to another land cover class (APAT, 2005; EC, 2005).
For this purpose ArcGIS8 was used. The intersection tool of ArcGIS8 allowed the intersection of the two layers, in which the input layer was cut with the features from the overlay layer to produce the output land cover change map with features that had attributes data from both layers. The output from this geoprocessing operation[29] was in the same coordinate system as the data frame. In this case the layers used in the geoprocessing operation were in the same coordinate system, thus assuring the most accurate result.

After the geoprocessing a new field denominated Area was added in order to calculate the new values of the area of each polygon of change. In such a way the attribute table contained the Gridcode of the first map, indicating its land cover class, the Gridcode of the second map, indicating its land cover class, and the area of the polygons of change. The land cover trajectories, the area of change and the percentage of change were thus derived from the attribute table of the land cover change map.
According to CLC standard, land cover changes were mapped only if the area of the change was larger than 5 ha (EC, 2005).

[29] Geoprocessing is a GIS operation used to manipulate GIS data. A typical geoprocessing operation takes an input dataset, performs an operation on that dataset and returns the result of the operation as an output dataset. Common geoprocessing operations include geographic feature overlay, feature selection and analysis, topology processing, raster processing and data conversion.

4.4.5 Land cover change trajectories

In this study the term land cover change trajectory refers to successions of land cover types over more than two observations.

Land cover change maps represented the source for the analysis of land cover change trajectories. Based on the classification scheme, all possible land cover change trajectories are illustrated in figure 10.

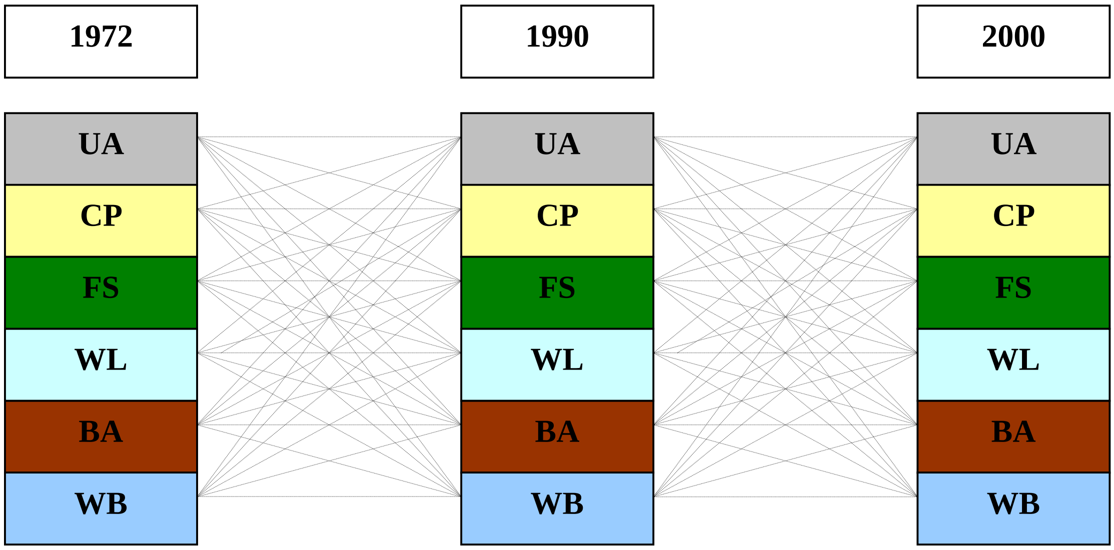

Figure 10 - All possible land cover change trajectories identified for the study area. UA = urban areas; CP = croplands; FS = forestlands; WL = wetlands; BA = barren areas; WB = water bodies.

A trajectory can be specified as FS -> CP -> UA, meaning that the land was found to be forestlands (FS) in 1972, croplands (CL) in 1990 and urban area (UA) in 2000 (Zhou Q. et al., 2008).

In this study we considered two broad categories of changes: changes that could potentially lead to land degradation and changes that could prevent it.

The following changes were attributed to the first category, denominated "negative":

i) urban driven changes;

ii) changes towards an enlargement of croplands;

iii) occurrence of barren areas;

and the following changes were attributed to the second category, denominated "positive":

i) gain of forests;

ii) increase in water bodies extension.

Obviously this classification is not absolute. Changes towards an enlargement of croplands are not necessarily negative so as the transformation from croplands to forestlands. In some cases in fact croplands could play a positive role in preserving soil characteristics and functions.

4.4.5 Landscape analysis

The first step before implementing any landscape-level research requires the definition of the landscape, and this is of course a prerequisite to quantifying landscape patterns and interpreting the results. In the present study the definition of landscape by Forman and Godron (1986), as "*a heterogeneous land area composed of a cluster of interacting ecosystems that is repeated in similar form throughout*" was assumed. In this case the landscape, spatially corresponding to the study area, could be considered as heterogeneous land area composed of a cluster of interacting different ecosystems: the urban ecosystems, the forest ecosystems, the agricultural ecosystems, the wetlands ecosystems and the aquatic ecosystems.

The second step was the definition of landscape units or patches. Like the landscape, patches must be defined relative to the phenomenon under consideration in order to specify which are the units that make up the landscape, otherwise the landscape patterns detected will have little meaning and there could be a good chance of reaching erroneous conclusions.

In the present research, the patch was defined by the pixels belonging together to one land cover class of the classified satellite image and delimiting an isolated structure with respect to the surrounding context (figure 11).


Figure 11 - Example of forest patch in the croplands matrix.

As the pattern detected in any ecological mosaic is a function of scale, the third step was to define the spatial scale. The ecological concept of spatial scale encompasses both extent and grain (Forman and Godron 1986; Turner, 1989; Wiens, 1989): *extent* is the overall area encompassed by an investigation or the area included within the landscape boundary, *grain* is the size of the individual units of observation. Extent and grain define the upper and lower limits of resolution of a study: it is not possible to detect patterns beyond the extent of the landscape or below the resolution of the grain (Wiens, 1989). In this research, extent and grain were dictated by the scale of the maps obtained by the processing of Landsat imagery (1:100.000): the extent corresponded to the study area and the grain to the spatial resolution of the images.

After the definition of the scale a list of detectable patterns, which were a function of the scale of investigation, was performed in order to better capture the phenomenon under consideration. Of the various processes related to desertification, only some were detectable at the scale of investigation: urban sprawl, forest fragmentation and change in landscape structure.

The preliminary definition of these basic concepts was required in order to get an acute awareness of the landscape context to be investigated.

The operational phase took the land cover maps resulting from the previous classification procedure as the sources of further procedures. Land cover maps represented the source map for landscape analysis and for landscape dynamic evaluation during the study period.

For this purpose, the three land cover maps of 1972, 1990 and 2000 were converted into GRID format and used as the input image into the FRAGSTATS software.

The following step required the appropriate parameters to be set. In this phase the input grid, the input data type, the analysis type, the class properties file and the levels of metrics to be computed, were defined.

The next step was to select the patch, class and landscape metrics and to define, in specific cases, the additional parameters required before the computation.

For this purpose, based on the most recent literature available on this issue we chose specific single landscape configuration and composition metrics able to capture the spatial patterns of our interest (table 13) and we therefore composed appropriate set of metrics able to reinforce the interpretation required.

LANDSCAPE COMPOSITION		**LANDSCAPE CONFIGURATION**	
Class level	**Landscape level**	**Class level**	**Landscape level**
NP	NP	LSI	LSI
PD	PD	ENN_MN	ENN_MN
AREA_MN	AREA_MN	IJI	IJI
LPI	LPI	COHESION	COHESION
			SHDI

Table 13 - Landscape metrics performed at class and landscape level. NP = Number of Patches; PD = Patch Density; AREA_MN = Mean Patch Area; LPI = Largest Patch Index; LSI = Landscape Shape Index; ENN_MN = Mean Euclidean Nearest Neighbor Distance; IJI = Interspersion and Juxtaposition Index; COHESION = Cohesion Index; SHDI = Shannon’s Diversity Index

In this way, we experimented fresh landscape analysis in the study area and combined our landscape indicators with the findings coming from the MEDALUS methodology for a comprehensive understanding of the processes that have occurred in the area investigated.

4.4.6 Landscape composition metrics at class level

Landscape composition at class level was analysed by means of the following landscape metrics: Number of Patches (NP), Patch Density (PD), Mean Patch Area (AREA_MN) and Largest Patch Index (LPI).

Number of Patches belongs to the landscape metric category "Area/density/edge metrics"[30] and its formula is:

$$NP = n_i$$

where n_i = number of patches in the landscape of patch type (class) i.

NP equals the number of patches of the corresponding patch type (class) and can be larger than 1, without limit. NP is equal to 1 when the landscape contains only one patch of the corresponding patch type, that is when the class consists of a single patch. NP of a particular patch type is a simple measure of the extent of subdivisions or fragmentation of the patch type.

Although the number of patches in a class may be fundamentally important to a number of ecological processes, often it has limited interpretative value by itself because it conveys no information about area, distribution or density of patches. Of course, if total landscape area and class area are held constant, then number of patches conveys the same information as Patch Density or Mean Patch Area and may be a useful index to interpret.

Patch Density belongs to the landscape metric category "Area/Density/Edge metrics" and its formula is:

$$PD = n_i / A\ (10.000)\ (100)$$

where:

n_i = number of patches in the landscape of patch type (class) i;

A = total landscape area (m^2).

PD equals the number of patches of the corresponding patch type divided by total landscape area (m^2), multiplied by 10.000 and 100 (to convert to 100 hectares).

The unit is number/100 hectares and values are larger than 0.

[30] Landscape metrics computed in FRAGSTATS are grouped according to the aspect of landscape pattern measured. The categories are: Area/density/edge metrics; Shape metrics; Core area metrics; Isolation/proximity metrics; Contrast metrics; Contagion/interspersion metrics; Connectivity metrics and Diversity metrics.

Patch Density is a limited, but fundamental, aspect of landscape pattern. It has the same basic utility as number of patches as an index, except that it expresses number of patches on a per unit area basis that facilitates comparisons among landscape of varying size. Like number of patches, PD often has limited interpretative value by itself because it conveys no information about the sizes and spatial distribution of patches.

Mean Patch Area belongs to the landscape metric category "Area/Density/Edge metrics". The formula for the area computation is:

$$AREA = a_{ij} (1/10.000)$$

where a_{ij} = area (m^2) of patch ij.

AREA equals the area (m^2) of the patch, divided by 10.000 (to convert to hectares). The units are in hectares (ha) and values are larger than 0, without limit.

The area of each patch comprising a landscape mosaic is perhaps the single most important and useful piece of information contained in the landscape. Not only is this information the basis for many of the patch, class and landscape indices, but patch area has a great deal of ecological utility in its own right.

The formula for AREA_MN is:

$$MN = \Sigma j = 1 \text{->} n \ x_{ij} / n_i$$

Mean equals the sum of the patch area, across all patches of the corresponding patch type, divided by the number of patches of the same type. MN is given in the same units as the corresponding patch metric (ha). This landscape metric could be indicative of a fragmentation process, particularly if associated with other metrics.

Largest Patch Index belongs to the landscape metric category "Area/Density/Edge metrics" and its formula is:

$$LPI = \max (a_{ij}) \ j = 1 \text{->} n / A$$

where:

a_{ij} = area (m^2) of patch ij;

A = total landscape area (m^2).

LPI equals the area (m^2) of the largest patch of the corresponding patch type divided by total landscape area (m^2), multiplied by 100 (to convert to a percentage).

In other words LPI equals the percentage of the landscape comprised by the largest patch. It is expressed in percent and the values range from 0 to 100.

LPI approaches 0 when the largest patch of the corresponding patch type is increasingly small. LPI is equal to 100 when the entire landscape consists of a single patch of the corresponding patch type, that is when the largest patch comprises 100% of the landscape. As such it is a simple measure of dominance (McGarigal et al., 2002).

4.4.7 Landscape configuration metrics at class level

Landscape configuration at class level was analysed by means of the following landscape metrics: Landscape Shape Index (LSI), Mean Euclidean Nearest-Neighbor Distance (ENN_MN), Interspersion and Juxtaposition Index (IJI) and Patch Cohesion Index (COHESION).

Landscape Shape Index belongs to the landscape metric category "Area/density/edge metrics" and its formula is:

$$LSI = e_i / \min e_i$$

where:

e_i = total length of edge (or perimeter) of class i in terms of number of cell surfaces;

min e_i = minimum total length of edge (or perimeter) of class i in terms of number of cell surfaces.

LSI equals the total length of edge (or perimeter) involving the corresponding class, given in number of cell surfaces, divided by the minimum length of class edge (or perimeter) possible for a maximally aggregated class, also given in number of cell surfaces, which is achieved when the class is maximally clumped into a single, compact patch. If a_i is the area of class i (in terms of number of cells) and n is the side of the largest integer square smaller than a_i and $m = a_i – n^2$, then the minimum edge or perimeter of class i, min-e_i, will take one of the three forms:

i) min-e_i = 4n, when m = 0, or

ii) min-e_i = 4n + 2, when $n^2 < a_i \leq n (1+n)$, or

iii) min-e_i = 4n + 4, when $a_i > n (1+n)$.

LSI is larger than 1, without limit and is equal to 1 when the landscape consists of a single square or maximally compact (i.e., almost square) patch of the corresponding type. LSI increases without limit as the patch type becomes more disaggregated (i.e., length of edge within the landscape of the corresponding patch type increases).

LSI provides a simple measure of class aggregation or clumpiness.

Mean Euclidean Nearest-Neighbor Distance belongs to the landscape category “Isolation/proximity metrics”. The formula for the distance is:

$$ENN = h_{ij}$$

where, h_{ij} = distance (m) from patch ij to nearest neighboring patch of the same type (class), based on patch edge-to-edge distance, computed from cell center to cell center.

ENN equals the distance in meters to the nearest neighboring patch of the same type, based on shortest edge-to-edge distance. The units are meters.

ENN is larger than 0, without limit and it approaches 0 as the distance to the nearest neighbor decreases. The minimum ENN is constrained by the cell size and is equal to twice the cell size when the 8-neighbor patch rule is used or the distance between diagonal neighbors when the 4-neighbor rule is used. The upper limit is constrained by the extent of the landscape. ENN is undefined if the patch has no neighbors (i.e., no other patches of the same class).

Euclidean nearest-neighbor distance is perhaps the simplest measure of patch context and has been used extensively to quantify patch isolation.

Here, nearest neighbor distance is defined using simple Euclidean geometry as the shortest straight-line distance between the focal patch and its nearest neighbor of the same class.

The Mean (MN) value is calculated as it follows:

$$MN = \Sigma j = 1\text{->}n \; x_{ij} / n_i$$

MN equals the sum, across all patches of the corresponding patch type, of the corresponding patch metric values, divided by the number of patches of the same type. MN is given in the same units as the corresponding patch metric.

Interspersion and Juxtaposition Index IJI belongs to the landscape metric category “Contagion/interspersion metrics” and its formula is:

$$\text{IJI} = \frac{-\sum_{k=1}^{m}\left[\left(\frac{e_{ik}}{\sum_{k=1}^{m} e_{ik}}\right)\ln\left(\frac{e_{ik}}{\sum_{k=1}^{m} e_{ik}}\right)\right]}{\ln(m-1)}(100)$$

where:

e_{ik} = total length (m) of edge in landscape between patch types (classes) i and k;

m = number of patch types (classes) present in the landscape, including the landscape border, if present.

IJI equals minus the sum of the length (m) of each unique edge type involving the corresponding patch type divided by the total length (m) of edge (m) involving the same type, multiplied by the logarithm of the same quantity, summed over each unique edge type; divided by the logarithm of the number of patch types minus 1; multiplied by 100 (to convert to a percentage).

In other words, the observed interspersion over the maximum possible interspersion for the given number of patch types.

The unit is percent and the values range from 0 to 100.

IJI approaches 0 when the corresponding patch type is adjacent to only 1 other patch type and the number of patch types increases. IJI is equal to 100 when the corresponding patch type is equally adjacent to all other patch types (i.e., maximally interspersed and juxtaposed to other patch types).

Interspersion and juxtaposition index is based on patch adjacencies. As such, it isolates the interspersion or intermixing of patch types.

Patch Cohesion Index belongs to the landscape metric category “Connectivity metrics” and its formula is:

$$\text{COHESION} = \left[1-\frac{\sum_{j=1}^{m} p_{ij}}{\sum_{j=1}^{m} p_{ij}\sqrt{a_{ij}}}\right]\left[1-\frac{1}{\sqrt{A}}\right]^{-1}(100)$$

where:

p_{ij} = perimeter of patch ij in terms of number of cell surfaces;

a_{ij} = area of patch ij in terms of number of cells;

A = total number of cells in the landscape.

COHESION equals 1 minus the sum of patch perimeter (in terms of number of cell surfaces) divided by the sum of patch perimeter times the square root of patch area (in terms of number of cells) for patches of the corresponding patch type, divided by 1 minus 1 over the square root of the total number of cells in the landscape, multiplied by 100 to convert to a percentage. The are no units and the values range from 0 to 100.

COHESION approaches 0 as the proportion of the landscape comprised of the focal class decreases and becomes increasingly subdivided and less physically connected.

The index increases monotonically as the proportion of the landscape comprised of the focal class increases until an asymptote is reached near the percolation threshold[31].

COHESION is given as 0 if the landscape consists of a single non-background cell.

The index measures the physical connectedness of the corresponding patch type. It increases as the patch type becomes more clumped or aggregated in its distribution, hence more physically connected (McGarigal et al., 2002).

4.4.8 Landscape composition metrics at landscape level

Landscape composition at landscape level was analysed by means of the following landscape metrics: Number of Patches (NP), Patch Density (PD), Mean Patch Area (AREA_MN) and Largest Patch Index (LPI).

Number of Patches at landscape level is:

$$NP = N$$

where:

N = total number of patches in the landscape;

NP at landscape level has the same meaning and characteristics as NP at the class level.

Patch Density at landscape level is:

[31] From percolation theory, connectedness can be inferred from patch density or be given as a binary response, indicative whether or not a spanning cluster or percolating cluster exists (i.e. a connection of patches of the same class that spans across the entire landscape).

$$PD = N / A (10.000) (100)$$

where:

N = total number of patches in the landscape;

A = total landscape area (m^2).

PD at landscape level has the same meaning and characteristics as NP at the class level.

The Mean of the Patch Area distribution at landscape level is calculated as it follows:

$$MN = \Sigma i = 1\text{->}m\ \Sigma j = 1\text{->}n\ x_{ij} / N$$

The Mean (MN) equals the sum, across all patches in the landscape, of the corresponding patch metric values, divided by the total number of patches. MN is given in the same units as the corresponding patch metric.

Largest Patch Index at landscape level is calculated as it follows:

$$LPI = \max (a_{ij}) / A (100)$$

where:

a_{ij} = area (m^2) of patch ij;

A = total landscape area (m^2).

LPI equals the area (m^2) of the largest patch in the landscape divided by total landscape area (m^2), multiplied by 100 (to convert to a percentage). In other words, LPI equals the percent of the landscape that the largest patch comprises. The units are percent and the values range from 0 to 100. LPI approaches 0 when the largest patch in the landscape is increasingly small. LPI is equal to 100 when the entire landscape consists of a single patch; that is, when the largest patch comprises 100% of the landscape (McGarigal et al., 2002).

4.4.9 Landscape configuration metrics at landscape level

Landscape configuration at landscape level was analysed by means of the following landscape metrics: Landscape Shape Index (LSI), Mean Euclidean Nearest-Neighbor Distance (ENN_MN), Interspersion and Juxtaposition Index (IJI), Patch Cohesion Index (COHESION) and SHannon’s Diversity Index (SHDI).

Landscape Shape Index at landscape level is calculated as it follows:

$$LSI = E / \min E$$

where:

E = total length of edge in landscape in terms of number of cell surfaces;

min E = minimum total length of edge in landscape in terms of number of cell surfaces.

LSI equals the total length of edge in the landscape, given in number of cell surfaces, divided by the minimum total length of edge possible, also given in number of cell surfaces, which is achieved when the landscape consists of a single patch.

If A is the landscape area, including all internal background (in terms of number of cells), and n is the side of the largest integer square smaller than A (denoted int $\sqrt{A}$) and $m = A - n^2$, then the minimum edge or perimeter of the landscape, min-E, will take one of the three forms:

i) min-E = 4n, when m = 0, or

ii) min-E = 4n + 2, when $n^2 < A \leq n(1+n)$, or

iii) min-E = 4n + 4, when $A > n(1+n)$.

LSI has no units and could be larger than 1 without limit.

LSI is equal to 1 when the landscape consists of a single square (or almost square) patch. LSI increases without limit as landscape shape becomes more irregular and/or as the length of edge within the landscape increases.

Landscape Shape Index provides a standardized measure of total edge or edge density that adjusts for the size of the landscape. Specifically as LSI increases, the patches become increasingly disaggregated.

The Mean of Euclidean Nearest Neighbor Distance distribution is calculated by means of the following formula:

$$MN = \Sigma i =1\text{->}m\ \Sigma j =1\text{->}n\ x_{ij} / N$$

MN (Mean) equals the sum, across all patches in the landscape, of the corresponding patch metric values, divided by the total number of patches. MN is given in the same units as the corresponding patch metric.

Interspersion and Juxtaposition Index at landscape level is calculated by means of the following formula:

$$\text{IJI} = \frac{-\sum_{i=1}^{m}\sum_{k=i+1}^{m}\left[\left(\frac{e_{ik}}{E}\right)\ln\left(\frac{e_{ik}}{E}\right)\right]}{\ln(0{,}5[m(m-1)])}(100)$$

where:

e_{ik} = total length (m) of edge in landscape between patch types (classes) i and k;

E = total length (m) of edge in landscape, excluding background;

M = number of patch types (classes) present in the landscape, including the landscape border, if present.

IJI equals minus the sum of the length (m) of each unique edge type divided by the total landscape edge (m), multiplied by the logarithm of the same quantity, summed over each unique edge type; divided by the logarithm of the number of patch types times the number of patch types minus 1 divided by 2; multiplied by 100 (to convert to a percentage). In other words, the observed interspersion over the maximum possible interspersion for the given number of patch types.

Units are in percent and the values range from 0 to 100.

IJI approaches 0 when the distribution of adjacencies among unique patch types becomes increasingly uneven. IJI is equal to 100 when all patch types are equally adjacent to all other patch types (i.e., maximum interspersion and juxtaposition).

Interspersion and juxtaposition index is based on patch adjacencies. As such it isolates the interspersion or intermixing of patch types.

Patch Cohesion Index is calculated by means of the following formula:

$$\text{COHESION} = \left[1-\frac{\sum_{i=1}^{m}\sum_{j=1}^{n}p_{ij}}{\sum_{i=1}^{m}\sum_{j=1}^{n}p_{ij}\sqrt{a_{ij}}}\right]\left[1-\frac{1}{\sqrt{A}}\right]^{-1}(100)$$

where:

p_{ij} = perimeter of patch ij in terms of number of cell surfaces;

a_{ij} = area of patch ij in terms of number of cells;

A = total number of cells in the landscape.

COHESION equals 1 minus the sum of patch perimeter (in terms of number of cells) divided by the sum of patch perimeter times the square root of patch area (in terms of number of cells) for all patches in the landscape, divided by 1 minus 1 over the square root of the total number of cells in the landscape, multiplied by 100 to convert to a percentage. There are no units.

SHannon's Diversity Index belongs to the landscape metric category "Diversity metrics" and is calculated as it follows:

$$SHDI = - \sum_{i=1->m} (P_i * \ln P_i)$$

P_i = proportion of the landscape occupied by patch type (class) i.

SHDI equals minus the sum, across all patch types, of the proportional abundance of each patch type multiplied by that proportion. SHDI can be larger than 0, without limit.

SHDI is equal to 0 when the landscape contains only one patch (i.e., no diversity). SHDI increases as the number of different patch types increases and/or the proportional distribution of area among patch types becomes more equitable. This metric is a popular measure of diversity in community ecology, applied here to landscapes (McGarigal et al., 2002; Bachmann et al., 1998).

4.4.10 Synthetic indexes for the monitoring of forest fragmentation, urbanization and landscape structure change

Some metrics are meaningful when interpreted in conjunction with other metrics. Based on the scientific research literature, we composed specific sets of metrics at class and landscape level in order to improve the understanding of spatial pattern change of interest for the monitoring of desertification and related to forest fragmentation (Geneletti, 2004; Yu and Ng, 2007; Baskent and Kadiogullari, 2007; Gonzalez et al., 2007; Cakir et al., 2008; Kadiogullari and Baskent, 2008), urbanization level (Weng, 2007; Gonzalez et al., 2007; Keles et al., 2008) and landscape structure (Li et al. 2004).

If we think to forest patches as resistant component to desertification, then forest fragmentation weakens this resistance, thus favouring the sensitivity level of the area. Hence, to reinforce the interpretation of forest fragmentation, we chose landscape metrics able to capture the increase in the number of forest patches, the

reduction in their mean area and the decrease in the largest forest area. In addition, we required metrics able to assess the isolation of patches and the variation of the physical connectivity of forest ecosystems.
Therefore we selected the following set of metrics:

Forest fragmentation = NP + AREA_MN + LPI + ENN_MN + COHESION

where:
NP = Number of Patches;
AREA_MN = Mean Patch Area;
LPI = Largest Patch Index;
ENN_MN = Mean Euclidean Nearest Neighbor Distance;
COHESION = Patch Cohesion Index.

Landscape metrics for capturing the spatial pattern of the urbanization degree in areas prone to desertification, were chosen taking into account that the dispersion of buildings leads to a high level of habitat fragmentation. In general, impacts of new buildings may be minor if they are located in close vicinity to existing ones (Gonzalez et al., 2007).
In this sense, urban sprawl was analysed by means of the following set of metrics:

Urbanization level = PD + AREA_MN + ENN_MN + LPI

where:
PD = Patch Density;
AREA_MN = Mean Patch Area;
ENN_MN = Mean Euclidean Nearest Neighbor Distance
LPI = Largest Patch Index.

Finally, the set of metrics for the analysis of landscape structure was composed on the basis of the main findings of Li (2004). In particular, we combined together landscape metrics able to capture the various aspects of landscape demonstrated to be linked to land degradation and desertification, such as landscape fragmentation, land cover diversity and irregularity of patches. Land cover diversity, in particular, is relevant to desertification if we assume that a greater land use diversity, in terms of small and contiguous plots of different land uses, generally implies a smaller risk of land degradation and higher biodiversity (Desertlinks, 2005). The following landscape metrics were therefore used for this purpose:

$$\text{Landscape structure} = NP + AREA\_MN + SHDI + LSI + ENN\_MN$$

where:

NP = Number of Patches;

AREA_MN = Mean Patch Area;

SHDI = SHannon's Diversity Index;

LSI = Landscape Shape Index;

ENN_MN = Mean Euclidean Nearest Neighbor Distance.

In order to obtain final synthetic indexes for each spatial pattern, for each landscape metric we calculated the variation, percentage-wise, occurred between the two study periods investigated. Then we classified them into six classes and we assigned a score on the basis of the positive or negative trend (table 14).

%	**0 – 20 %**	**20 – 40%**	**40 – 60%**	**60 – 80%**	**80 – 100%**	**> 100%**
Positive	0	+ 1	+ 2	+ 3	+ 4	+ 5
Negative	0	- 1	- 2	- 3	- 4	- 5

Table 14 – Classes and scores for the variation of the landscape metrics.

The final indexes were then calculated by means of the algebraic sum of the scores and then classified into the following five classes: low (- 25 ÷ –15), medium – low (- 15 ÷ - 5), medium (-5 ÷ + 5), medium – high (+ 5 ÷ + 15), high (+ 15 ÷ 25).

The indexes thus obtained have the potential to reflect in a synthetic value various aspects of the spatial pattern investigated and their variation over time.

5. RESULTS

The present chapter provides a description of the results obtained by means of the methodology described in the previous chapter. The results were analyzed for each municipality and for each land cover class in order to better characterize the spatial patterns as they occurred over time in areas with different sensitivity to desertification.

5.1 Land cover

5.1.1 Land cover classes distribution in the study area

Land cover maps for 1972, 1990 and 2000 were derived from the classification procedure described in the par. 4.4.3 and are illustrated in the figures 12, 13 and 14.

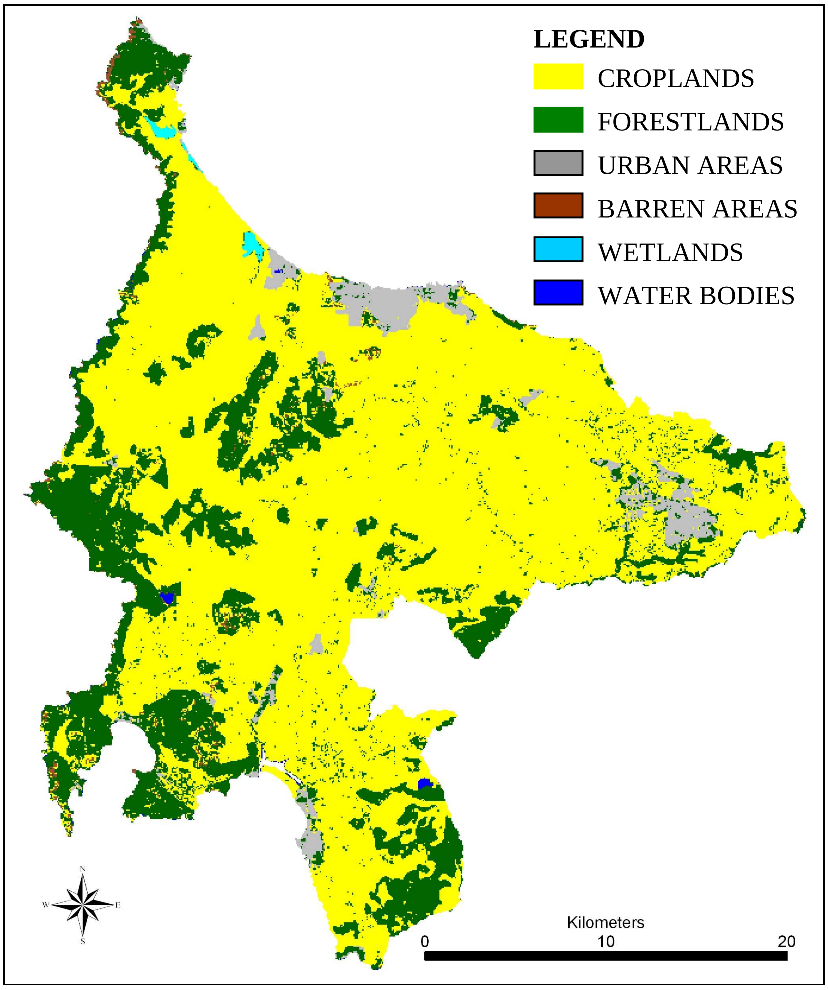

Figure 12 - Land cover map of 1972.

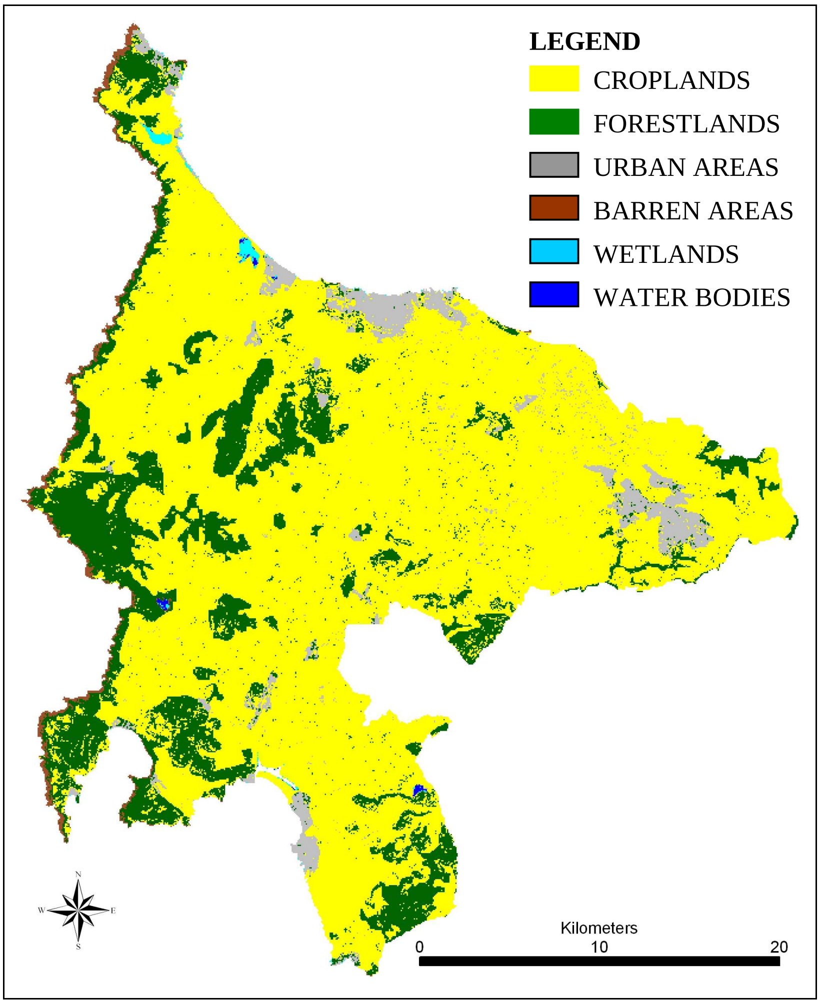

Figure 13 - Land cover map of 1990.

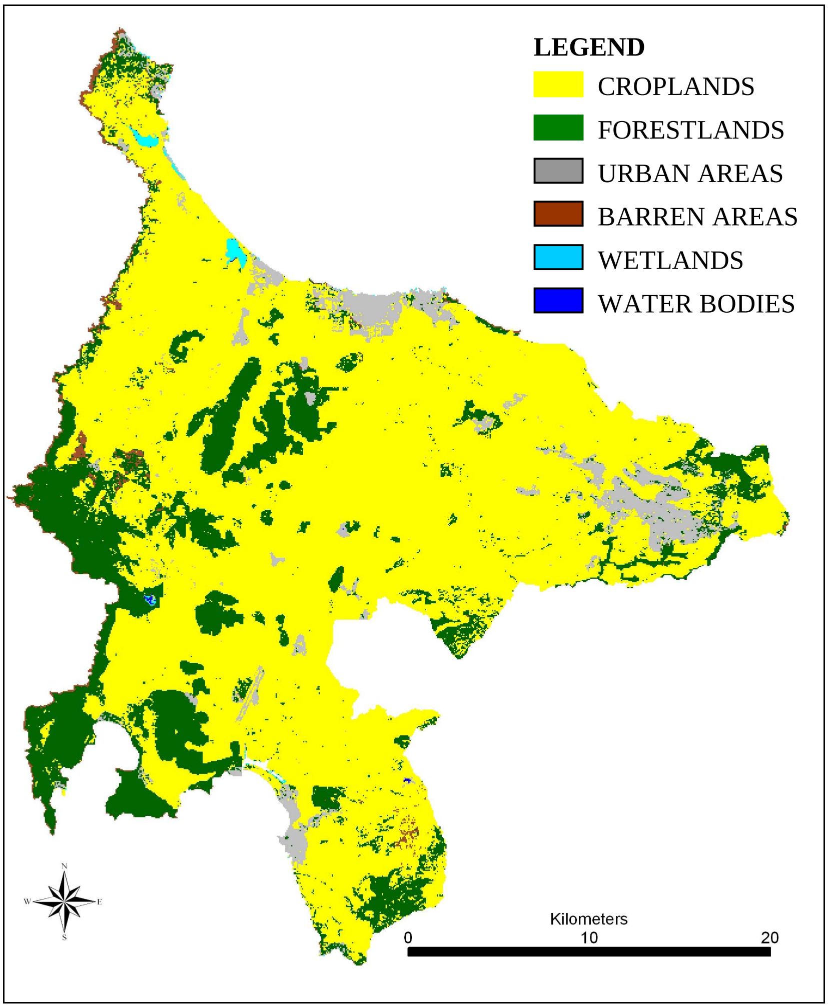

Figure 14 - Land cover map of 2000.

In the study area the landscape was clearly dominated by croplands. As such, croplands can be considered the matrix of the landscape, representing the most extensive and most connected landscape element type and thus playing a dominant role in the functioning of the landscape.

Figures 15, 16 and 17 show the quantitative data obtained for the different land cover classes distribution.

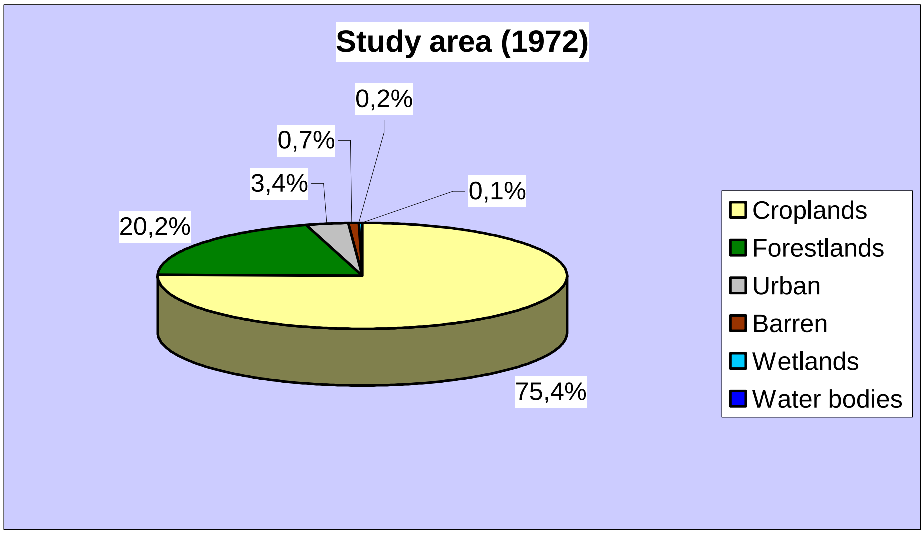

Figure 15 - Land cover classes distribution in 1972 (%).

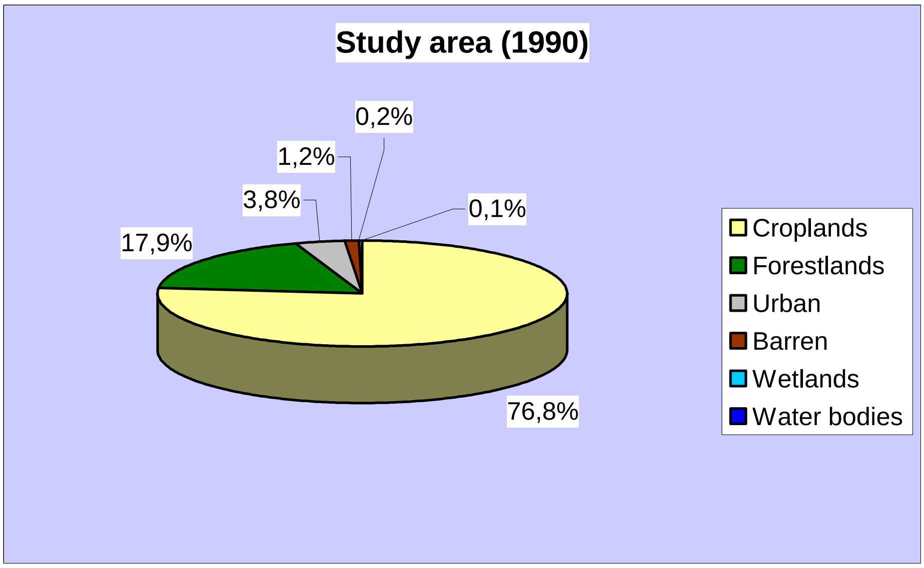

Figure 16 – Land cover classes distribution in 1990 (%).

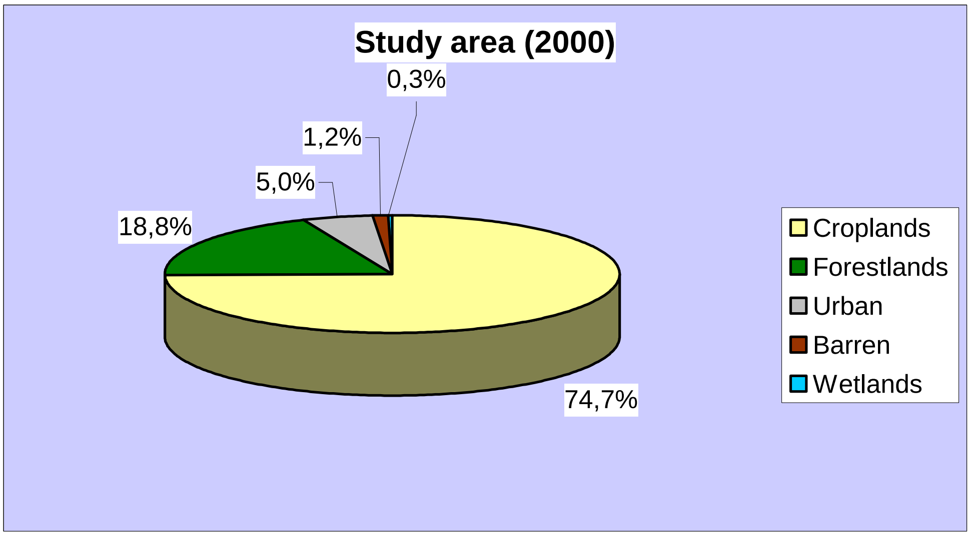

Figure 17 - Land cover classes distribution in 2000 (%).

Over time the land cover classes maintained the same order of importance: croplands, forestlands, urban areas, barren areas, wetlands and water bodies. However, the relative proportion changed.

Croplands rose between 1972 and 1990 (from 75,4% to 76,8%) and decreased between 1990 and 2000 (from 76,8% to 74,7%), with a net loss of 0,7% over the overall period.

Forestlands showed the opposite tendency in comparison with croplands. In fact, forestlands declined between 1972 and 1990 (from 20,2% to 17,9%) and slightly expanded between 1990 and 2000 (from 17,9% to 18,8%), with a net forest loss of 1,4% over the period investigated. According to the compound-interest-rate formula[32] (Puyravaud, 2003) the annual rate of forest change was -0,68% between 1972 and 1990 and 0,46% between 1990 and 2000, with a total annual rate of forest loss of -0,27% between 1972 and 2000.

Urban areas were the third land cover class in the area investigated and showed a continuous trend to rise, with a significant growth in particular between 1990 and 2000. In fact, urban areas grew from 3,4% to 3,8% between 1972 and 1990 and expanded considerably to 5,0% in 2000, with a net gain of 1,6%. According to Yu

[32] Annual rate of forest change was calculated with the following formula: $P = 100 / t_2 - t_1 \ln A_2 / A_1$ where P is percentage of forest loss per year, and A_1 and A_2 are the corrected forest cover estimates at time t_1 and t_2, respectively.

and Ng (2007) annual urban growth[33] was 21,8 ha/year between 1972 and 1990, 107,6 ha/year between 1990 and 2000, with a total of 52,5 ha/year over the period analysed.

Barren areas, wetlands and water bodies covered a minor part of the study area.

Barren areas showed a relevant expansion between 1972 (0,7%) and 1990 (1,2%) and maintained constant values between 1990 and 2000 (1,2%), with a net increase of 0,5% over the overall period.

Any significant changes in the extension of wetlands were measured between 1972 and 1990, but a slight enlargement between 1990 and 2000 (0,3%) was registered. Water bodies suffered from a slight reduction between 1990 and 2000, almost approaching the complete disappearance in 2000.

5.1.2 Land cover classes distribution by municipality

Taking into account that each municipality in the study area showed a different level of sensitivity to desertification (see par. 3.2), we analysed the land cover classes distribution by municipality.

In table 15 the land cover classes distribution observed in the municipality of Alghero is illustrated.

	1972		**1990**		**2000**		**Var %**	**Var %**	**Var %**
	ha	**%**	**ha**	**%**	**ha**	**%**	**72 - 90**	**90 - 00**	**Tot.**
Croplands	14.909,5	*66,2*	15.830,4	*70,3*	15.454,5	*68,6*	*+ 6,2*	*- 2,4*	*+ 3,7*
Forestlands	6.884,9	*30,6*	5.745,8	*25,5*	6.009,3	*26,7*	*- 16,5*	*+ 4,6*	*- 12,7*
Urban a.	574,2	*2,6*	660,9	*2,9*	773,3	*3,4*	*+ 15,1*	*+ 17,0*	*+ 34,7*
Barren a.	117,8	*0,5*	249,3	*1,1*	249,3	*1,1*	*+ 111,6*	-	*+ 111,6*
Wetlands	1,0	*0,0*	1,0	*0,0*	20,0	*0,1*	-	*+ 1900,0*	*+ 1900,0*
Water b.	26,2	*0,1*	26,2	*0,1*	7,2	*0,0*	-	*- 72,5*	*- 72,5*

Table 15 - Land cover classes distribution in the municipality of Alghero.

[33] Annual urban growth was calculated with the following formula: UAi+n – Uai / n where n is the interval of the calculating period (in years); UAi+n and UAi are the urban built-up areas at time i+1 and 1, respectively.

Croplands consistently enlarged from 66,2% (14.909,5 ha) to 70,3% (15.830,4 ha) between 1972 and 1990 and then diminished to 68,6% (15.454,5 ha) in 2000, with a net gain of 2,4% over the period analysed. Croplands in this area, percentage-wise, were lower when compared to the values obtained for the study area.

Forestlands declined from 30,6% (6.884,9 ha) in 1972 to 25,5% (5.745,8 ha) in 1990 and rose to 26,7% (6.009,3 ha) in 2000, with a net reduction of 3,9%. The municipality of Alghero showed a higher percentage of forestlands compared to the overall study area.

Urban areas grew from 2,6% (574,2 ha) to 2,9% (660,9 ha) between 1972 and 1990 and expanded up to 3,4% (773,3 ha) between 1990 and 2000, with a net growth of 0,8%. These values, percentage-wise, were lower when compared to the extension of urban areas in the study area.

Barren areas expanded from 0,5% (117,8 ha) to 1,1% (249,3 ha) and maintained the same extension in 2000. Wetlands and water bodies covered very small areas.

Table 16 illustrates the land cover classes distribution registered in the municipality of Sassari.

	1972		1990		2000		Var % 72 - 90	Var % 90 - 00	Var % Tot.
	ha	%	ha	%	ha	%			
Croplands	43.577,0	*79,5*	43.729,8	*79,7*	42.352,0	*77,2*	*+ 0,4*	*- 3,2*	*- 2,8*
Forestlands	9.469,9	*17,3*	8.970,7	*16,4*	9.451,2	*17,2*	*- 5,3*	*+ 5,4*	*- 0,2*
Urban a.	1.338,2	*2,4*	1.494,2	*2,7*	2.371,6	*4,3*	*+ 11,7*	*+ 58,7*	*+ 77,2*
Barren a.	324,4	*0,6*	514,8	*0,9*	534,7	*1,0*	*+ 58,7*	*+ 3,9*	*+ 64,8*
Wetlands	97,3	*0,2*	103,2	*0,2*	119,8	*0,2*	*6,1*	*16,1*	*23,1*
Water b.	39,0	*0,1*	33,1	*0,1*	16,5	*0,0*	*- 15,1*	*- 50,2*	*-57,7*

Table 16 - Land cover classes distribution in the municipality of Sassari.

In the municipality of Sassari croplands showed higher values, percentage-wise, compared to the values measured in the study area. Croplands enlarged from 79,5% (43.577,0 ha) in 1972 to 79,7% (43.729,8 ha) in 1990 and then decreased to 77,2% (42.352,0 ha) in 2000, with a net loss of 2,3%.

Forestlands showed lower values, percentage-wise, than those assessed in the study area. The extension of forests declined from 17,3% (9.469,9 ha) in 1972 to 16,4% (8.970,7 ha) in 1990 and expanded to 17,2% (9.451,2 ha) over the second period investigated, with a net loss of 0,1%.

Urban areas showed lower values, percentage-wise, than those obtained for the study area, with a growth from 2,4% (1.338,2 ha) in 1972 to 2,7% (1.494,2 ha) in 1990 and a further strong expansion to 4,3% (2.371,6 ha) between 1990 and 2000, with a net gain of 1,9%.

Barren areas showed an increase from 0,6% (324,4 ha) in 1972 to 0,9% (514,8 ha) in 1990 and a subtle increase between 1990 and 2000 (1,0%).

In table 17 the land cover classes distribution observed in the municipality of Stintino is displayed.

	1972		**1990**		**2000**		**Var % 72 - 90**	**Var % 90 - 00**	**Var % Tot.**
	ha	***%***	**ha**	***%***	**ha**	***%***			
Croplands	4.680,9	*78,8*	4.766,3	*80,2*	4.831,3	*81,3*	*+ 1,8*	*+ 1,4*	*+ 3,2*
Forestlands	986,8	*16,6*	612,6	*10,3*	505,9	*8,5*	*- 37,9*	*- 17,4*	*- 48,7*
Urban a.	63,0	*1,1*	188,8	*3,2*	228,3	*3,8*	*+ 199,7*	*+ 20,9*	*+ 262,4*
Barren a.	105,6	*1,8*	271,8	*4,6*	271,8	*4,6*	*+ 157,4*	-	*+ 157,4*
Wetlands	100,9	*1,7*	100,1	*1,7*	100,1	*1,7*	*+ 0,8*	-	*- 0,8*
Water b.	3,5	*0,1*	1,1	*0,0*	3,3	*0,1*	*- 68,6*	*+ 200,0*	*- 5,7*

Table 17 – Land cover classes distribution in the municipality of Stintino.

In the municipality of Stintino croplands showed higher values, percentage-wise, compared to those observed in the study area. The agricultural areas expanded from 78,8% (4.680,9 ha) to 80,2% (4.766,3 ha) between 1972 and 1990, and reached 81,3% (4.831,3 ha) in 2000, with a net expansion of 2,5%.

Forest extension was significantly lower than the extension observed in the study area. Forestlands, in fact, dramatically dropped from 16,6% (986,8 ha) in 1972 to 10,3% (612,6 ha) in 1990 and suffered from a further reduction to 8,5% (505,9 ha) over the decade 1990-2000, with a significant net forest loss of 8,1%. These values clearly indicate that the municipality of Stintino is the only municipality in which forestlands showed a continuous tendency to decrease, with a halving of the resources over the period analysed.

Urban areas were lower, percentage-wise, than those evaluated in the study area and rose from 1,1% (63,0 ha) in 1972 to 3,2% (188,8 ha) in 1990 and successively from 3,2% to 3,8% (228,3 ha), with a net expansion of 2,7%.

In the municipality of Stintino barren areas and wetlands covered a relevant portion of the territory with values of respectively 1,8% (105,6 ha) in 1972, 4,6% (271,8 ha) in 1990 and 4,6% in 2000 and 1,7% (100,9 ha) over the study period.

Land cover classes distribution observed in the municipality of Porto Torres is illustrated in table 18.

	1972		**1990**		**2000**		**Var %**	**Var %**	**Var %**
	ha	**%**	**ha**	**%**	**ha**	**%**	**72 - 90**	**90 - 00**	**Tot.**
Croplands	3.529,1	*68,5*	3.577,1	*69,5*	3.505,1	*68,1*	*+ 1,4*	*- 2,0*	*- 0,7*
Urban a.	1.010,2	*19,6*	1.034,7	*20,1*	1.081,8	*21,0*	*+ 2,4*	*+ 4,6*	*+ 7,1*
Forestlands	561,7	*10,9*	506,3	*9,8*	518,1	*10,1*	*- 9,9*	*+ 2,3*	*- 7,8*
Barren a.	47,0	*0,9*	28,6	*0,6*	39,4	*0,8*	*- 39,1*	*+ 37,8*	*- 16,2*
Wetlands	1,0	*0,0*	3,4	*0,1*	4,8	*0,1*	*+ 240,0*	*41,2*	*+ 380,0*
Water b.	1,0	*0,0*	-	-	0,9	*0,0*	*- 100*	-	*-10,0*

Table 18 - Land cover classes distribution in the municipality of Porto Torres.

In this area, croplands and forestlands were significantly narrow compared to those assessed in the study area and urban areas were significantly more extended than those estimated in the study area (up to more than four times). The municipality of Porto Torres is the only municipality in which urban areas represented the second land cover class in terms of extension.

Croplands expanded from 68,5% (3.529,1 ha) in 1972 to 69,5% (3.577,1 ha) in 1990 and successively diminished to 68,1% (3.505,1 ha). Forestlands lowered from 10,9% (561,7 ha) in 1972 to 9,8% (506,3 ha) in 1990 and rose to 10,1% (518,1 ha) in 2000.

Urban areas expanded from 19,6% (1.010,2 ha) in 1972 to 20,1% (1.034,7 ha) in 1990 and further enlarged to 21,0% (1.081,8 ha) over the decade 1990-2000.

Barren areas, wetlands and water bodies showed very slight values.

5.1.3 Land cover change maps

As described in the par. 4.4.4 land cover change maps were performed by intersecting two-by-two the land cover maps obtained. Only changes larger than 5 ha were included in the maps.

In figures 18 and 19 the land cover change maps are displayed.

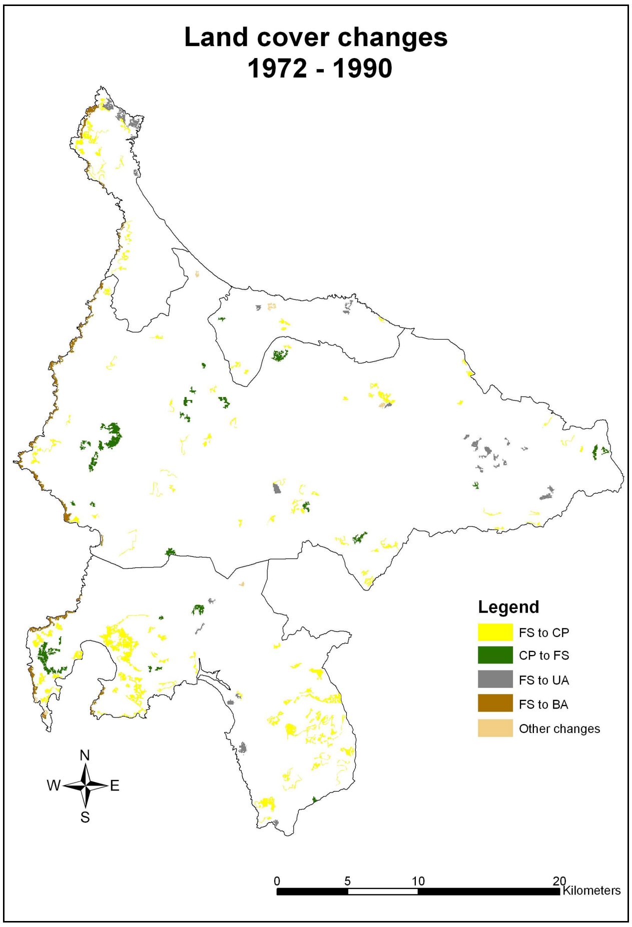

Figure 18 - Land cover change map (1972–1990). FS = Forestlands; CP = Croplands; UA = Urban areas; BA = Barren areas.

As seen in figure 18 between 1972 and 1990 different types of changes took place in the study area, covering about 3,7 % (3227,8 ha) of the total area. A visual analysis of the map clearly indicates that in the municipality of Alghero the conversion from forestlands to croplands was sparsely distributed over the territory. The loss of forests was highly concentrated along the western coast, where new barren areas were identified. New settlements occurred, in particular, around the urban centres of Sassari, Stintino and Alghero.

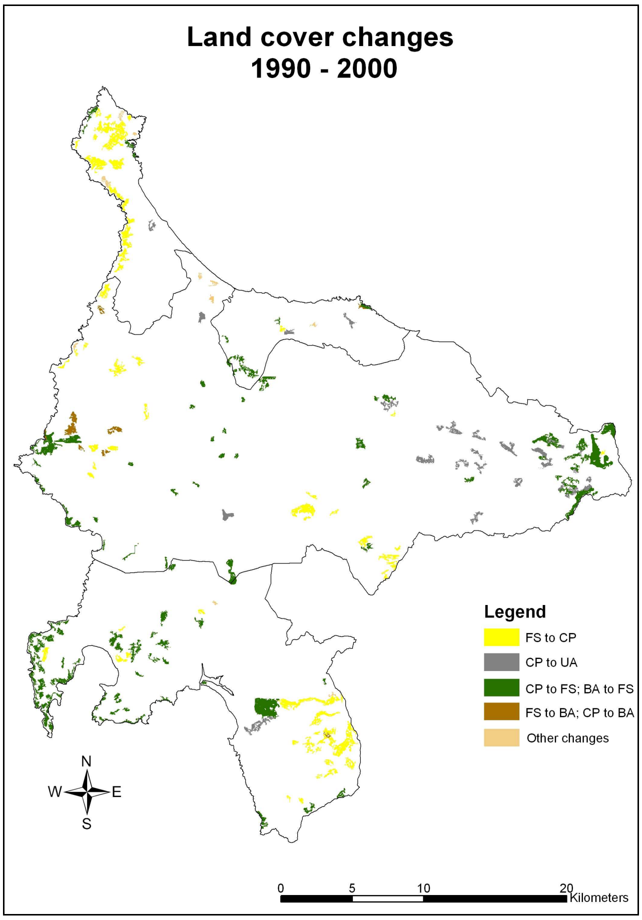

Figure 19 - Land cover change map (1990–2000). FS = Forestlands; CP = Croplands; UA = Urban areas; BA = Barren areas.

Between 1990 and 2000, 4,9% (4367,2 ha) of the total area showed changes, thus indicating an accelerating trend of change in the study area.

Over this period forests were partially recovered, in particular in the eastern part of the municipality of Sassari and along the coastal areas of the municipality of Alghero. New urban settlements were identified in particular around the city of Sassari.

In the municipality of Stintino new croplands and barren areas were identified on the western side. Between 1990 and 2000 the conversion from forestlands to croplands dominated the landscape evolution, in particular in the northern and eastern part of the area.

5.1.4 Land cover change trajectories in the study area

The elaboration of the results obtained by the land cover change maps were useful in order to analyze the land cover change trajectories over the period investigated.

In table 19 the main land cover change trajectories that have occurred in the study area, the change in percentage and hectares, and the type of change are illustrated for the period 1972 – 1990.

Land cover change trajectories (1972 – 1990)	%	ha	Type
FS to CP	54,2	1.748,5	N
CP to FS	19,0	612,5	P
FS to BA	13,6	439,9	N
FS to UA	12,0	387,2	N

Table 19 - Main land cover change trajectories occurred in the study area between 1972 and 1990, percentage, hectares and type of change over the total change. FS = Forestlands; CP = Croplands; BA = Barren areas; UA = Urban areas. N indicates the "Negative" category of change and P indicates the "Positive" one.

As seen in the table the major type of conversion was FS -> CP for about 54,2% of the total change. A further 13,6% of forests changed into barren areas and 12% into urban areas. Also croplands suffered from a wide conversion to forestlands (19,0%).
A large amount of change belonged to the negative category, as about 80% of changes led to the loss of forests.

In table 20 the main land cover change trajectories that have occurred in the study area, the change in percentage and hectares, and the type of change are illustrated for the decade 1990 – 2000.

Land cover change trajectories (1990-2000)	%	ha	Type
CP to FS	42,9	1.873,2	P
FS to CP	32,9	1.437,8	N
CP to UA	13,7	598,8	N
BA to FS	5,2	226,7	P

Table 20 - Main land cover change trajectories occurred in the study area between 1990 and 2000, percentage, hectares and type of change over the total change. FS = Forestlands; CP = Croplands; UA = Urban areas; BA = Barren areas. N indicates the "Negative" category of change and P indicates the "Positive" one.

As seen in the table, 42,9% of the total changes led to the transformation of croplands to forestlands and 32,9% represented the conversion of forestlands to croplands. A further 13,7% was converted from croplands to urban areas and minor changes led to the recover of vegetation over barren areas (5,2%). Over the decade negative and positive changes were rather balanced.

5.1.5 Land cover change trajectories by municipality

The 3227,8 ha of changes which occurred between 1972 and 1990 were subdivided per municipality, as reported in figure 20.

In particular, the larger amount of changes took place in the municipality of Alghero where about 46,7% of the total changes occurred. In the municipality of Sassari this percentage was lower and equal to about 38,6%, while in the municipality of Stintino it was about 12,3% and, finally, in the municipality of Porto Torres it was about 2,5%.

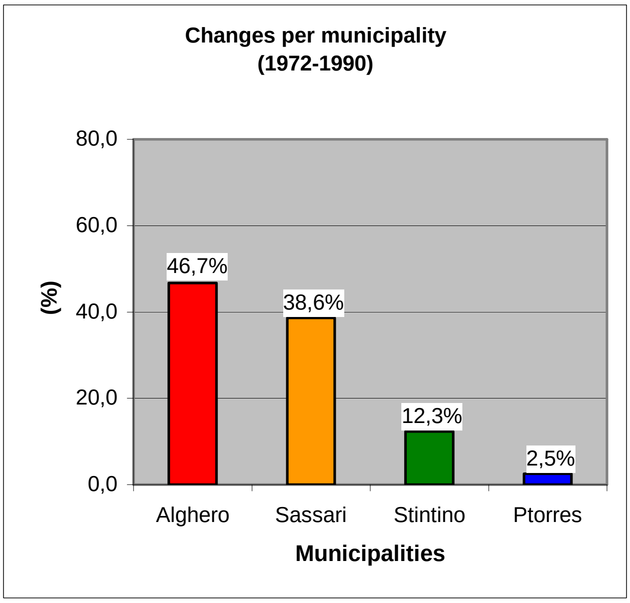

Figure 20 - Percentage of changes per municipality over the total change occurred in the study area (1972 – 1990).

In figure 21 the 4367,2 ha of changes occurred in the study area between 1990 and 2000 were subdivided by municipality.

Unlike the previous period, the larger amount of changes which occurred in the study area took place in the municipality of Sassari (47,3%). In the municipality of Alghero this percentage was about 35,3%, while in the municipality of Stintino it was about 13,8% and in the municipality of Porto Torres it was only 3,6%.

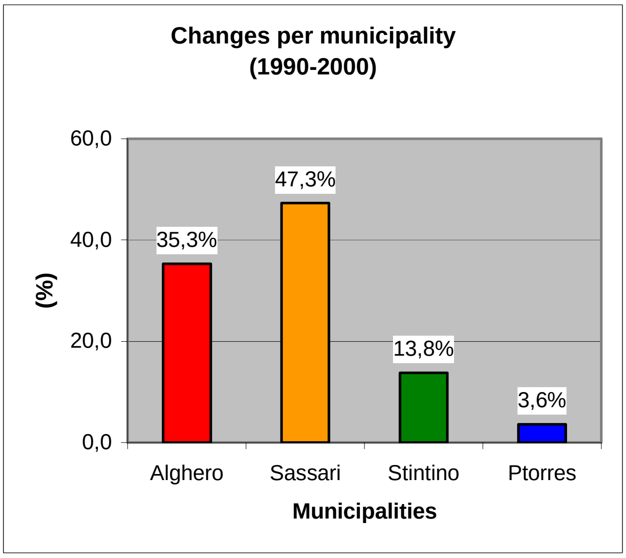

Figure 21 - Percentage of changes per municipality over the total changes in the study area (1990 – 2000).

In table 21 the main land cover change trajectories per municipality are reported.

	Land cover change trajectories	1972 – 1990 % [ha]	1990 – 2000 % [ha]	Type
Al	FS to CP	72,4 [1.091,6]	34,8 [536,3]	N
	CP to FS	12,8 [193,2]	50,6 [779,7]	P
	FS to BA	8,4 [126,4]	9,3 [143,1]	N
	FS to UA	5,1 [76,2]		N
	CP to UA		4,2 [64,3]	N
Sa	FS to CP	34,2 [425,7]	18,8 [387,4]	N
	CP to FS	33,1 [412,4]	47,2 [974,5]	P
	FS to BA	18,5 [229,8]	6,0 [122,9]	N
	FS to UA	13,0 [161,3]		N
	CP to UA		23,3 [480,6]	N
St	FS to CP	48,6 [192,8]	83,4 [504,2]	N
	FS to UA	30,3 [120,0]	4,2 [25,3]	N
	FS to BA	21,1 [83,7]		N
	CP to FS		3,4 [20,8]	P
	BA to FS		4,3 [26,1]	P
Pt	FS to CP	48,2 [38,4]	6,3 [9,9]	N
	FS to UA	37,3 [29,7]		N
	CP to FS	8,7 [6,9]	62,9 [98,2]	P
	CP to UA		23,1 [36,1]	N

Table 21 - Main land cover change trajectories per municipality over the two study periods, percentage, hectares and type of change over the total change. FS = Forestlands; CP = Croplands; UA = Urban areas; BA = Barren areas. N indicates the “Negative” category of change and P indicates the “Positive” one.

Alghero

As illustrated in table 21, between 1972 and 1990 in the municipality of Alghero 72,4% of changes concerned the transformation from forestlands to croplands, thus representing largely the most relevant type of transformation that has occurred in the area. Furthermore, changes lower than 10% led to the conversion of forestlands to barren areas (8,4%) and to urban areas (5,1%). The transformations that occurred were therefore largely negative in terms of spatial patterns related to desertification.

Only 12,8% of positive changes came about in the opposite direction, thus leading to a small gain in forests from croplands.

Over the decade 1990–2000 the majority of changes was positive and due to the transformation from croplands to forestlands, while 34,8% led to the opposite conversion.

FS to CP and CP to FS represented the main types of transformation that occurred in the municipality of Alghero over the two study periods. However, the gain in forests identified over the second period did not compensate the loss of forests observed over the first period. Urban and barren areas showed a continuous gain over time.

Sassari

Over the period 1972–1990 in the municipality of Sassari the two main types of conversion concerned the transformation from forestlands to croplands (34,2%) and the opposite one, from croplands to forestlands (33,1%). The growth of barren and urban areas mainly took place to the detriment of forestlands (18,5% and 13,0%).

Over the second study period, 47,2% of changes concerned the transformation from croplands to forestlands and only 18,8% from forestlands to croplands. Urban areas mainly expanded to the detriment of croplands (23,3%).

In the municipality of Sassari, the net balance of croplands over the study period was clearly negative. The recovery of forestlands over the decade 1990-2000 significantly compensated the loss of forests observed over the first period. The process of urban sprawl was intense, in particular over the last decade in which a relevant portion of changes created new urban settlements.

Stintino

The changes observed in the area of Stintino over the first study period were solely negative. In fact, three main conversions were identified: forestlands to croplands (48,6%), forestlands to urban areas (30,3%) and forestlands to barren areas (21,1%).

All the changes came about to the detriment of the forest ecosystems and were therefore negative.

Again, over the second study period the larger amount of changes led to the loss of forests for the expansion of croplands (83,4 %) and urban areas (4,2%). Only a slight portion of forests was recovered (3,4% from croplands and 4,3% from barren areas).

The municipality of Stintino was the only municipality in which the net balance of forests was clearly negative over the two study periods.

Porto Torres

In the municipality of Porto Torres between 1972 and 1990 two main conversions led respectively to new croplands (48,2%) and new urban areas (37,3%) to the detriment of forestlands. Only a slight portion of changes favoured a recovery of forests (8,7%). Over the decade 1990-2000 the main conversions concerned the transformation from croplands to forestlands (62,9%) and from croplands to urban areas (23,1%). The partial recovery of forests observed over the decade 1990-2000 did not compensate the loss occurred over the first period.

5.2 Landscape composition at patch and class level

The following paragraphs illustrate the results of the landscape analysis performed at patch and class level for the three dates considered and show the comparison between the landscape metrics obtained for the different areas investigated.

In particular, we performed patch level analysis in order to get information on the number of patches over size class for the four main land cover class (croplands,

forestlands, urban areas and barren areas). We considered the treshold limit of 1 ha in order to capture the spatial patterns of some relevance for the processes investigated.
In addition, class level analysis was performed by means of the Number of Patches (NP), the Patch Density (PD), the Largest Patch Index (LPI) and the Mean Patch Area (AREA_MN) in order to define the landscape composition of the study area and of each municipality analysed.

5.2.1 Urban areas

Table 22 illustrates the temporal variation of the number of urban patches in the study area and in the different municipalities. The table includes only patches larger than 1 ha, subdivided into three classes: 1 to 100 ha, 100 to 500 ha and more than 500 ha.

P. size (ha)	Study area			Alghero			Sassari			Stintino			P. Torres		
	72	90	00	72	90	00	72	90	00	72	90	00	72	90	00
1–100	49	95	121	19	21	29	16	55	61	11	7	9	4	11	19
100-500	2	3	4	1	2	1	1	1	2	-	-	-	-	-	1
>500	2	2	2	-	-	-	1	1	1	-	-	-	1	1	1

Table 22 - Number of urban patches over patch size class (area > 1 ha).

In the study area in 1972, about 92,5% of patches was concentrated in the class 1 – 100 ha (49 patches over 53). This value tended to rise over time: 95% of patches in 1990 belonged to the first class and 95,3% in 2000. The medium urban areas increased by one unit for each period and the number of large urban areas (> 500 ha) maintained constant values equal to 2.
In the municipality of Alghero the number of small urban patches (1–100 ha) grew by ten units between 1972 and 2000. Medium urban patches oscillated between 1 and 2 over the period investigated. No large urban patches were detected in the area.
In the municipality of Sassari between 1972 and 1990 the number of small urban patches grew significantly, while medium and large ones maintained constancy. Between 1990 and 2000 smaller patches still slightly increased, with a small patch

moving to the medium size class. One large urban patch was maintained, which enlarged to 1338 ha thus leading to an increase of LPI.

In the municipality of Stintino between 1972 and 1990 the urban landscape was characterised by a slight reduction in the number of small patches. A few small urban patches probably were merged together to form new larger urban areas, still belonging to the smaller class (1-100 ha). Between 1990 and 2000 two more small urban patches were identified, as the number grew by two units. Over the period considered no medium nor large urban patches were recognized.

In the municipality of Porto Torres between 1972 and 1990 an increase in the number of small urban patches was observed, while the landscape maintained the largest urban patch. Between 1990 and 2000 the number of small urban patches slightly rose.

The municipalities of Alghero, Sassari and Porto Torres showed the same trend as the study area in terms of the number of small patches. The number of large urban patches was constant everywhere over the period considered.

In the following figure the trend of the total NP larger than 1 ha is represented.

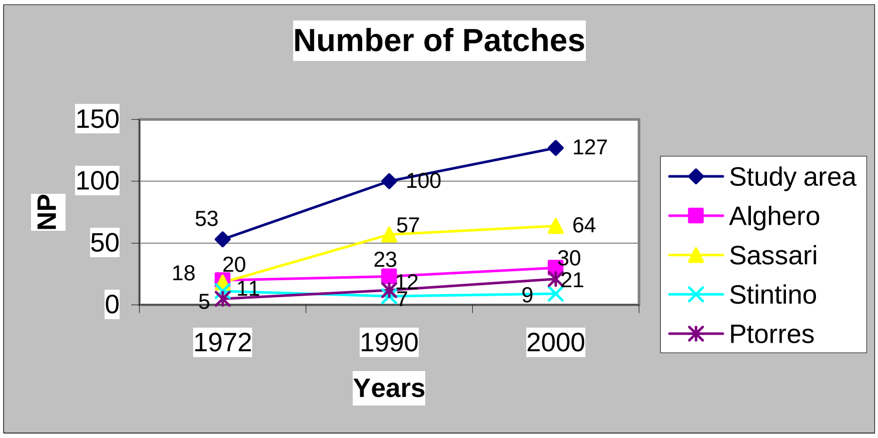

Figure 22 - Number of Patches (area > 1 ha) in 1972, 1990 and 2000.

The number of urban patches rose in the study area as in the municipalities of Alghero, Sassari and Porto Torres.

Only in the municipality of Stintino was there a slight reduction between 1972 and 1990 and a slight growth between 1990 and 2000.

In the following figure the Patch Density of urban areas is illustrated.

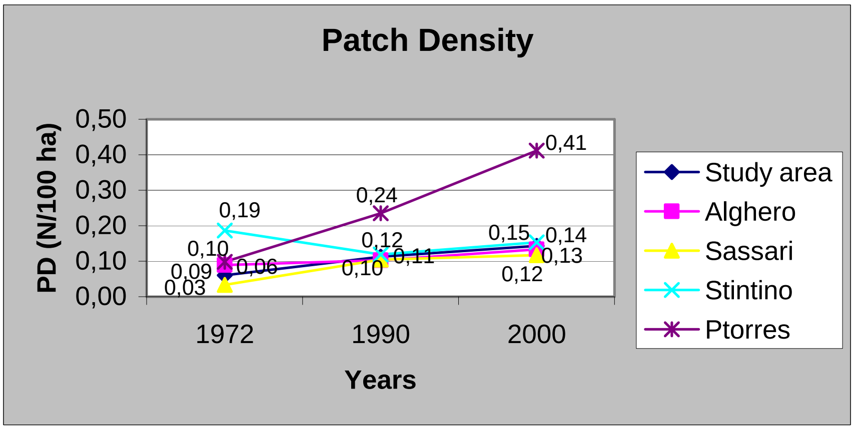

Figure 23 - Patch Density in 1972, 1990 and 2000.

Patch Density increased over time in the study area, as in the municipalities of Alghero, Sassari and Porto Torres. In the set analysed, the highest values of PD (0,41 urban patches per 100 ha) and the highest values of increasing rate (slope equal to 0.16), were identified in the municipality of Porto Torres.

In figure 24 the temporal trend of the Largest Patch Index is reported.

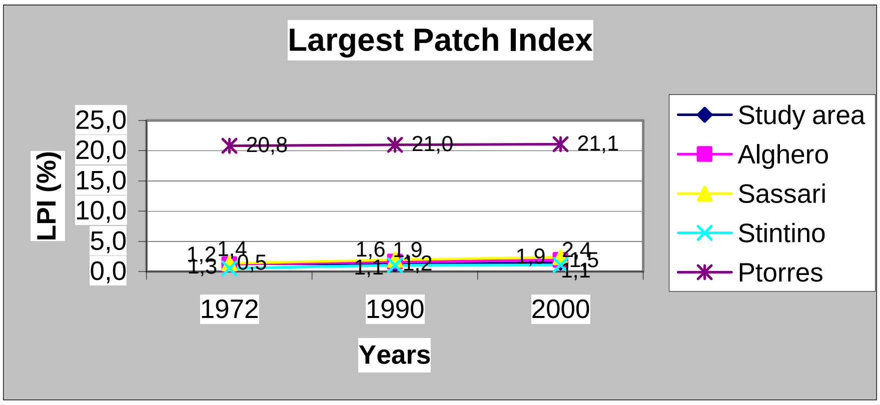

Figure 24 - Largest Patch Index in 1972, 1990 and 2000.

In the study area the slight increase of LPI between 1990 and 2000 (from 1,2% to 1,5%) indicated that the largest urban patch, belonging to the municipality of Sassari and larger than 500 ha in 1990 (1061,5 ha), further enlarged to 1313,6 ha in 2000.

In the municipality of Alghero the largest urban patch, belonging to medium size class (100-500 ha), enlarged from 278,3 ha in 1972 to 372,6 ha in 1990 and further expanded to 433,2 ha in 2000.

In the municipality of Sassari the largest urban patch expanded from 777,3 ha in 1972 to 972,8 ha in 1990 and to 1338 ha in 2000.

Between 1972 and 1990 in the municipality of Stintino more than a doubling of LPI was registered: the largest urban patch increased, in fact, from about 30 ha to 65 ha. Between 1990 and 2000 LPI maintained constant values.

In the municipality of Porto Torres LPI showed the highest values found in the set analysed, indicating a dominance of urban areas in the landscape.

In figure 25 the Mean Patch Area Distribution for urban areas is illustrated.

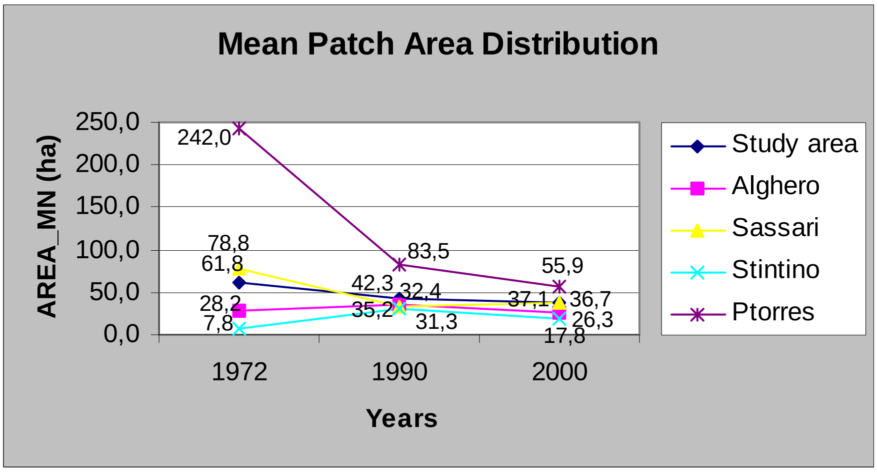

Figure 25 - Mean Patch Area in 1972, 1990 and 2000.

In the study area the decrease in the AREA_MN was continuous over time, from about 62 ha in 1972 to about 42 ha in 1990 and to about 36,7 ha, and was probably mainly due to the increase in the number of the small urban areas.

In the municipalities of Alghero and Stintino the trend of AREA_MN was characterised by a growth between 1972 and 1990 (from 28,2 ha to 35,2 ha and from 7,8 ha to 31,3 ha, respectively) and a decline between 1990 and 2000 (from 35,2 ha to 26,3 ha and from 31,3 ha to 17,8 ha, respectively).

In the municipality of Sassari between 1972 and 1990 AREA_MN lowered, mainly as a consequence of the large increase in the number of small urban patches. Over the second study period, the index showed a slight increase probably due to the enlargement in the size of urban patches.

The municipality of Porto Torres showed a continuous decreasing trend, with a strong reduction between 1972 and 1990 (from 242,0 ha to 83,5 ha) and a slighter decline between 1990 and 2000 (from 83,5 ha to 55,9 ha).

5.2.2 Forestlands

Table 23 illustrates the temporal variation of the number of forest patches in the study area and in the different municipalities. The table includes only patches larger than 1 ha, subdivided into three classes: 1 to 100 ha, 100 to 500 ha and more than 500 ha.

P. size (ha)	**Study area**			**Alghero**			**Sassari**			**Stintino**			**P. Torres**		
	72	**90**	**00**	**72**	**90**	**00**	**72**	**90**	**00**	**72**	**90**	**00**	**72**	**90**	**00**
1–100	527	216	311	167	65	94	321	115	164	8	11	35	31	32	28
100-500	14	14	8	3	4	2	8	8	7	2	3	1	1	-	1
>500	8	6	8	3	3	4	4	4	5	1	-	-	-	-	-

Table 23 - Number of forest patches over patch size class (area > 1 ha).

In the study area between 1972 and 1990 the loss of forest patches concerned the small ones (1-100 ha) and, to a small extent, the large ones (> 500 ha). Medium patches (100 – 500 ha) maintained constancy in number. The reduction in the number of small patch per size, was probably due to a complete loss in the patches or the reduction in the extension to a lower dimension than 1 ha. At the same time the reduction in the number of the larger patches should mean a shrink in areas moving from the larger class to the medium class.

Between 1990 and 2000 the recovery of some small forest areas could be linked mainly to the appearance of new small forest patches. A slight increase in the number of larger forest patches from 6 to 8, on the other side, could be due to the enlargement of some medium forest patches.

In the municipality of Alghero between 1972 and 1990 the number of small forest patches suffered from a large reduction (from 167 to 65), while medium forest patches increased by one unit and larger forest patches mantained three units. Between 1990 and 2000 a reversal trend was registered. Smaller and larger forest

patches grew in number (from 65 to 94 and from 3 to 4, respectively). At the same time a slight reduction in the number of medium patches was observed (from 4 to 2).
Between 1972 and 1990 in the municipality of Sassari the number of small forest patches clearly declined from 321 to 115, indicating that the small patches totally disappeared or suffered from a reduction in dimension. Medium and large forest patches maintained a constant number. Between 1990 and 2000 smaller forest patches rose and one medium forest patch probably moved to the larger patch class.
Between 1972 and 1990 the forested landscape in the municipality of Stintino was characterised by a small increase in the number of small (from 8 to 11) and medium patches (from 2 to 3). Between 1990 and 2000 the number of smaller forest patches still increased from 11 to 35, while the medium ones lost two units.
As regards the number of small forest patches, the municipalities of Alghero and Sassari showed the same trend as the study area: the recovery of small forest patches that have occurred in 2000 did not balance the loss which took place between 1972 and 1990. The municipality of Stintino was the only area in which the number of small patches continuously increased over time.
In the municipalities of Stintino and Porto Torres the number of medium patches was low and the only large patch found in the municipality of Stintino in 1972 disappeared over time.
In figure 26 the Number of Patches is illustrated.

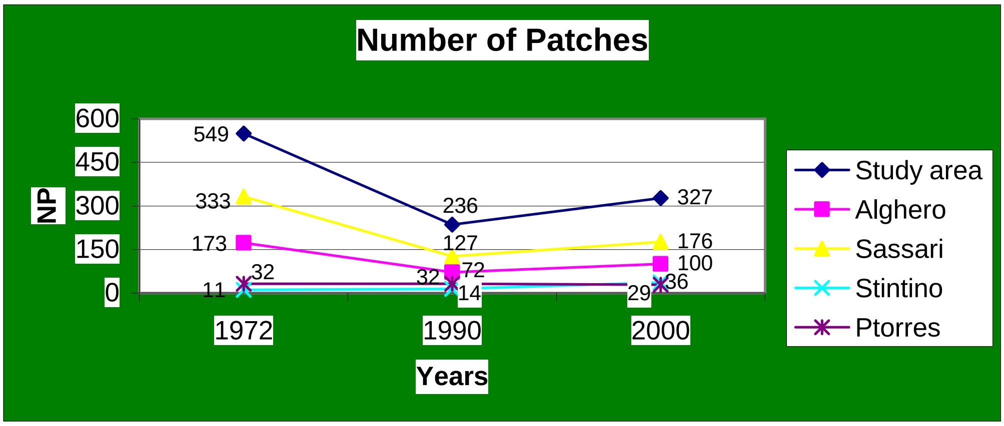

Figure 26 - Number of Patches (area > 1 ha) in 1972, 1990 and 2000.

In the study area and in the municipalities of Alghero and Sassari NP declined between 1972 and 1990 and grew between 1990 and 2000. The municipality of

Stintino was the only municipality in which NP showed a continuous increase, while the municipality of Porto Torres showed a slight reduction between 1990 and 2000 (from 32 to 29). Both these municipalities showed the lowest values of NP in the set analysed.

The Patch Density is illustrated in figure 27.

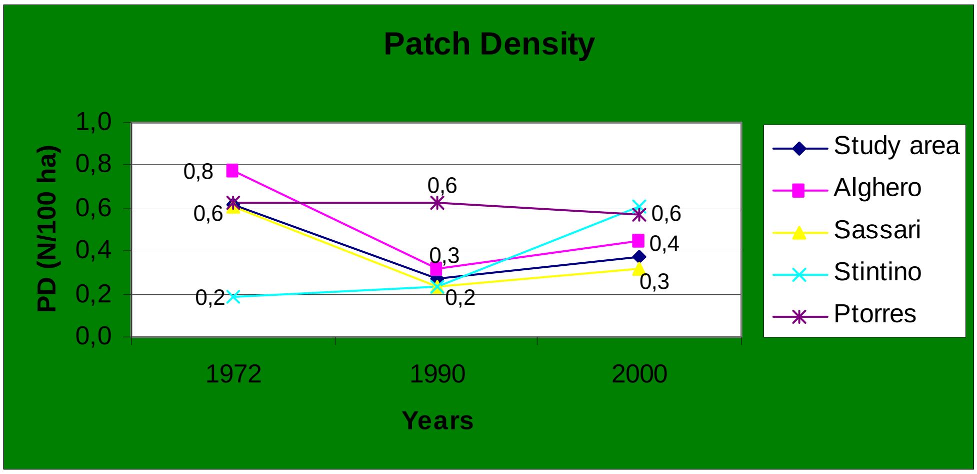

Figure 27 - Patch Density in 1972, 1990 and 2000.

Patch Density in the study area, as in the municipality of Alghero and Sassari, slightly lowered between 1972 and 1990 and slightly grew between 1990 and 2000.

A clear increase in PD was observed only in the municipality of Stintino, where it increased from 0,2/100 ha to 0,6/100 ha between 1990 and 2000. PD in the municipality of Porto Torres maintained values equal to 0,6/100 ha.

The Largest Patch Index for forestlands is illustrated in figure 28.

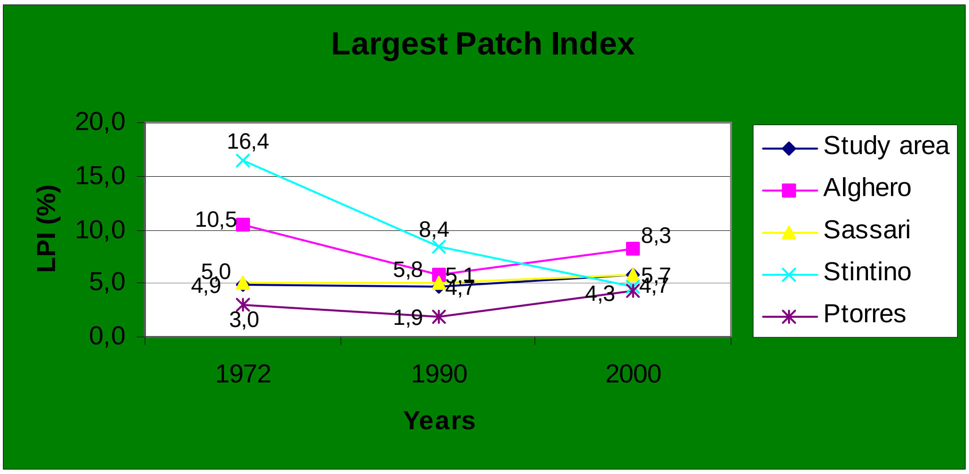

Figure 28 - Largest Patch Index in 1972, 1990 and 2000.

In the study area the slight reduction in LPI from 4,9% to 4,7% indicated that the largest forest patch, belonging to the municipalities of Sassari and Alghero, suffered from a reduction (from 4342,4 ha to 4123,4 ha) between 1972 and 1990. Over the second study period the slight increase in LPI (up to 5,7% in 2000) reflected the enlargement of the forest patch (from 4123,4 ha to 5072,1 ha), which probably benefited from the new occurrence of forest patches adjacent to the old ones.

In the municipality of Alghero a halving in LPI (10,5% to 5,8%) between 1972 and 1990 was observed, leading from a forest patch of 2357 ha to a small one of about 1311 ha. Between 1990 and 2000 LPI grew from 5,8% to 8,3%.

In the municipality of Sassari the largest forest patch continuously increased from 2759 ha in 1972 to 2806 ha in 1990, successively approaching 3215 ha in 2000. The municipality of Sassari was the only municipality in which LPI continuously increased over time.

An opposite trend was found in the municipality of Stintino, where LPI dramatically lowered: between 1972 and 1990 a halving in the index was registered (from 16,4% to 8,4%) and a comparable reduction was observed over the second study period (from 8,4% to 4,7%).

A reduction in the largest forest patch in the municipality of Porto Torres was observed between 1972 and 1990, from about 153 ha to 95 ha, and an increase to about 220 ha over the second study period was observed.

In figure 29 the Mean Patch Area Distribution for forestlands is illustrated.

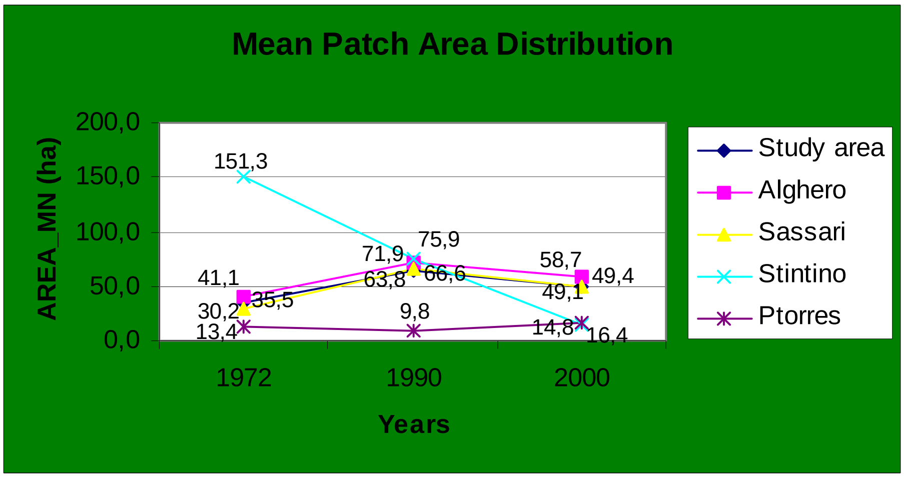

Figure 29 - Mean Patch Area in 1972, 1990 and 2000.

In the study area, AREA_MN showed an increasing trend between 1972 and 1990 from about 35 ha to 64 ha. Over the second period investigated the index lowered to about 49 ha, as a likely consequence of the increase in the number of small patches.
The same behavior was observed in the municipalities of Alghero and Sassari, where AREA_MN between 1972 and 1990 grew respectively from 41,1 ha to 71,9 ha and from 30,2 ha to 66,6 ha and between 1990 and 2000 showed a reduction respectively to 58,7 ha and to 49,4 ha. Between 1990 and 2000 a decline in the AREA_MN could probably reflect the increase in the number of the smaller forest patches in the landscape.
The municipality of Stintino was the only municipality in which AREA_MN continuously and significantly decreased, thus reducing from 151,3 ha in 1972 to 75,9 ha in 1990 and further to 14,8 ha.
Slight changes were assessed in the municipality of Porto Torres, where AREA_MN lowered between 1972 and 1990 from 13,4 ha to 9,8 ha and increased between 1990 and 2000 from 9,8 ha to 16,4 ha. In this area the lowest values of AREA_MN were registered.

5.2.3 Croplands

In table 24 the temporal variation in the number of patches of croplands is illustrated. The table includes only patches larger than 1 ha, subdivided into three classes: 1 to 100 ha, 100 to 500 ha and more than 500 ha.

P. size (ha)	Study area			Alghero			Sassari			Stintino			P. Torres		
	72	**90**	**00**	**72**	**90**	**00**	**72**	**90**	**00**	**72**	**90**	**00**	**72**	**90**	**00**
1–100	197	223	174	100	112	51	87	80	77	6	19	20	10	13	28
100-500	4	1	-	4	1	-	-	-	-	-	-	-	-	-	-
>500	1	1	3	1	1	1	1	1	3	1	1	1	1	1	1

Table 24 - Number of crop patches over patch size class (area > 1 ha).

In the study area between 1972 and 1990 an increase in small crop patches was registered, probably due to the enlargement of the smaller crop patches (< 1 ha) and/or to the appearance of completely new small agricultural areas (1-100 ha). Between 1990 and 2000 the drop in the number of smaller crop patches was partly due to their complete loss and partly to their reduction in size. On the other side, the increase in the number of larger crop patches (1 to 3) could probably be due to the separation of two big areas from the largest one identified in 1990. Between 1990 and 2000 a decline in the number of small patches was observed (from 223 to 174) and two new large patches were identified in the study area.

In the municipality of Alghero between 1972 and 1990 the landscape dynamic of croplands was characterised by a slight rise in the small crop areas, a decrease in medium ones and an unchanged number of the larger ones. Between 1990 and 2000 small patches showed a halving in the number, the medium one disappeared and the largest patch persisted.

In the municipality of Sassari between 1972 and 1990 smaller crop areas slightly diminished from 87 to 80. No medium patches were found and only one large crop area was recognized. Between 1990 and 2000 the number of smaller patches decreased by three units, while the medium class acquired two new units. Only in this area was an increase in the large patches, from one to three units between 1990 and 2000, registered.

In the municipalities of Stintino and Porto Torres the agricultural landscape was characterised by a growth in small crop patches. No medium patches were found and only one large patch was observed.

The Number of crop Patches is illustrated in the following figure.

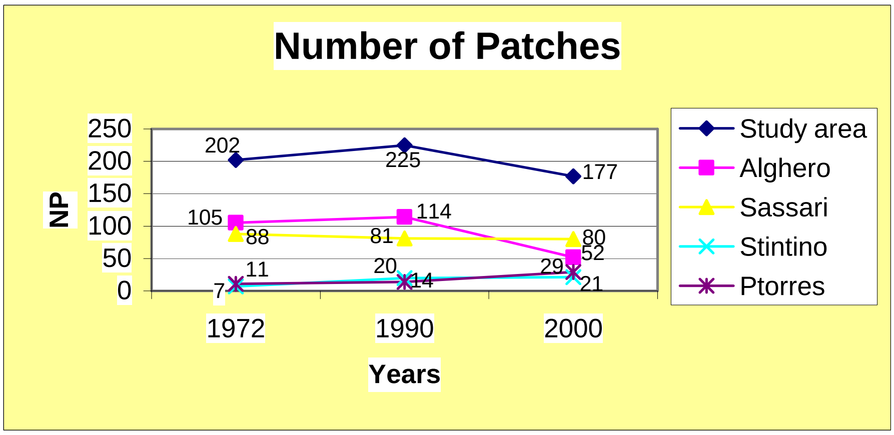

Figure 30 - Number of Patches (area > 1 ha) in 1972, 1990 and 2000.

In the study area, as in the municipality of Alghero, NP rose between 1972 and 1990 and fell over the decade 1990-2000. Only in the municipality of Sassari did NP show a slight trend towards growth, while the opposite trend was observed in the municipalities of Stintino and Porto Torres, where NP slightly increased over time.

Patch Density is displayed in figure 31.

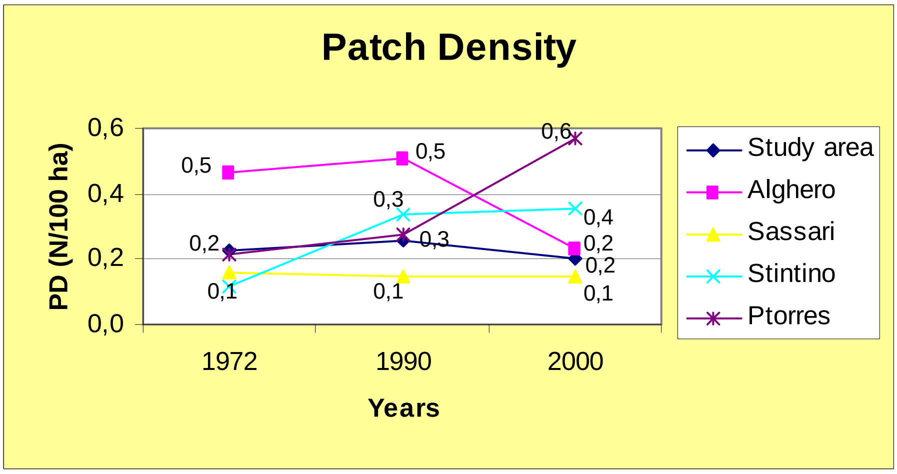

Figure 31 - Patch Density in 1972, 1990 and 2000.

PD in the study area, as in the municipality of Sassari, was quite constant. A slight trend in growth was showed in the municipalities of Stintino and Porto Torres, while a clear trend to drop was illustrated in the municipality of Alghero, in particular over the period 1990-2000.

Figure 32 illustrates the temporal trend of the Largest Patch Index for croplands.

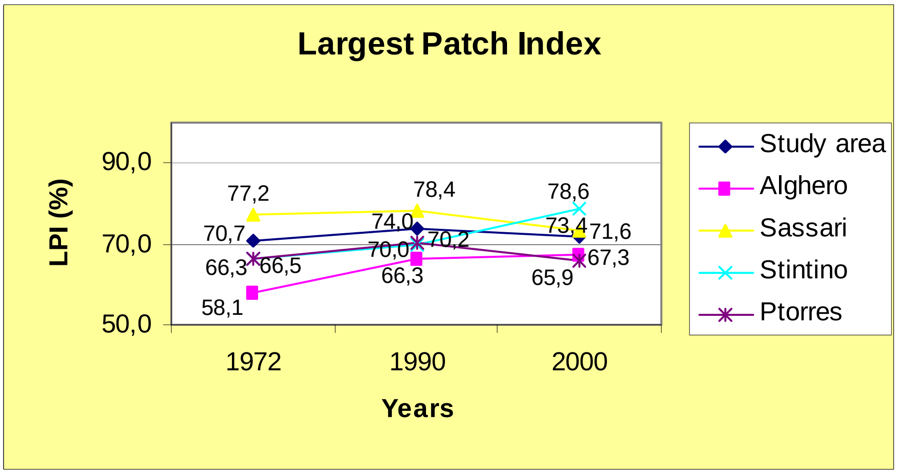

Figure 32 - Largest Patch Index in 1972, 1990 and 2000.

LPI values were in general very high as croplands represented the matrix of the landscape.

In the study area between 1972 and 1990 the huge agricultural patch, larger than 60.000 ha, covered almost the overall study area and showed an expansion. LPI, in fact, rose from 70,7% to 74,0%. Some new crop areas probably appeared adjacent to the largest crop area, thus leading to its increase. A slight decrease in LPI from 74,0% to 71,6% was observed between 1990 and 2000.

The municipalities of Alghero and Stintino were the only municipalities where LPI showed a continuous increase over time. In particular, in the municiplity of Alghero the largest crop area increased from 58,1% in 1972 to 66,3% in 1990 and expanded further to 67,3% in 2000. In the municipality of Stintino LPI enlarged from 66,3% in 1972 to 70,0% in 1990 up to 78,6% in 2000.

In the municipalities of Sassari and Porto Torres, as in the study area, LPI showed an increase between 1972 and 1990 and a reduction between 1990 and 2000.

The highest values of LPI in the set analysed (about 78%) were observed in the municipality of Sassari.

In figure 33 the Mean Patch Area Distribution for croplands is illustrated.

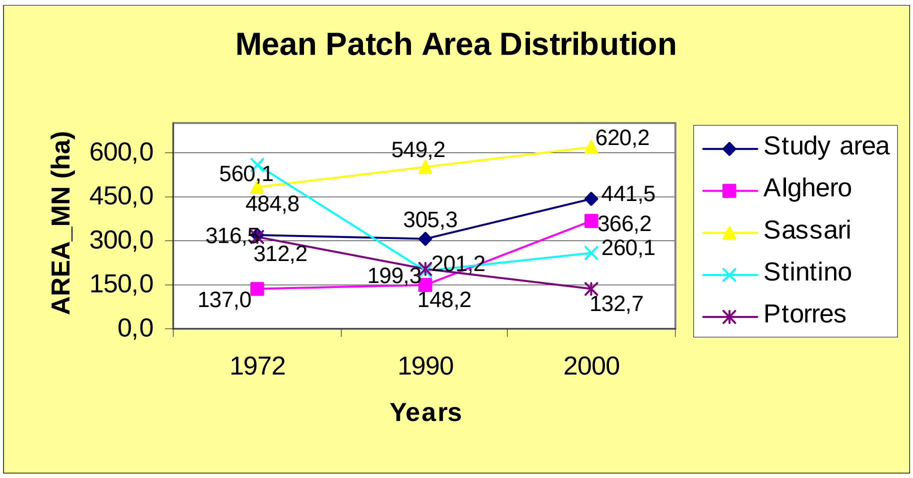

Figure 33 - Mean Patch Area in 1972, 1990 and 2000.

In the study area AREA_MN showed a slight reduction between 1972 and 1990 (from 316,5 ha to 305,3 ha) and a large growth between 1990 and 2000 (from 305,3 ha to 441,5 ha).

In the municipality of Alghero AREA_MN slightly rose between 1972 and 1990 (from 137,0 ha to 148,2 ha) and then strongly increased between 1990 and 2000 (from 148,2 ha to 366,2 ha).
The municipalities of Alghero and Sassari were the only municipalities in which AREA_MN continuously increased over time.
The opposite trend was registered in the municipality of Porto Torres, in which AREA_MN continuously declined over time, probably due to the increase in the number of smaller patches.
In the municipality of Stintino a significant fall between 1972 and 1990 (from 560,1 ha to 201,2 ha) and a growth between 1990 and 2000 (from 201,2 ha to 260,1 ha) were observed.

5.2.4 Barren areas

Table 25 illustrates the temporal variation of the number of patches of barren areas in the study area and in the different municipalities. The table includes only patches larger than 1 ha, subdivided into three classes: 1 to 50 ha, 50 to 100 ha and more than 100 ha.

P. size (ha)	Study area			Alghero			Sassari			Stintino			P. Torres		
	72	90	00	72	90	00	72	90	00	72	90	00	72	90	00
1–50	124	32	121	45	10	39	48	10	49	21	8	23	10	4	13
50-100	-	3	4	-	1	1	-	2	-	-	-	1	-	-	-
>100	-	3	1	-	1	-	-	-	-	-	2	1	-	-	-

Table 25 - Number of barren patches over patch size class (area > 1 ha).

The number of barren patches changed significantly over time, showing in general a strong fall between 1972 and 1990 and a rise over the decade 1990-2000 in all the areas investigated.
Large barren patches were found only in the municipalities of Alghero and Stintino.

In the following figures (figure 34 and 35) the Number of barren Patches and the Patch Density are illustrated.

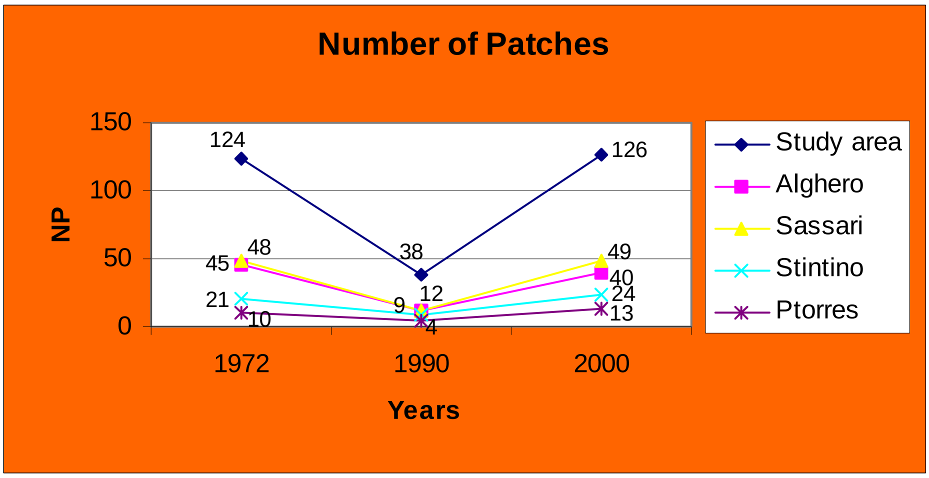

Figure 34 - Number of Patches in 1972, 1990 and 2000.

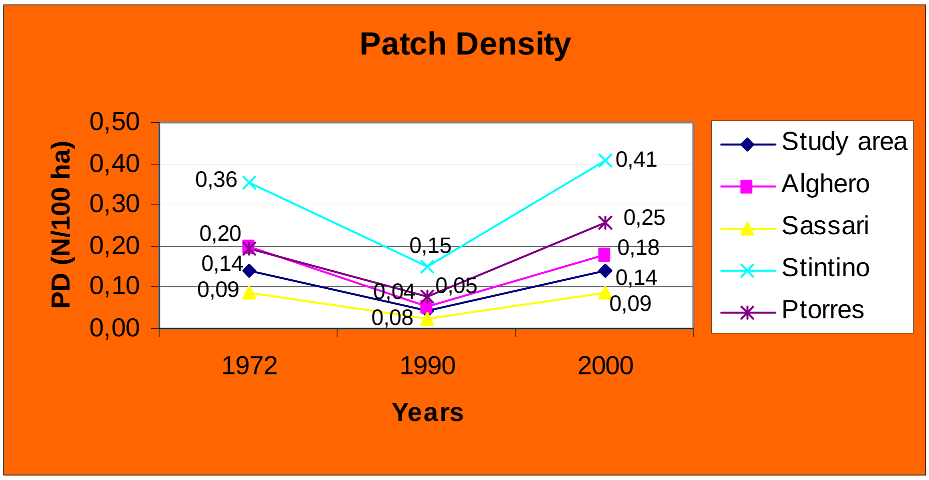

Figure 35 - Patch Density in 1972, 1990 and 2000.

In general, NP and PD showed a strong reversal trend in 1990 in all the areas investigated. The highest values of barren Patch Density were found in the municipality of Stintino and the lowest values in the municipality of Sassari.

The Largest Patch Index of barren patches is represented in figure 36.

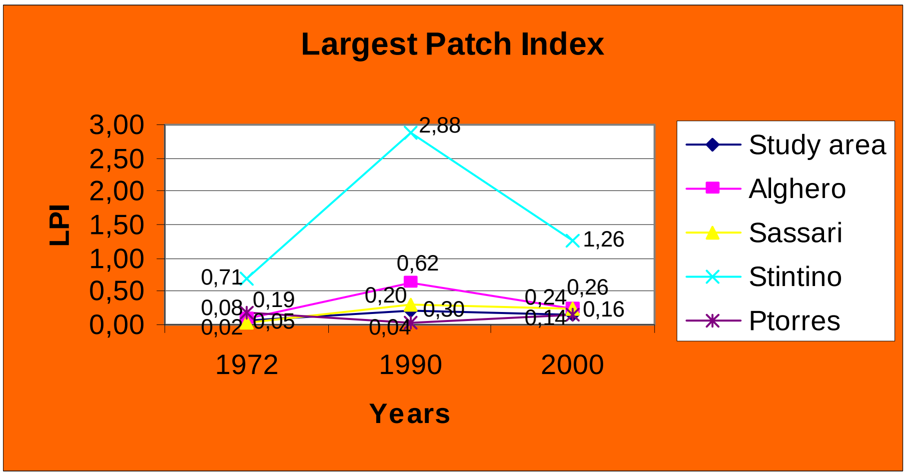

Figure 36 - Largest Patch Index in 1972, 1990 and 2000.

The highest values of LPI assessed in the study set were found in the municipality of Stintino, where the index largely grew over the first study period and declined between 1990 and 2000. The same temporal trend was measured in the study area, as in the municipalities of Alghero and Sassari.

In figure 37 the Mean Patch Area Distribution for barren areas is illustrated.

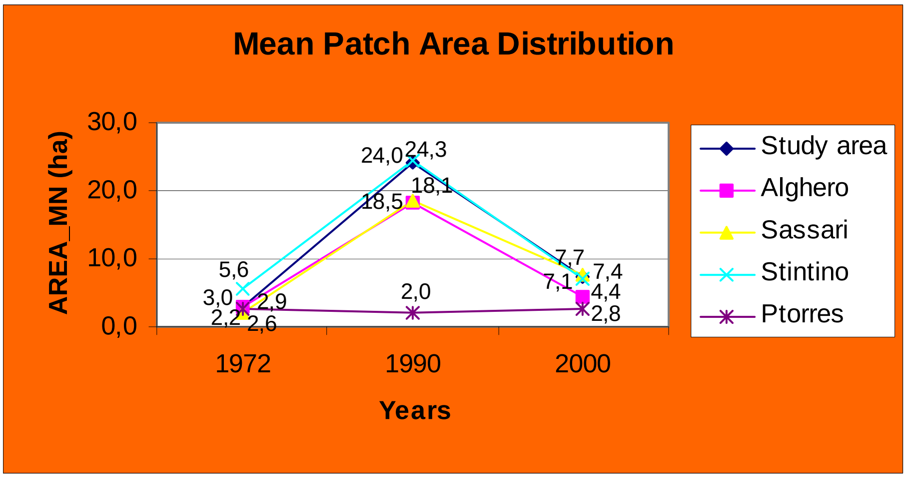

Figure 37 - Mean Patch Area in 1972, 1990 and 2000.

Except for the municipality of Porto Torres, in which the Mean Patch Area values were low and constant, in the other municipalities and in the study area, the Mean Patch Area rose strongly between 1972 and 1990 and then fell over the period 1990-2000. The highest mean values for barren areas were found in 1990.

5.3 Landscape configuration at class level

The following paragraphs illustrate the trends of the landscape configuration metrics performed at class level for each land cover class and show the comparison between the landscape metrics obtained for the different areas investigated.

The analysis was performed by means of the Landscape Shape Index (LSI), the Mean Euclidean Nearest-Neighbor Distance (ENN_MN), the Interspersion and Juxtaposition Index (IJI) and the Patch Cohesion Index (COHESION), in order to define the landscape configuration of the study area and of each municipality analysed.

5.3.1 Urban areas

In figure 38 the temporal trend of the Landscape Shape Index for urban areas is illustrated.

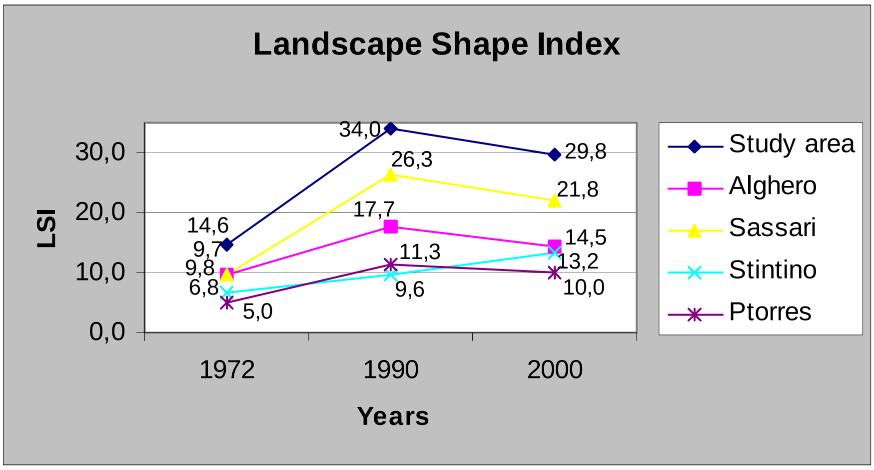

Figure 38 - Landscape Shape Index in 1972, 1990 and 2000.

In the municipalities of Sassari, Alghero and Porto Torres the values of LSI showed the same behavior assessed in the study area, with a growth between 1972 and 1990 and a slight decline over the decade 1990-2000. The only municipality in which LSI constantly grew was the municipality of Stintino, in which LSI increased from 6,8 in 1972 to 9,6 in 1990 and further expanded up to 13,2 in 2000. Hence, new urban settlements led to slightly more complex urban patches over time.

In figure 39 the Mean Euclidean Nearest-Neighbor Distance is represented.

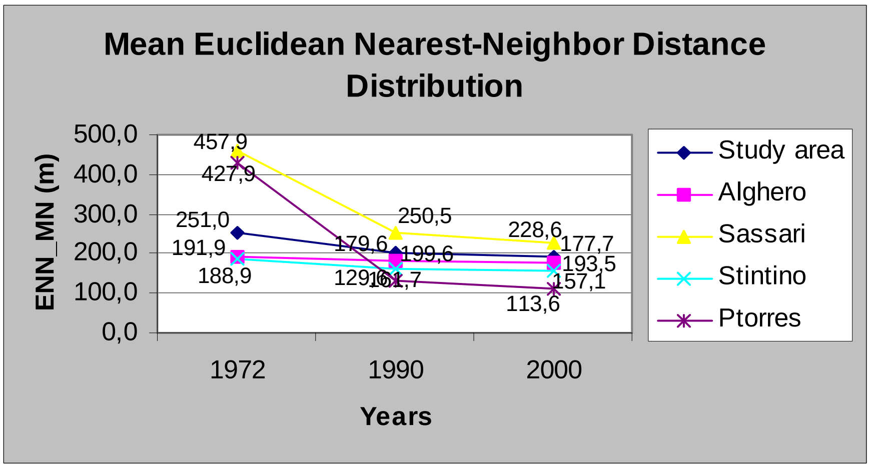

Figure 39 - Mean Euclidean Nearest-Neighbor Distance in 1972, 1990 and 2000.

In all the municipalities analysed and in the study area, the ENN_MN showed a decline over time. In the municipalities of Sassari and Porto Torres between 1972 and 1990 the decrease was significant (from 457,9 m to 250,5 m and from 427,9 m to 129,6 m). The continuous reduction of ENN_MN indicated that the distance of urban patches to the nearest neighbor of the same class increasingly shortened.

In the municipality of Stintino and Alghero ENN_MN was rather constant over time.

In figure 40 the Interspersion and Juxtaposition Index is illustrated.

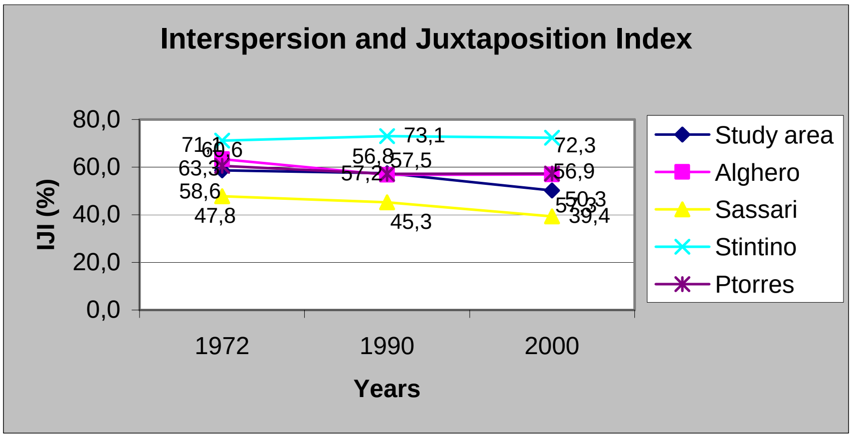

Figure 40 - Interspersion and Juxtaposition Index in 1972, 1990 and 2000.

IJI is in general rather constant over time for the municipalities investigated. The lower interspersion of new urban fragments were observed in the municipality of Sassari, while the highest interspersion (71%-73%) was identified in the municipality of Stintino.

In figure 41 the Patch Cohesion Index is illustrated.

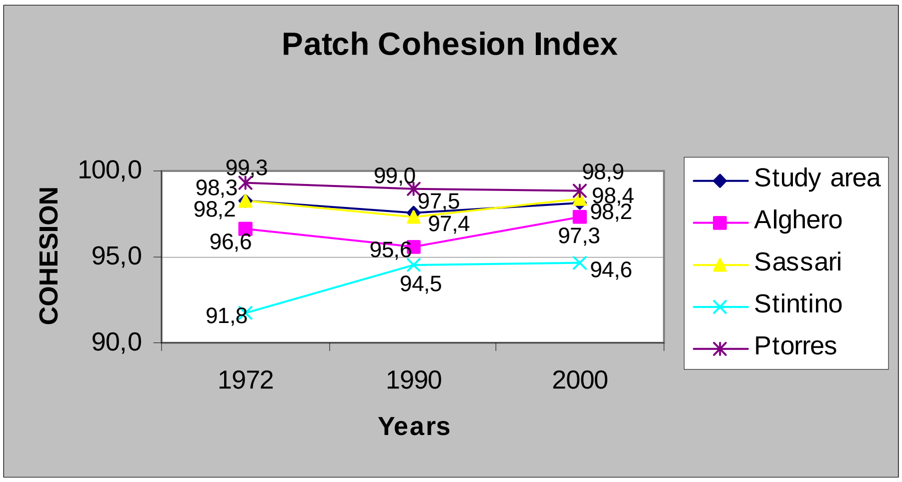

Figure 41 - Patch Cohesion Index in 1972, 1990 and 2000.

Patch Cohesion Index was, in general, high for urban areas and maintained rather constant values over time in the municipalities of Porto Torres, Sassari and in the study area. The most considerable variation was observed over the period 1972-1990 in the municipality of Stintino, where the index increased from 91,8 to 94,5.

5.3.2 Forestlands

In figure 42 the temporal trend of the Landscape Shape Index for forestlands is illustrated.

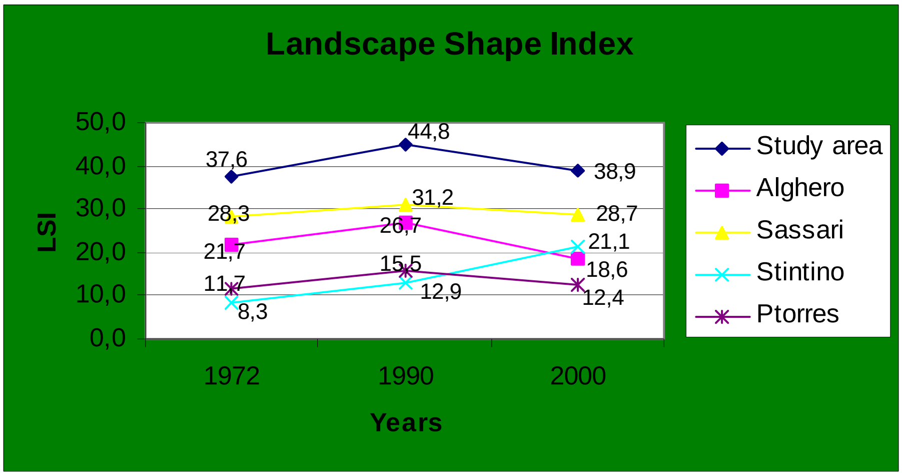

Figure 42 - Landscape Shape Index in 1972, 1990 and 2000.

In the study area, and in the municipality of Alghero and Porto Torres, LSI showed a rising trend between 1972 and 1990 (from 21,7 to 26,7 and from 11,7 to 15,5, respectively) and a decline between 1990 and 2000 (from 26,7 to 18,6 and from 15,5 to 12,4, respectively). A rather constant trend was observed only in the municipality of Sassari, while the municipality of Stintino was the only area in which LSI for forests increased, in particular between 1990 and 2000, thus indicating an increasing complexity in the structure of forests.

LSI values for forestlands were high in general compared to the values of urban areas and croplands.

In figure 43 the Mean Euclidean Nearest Neighbor Distance Distribution is represented.

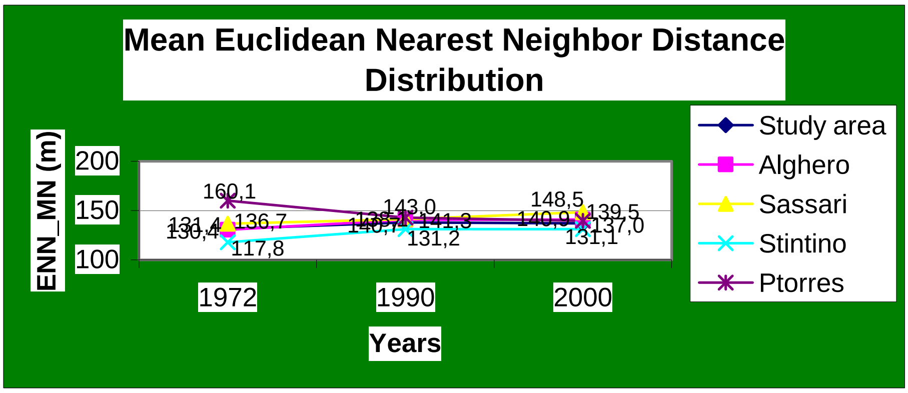

Figure 43 - Mean Euclidean Nearest-Neighbor Distance in 1972, 1990 and 2000.

ENN_MN values did not change considerably over time. In the municipality of Stintino a rise between 1972 and 1990 and a constant value over the second study period were observed. In the municipality of Sassari ENN_MN showed a continuous slight increase, while in the municipality of Porto Torres the index showed the opposite trend.

In figure 44 the Interspersion and Juxtaposition Index is illustrated.

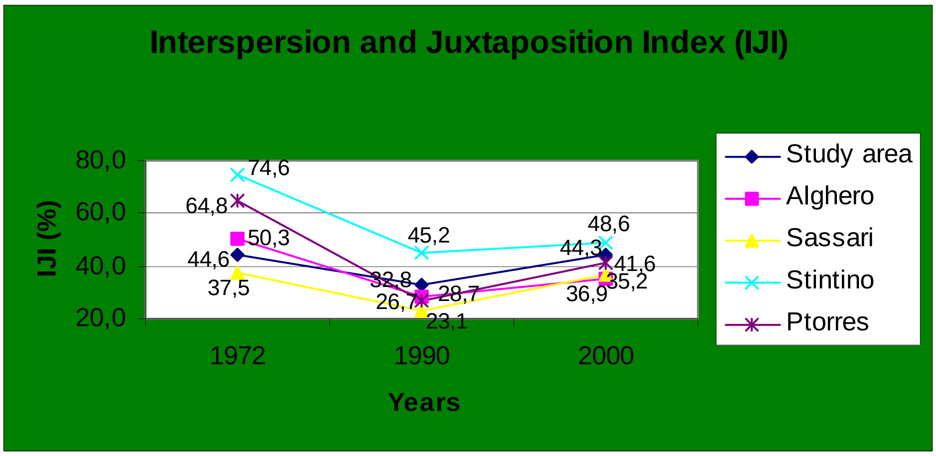

Figure 44 - Interspersion and Juxtaposition Index in 1972, 1990 and 2000.

IJI showed the same trend in all the areas analysed, with an initial decrease between 1972 and 1990 and a successive increase over the second period. More significant reductions were observed in the municipalities of Stintino and Porto Torres, in particular over the first period investigated (from 74,6% to 45,2% and from 64,8% to 26,7%). The municipality of Stintino showed the highest values assessed in the set analysed.

Finally, Patch Cohesion Index is illustrated in figure 45.

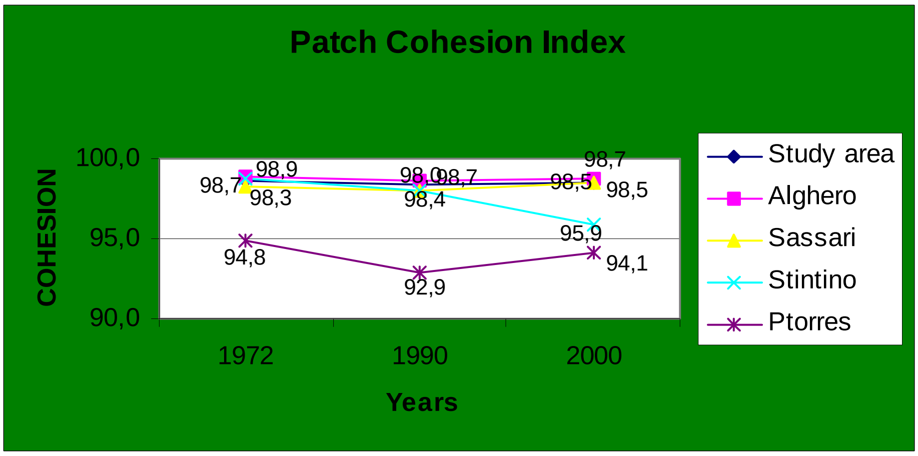

Figure 45 - Patch Cohesion Index in 1972, 1990 and 2000.

In general, Patch Cohesion Index showed constant values over time in the study area and in the municipalities of Alghero and Sassari. A continuous trend to decrease was assessed in the municipality of Stintino, thus indicating that the forests were less cohesive and less physically connected. Lower values were registered in the municipality of Porto Torres, where the index declined over the first period and increased over the decade 1990-2000.

5.3.3 Croplands

In figure 46 the Landscape Shape Index for croplands is showed.

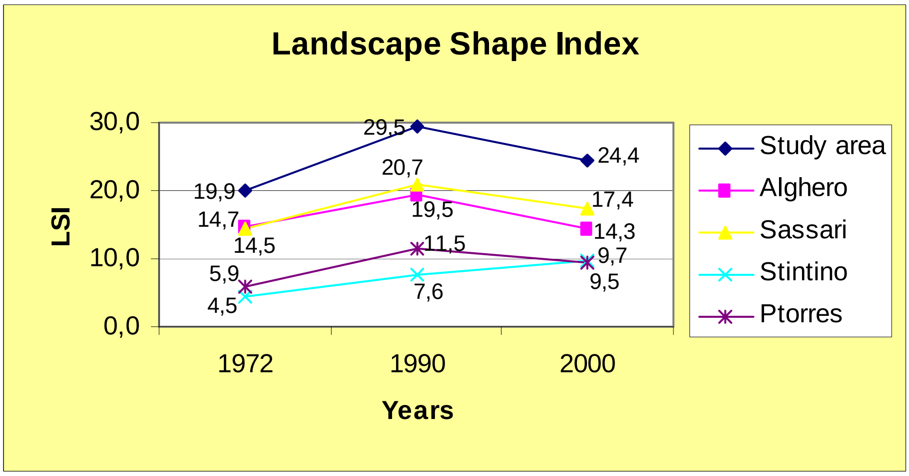

Figure 46 - Landscape Shape Index in 1972, 1990 and 2000.

In the municipalities of Alghero, Sassari and Porto Torres, and in the study area, LSI initially increased and then showed a decline over the second study period.

Only the municipality of Stintino showed a continuous increasing trend over time (from 4,5 in 1972 to 7,6 in 1990 and to 9,5 in 2000).

In figure 47 the Mean Euclidean Nearest Neighbor Distance is represented.

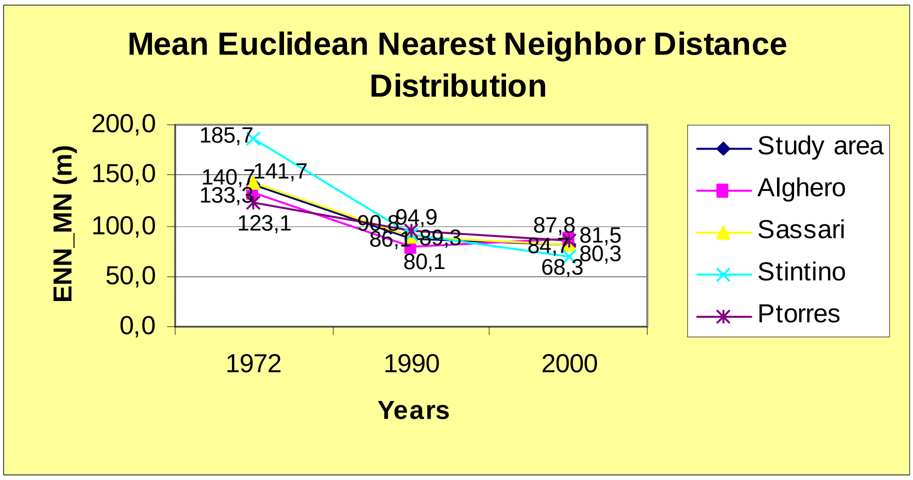

Figure 47 - Mean Euclidean Nearest Neighbor Distance in 1972, 1990 and 2000.

In the study area between 1972 and 1990 the decrease of ENN_MN reflected the occurrence of small crop patches inside the few non-cultivated spaces within the landscape.

ENN_MN showed a strong fall between 1972 and 1990 in all the areas investigated, in particular in the municipality of Stintino. Between 1990 and 2000 ENN_MN continued to decline in both the study area and in the municipalities of Sassari, Stintino and Porto Torres. The only area in which ENN_MN increased between 1990 and 2000 was the municipality of Alghero (from 80,1% to 87,8%).

In figure 48 the Interspersion and Juxtaposition Index is represented.

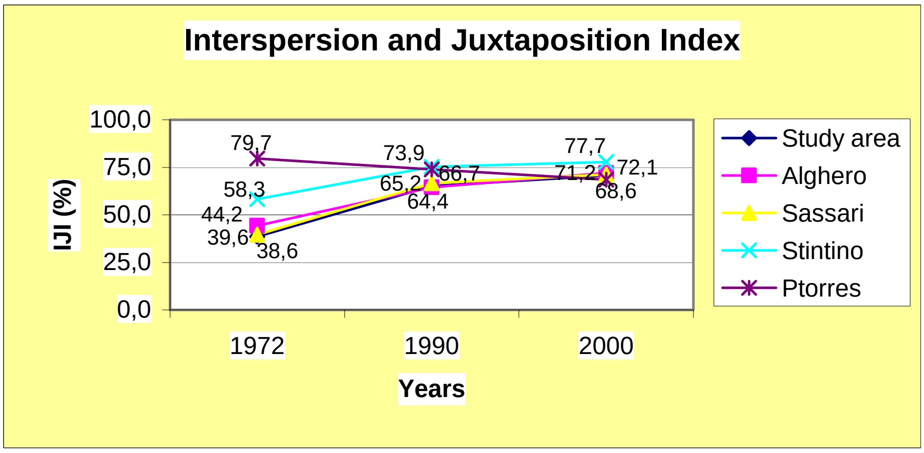

Figure 48 - Interspersion and Juxtaposition Index in 1972, 1990 and 2000.

In the municipalities of Alghero, Sassari and Stintino, and in the study area, IJI showed a continuos increasing trend, in particular between 1972 and 1990. Only in the municipalities of Porto Torres did IJI show a slight continuous trend to decrease (from 79,7% to 73,9% and to 68,6%).

5.3.4 Barren areas

In figure 49 the Landscape Shape Index for barren areas is illustrated.

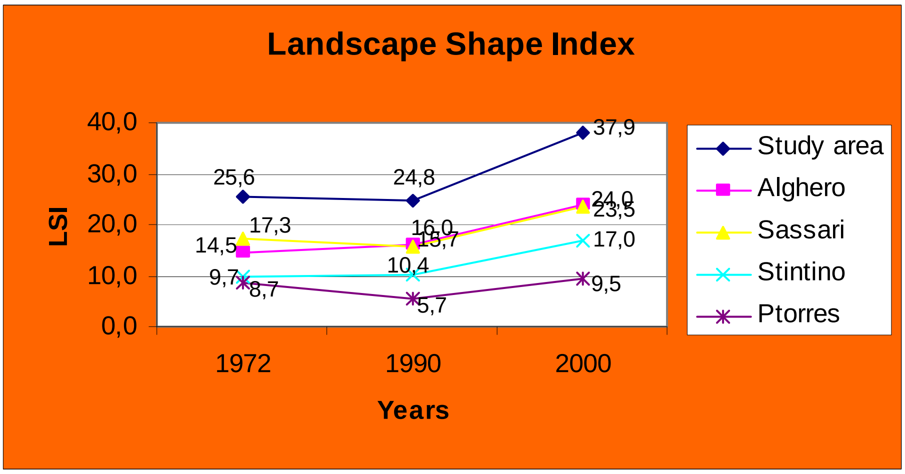

Figure 49 - Landscape Shape Index in 1972, 1990 and 2000.

In the study area, as in the municipalities of Sassari and Porto Torres, LSI decreased between 1972 and 1990 and grew over the period 1990-2000. In the municipalities of Alghero and Stintino the index showed an increasing trend over time (from 14,5 in 1972 to 16,0 in 1990 and to 24,0 in 2000 and from 9,7 in 1972 to 10,4 in 1990 to 17,0 in 2000).

In figure 50 the Mean Euclidean Nearest Neighbor Distance is represented.

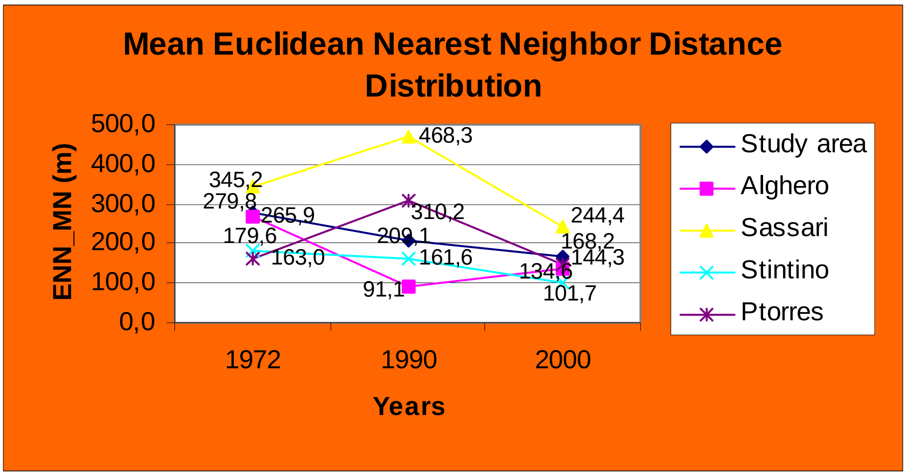

Figure 50 - Mean Euclidean Nearest-Neighbor Distance in 1972, 1990 and 2000.

ENN_MN tended to decrease in the study area over time (from 279,8 m in 1972 to 209,1 m in 1990 to 168,2 m in 2000). Only the municipality of Stintino showed the same decreasing trend as the study area (from 179,6 m in 1972 to 161,6 m in 1990 to 101,7 m in 2000). In the municipality of Alghero ENN_MN showed a drop between 1972 and 1990 (from 265,9 m to 91,1 m) and a rise between 1990 and 2000 (from 91,1 m to 134,6 m). The municipalities of Sassari and Porto Torres showed the opposite behavior, thus increasing between 1972 and 1990 (from 345,2 m to 468,3 m) and declining over the period 1990-2000 (from 468,3 m to 244,4 m).

In figure 51 the Interspersion and Juxtaposition Index is represented.

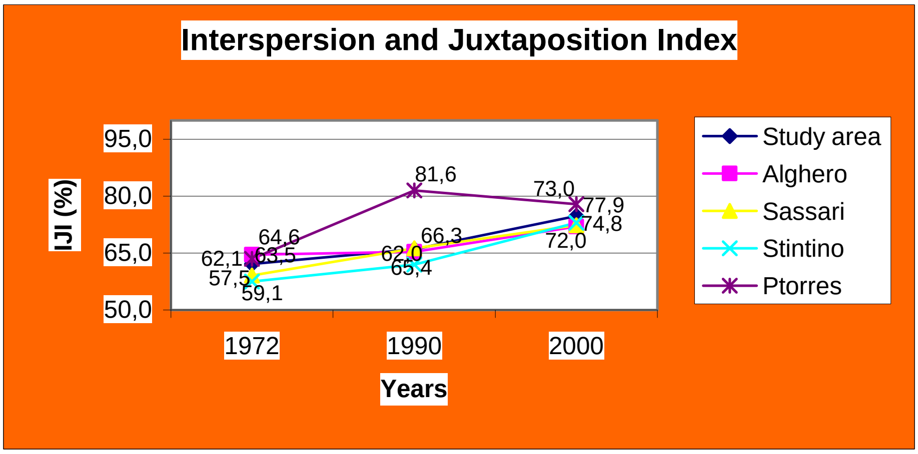

Figure 51 - Interspersion and Juxtaposition Index in 1972, 1990 and 2000.

In general, IJI showed a continuous increasing trend over time in the study area, as in the municipalities of Alghero, Sassari and Stintino. IJI values in these cases ranged between about 57% and 75%.

In the municipality of Porto Torres IJI showed a considerable growth between 1972 and 1990 and a slight decline between 1990 and 2000. In 1990 IJI reached the highest value for barren areas (81,6%).

In figure 52 the Patch Cohesion Index is represented.

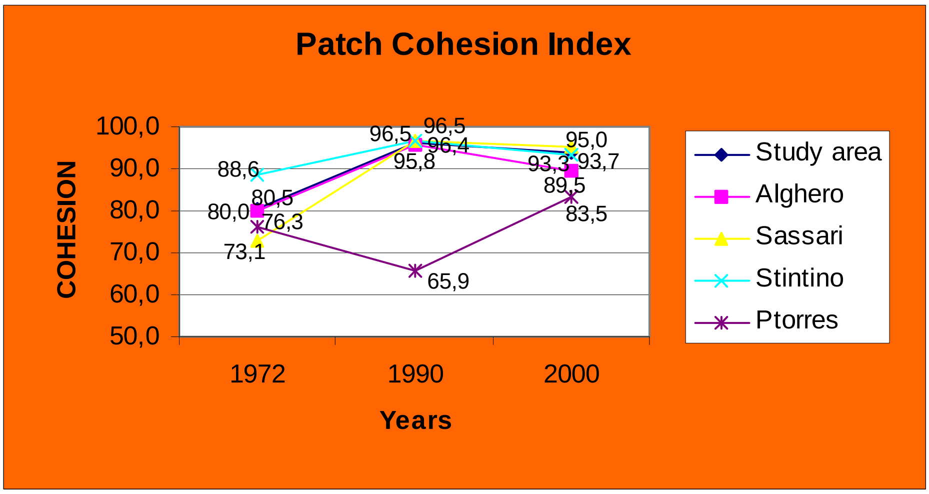

Figure 52 - Patch Cohesion Index in 1972, 1990 and 2000.

The COHESION Index increased over the first study period in the study area and in the municipalities of Alghero, Sassari and Stintino, approaching values equal to 95-96.

Only in the municipality of Porto Torres did the index show an initial decline (from 73,1 to 65,9) and a successive increase (from 65,9 to 83,5).

5.4 Landscape composition at landscape level

Landscape composition at landscape level was investigated through the following metrics: Number of Patches (NP), Patch Density (PD), Mean Patch Area (AREA_MN), Largest Patch Index (LPI) and Shannon's Diversity Index (SHDI).

In figure 53 NP for the overall study area and the four municipalities is illustrated.

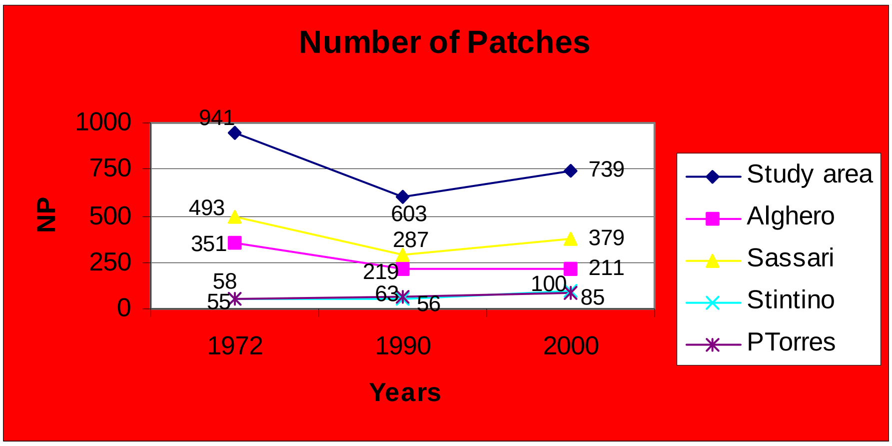

Figure 53 - Number of Patches in 1972, 1990 and 2000.

In the study area and in the municipalities of Sassari, NP decreased between 1972 and 1990 and increased between 1990 and 2000. A continuous trend to decrease was identified in the municipality of Alghero, while a continuous trend to increase was observed in the municipalities of Stintino (58 in 1972, 63 in 1990 and 100 in 2000) and Porto Torres (55 in 1972, 56 in 1990 and 85 in 2000).

In the following figure the Patch Density is illustrated.

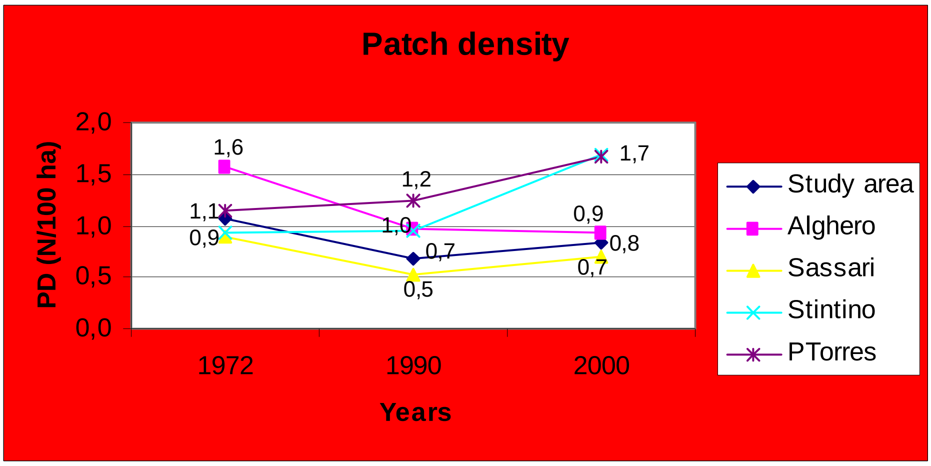

Figure 54 - Patch Density in 1972, 1990 and 2000.

Patch Density in the study area, and in the municipality of Sassari, showed a decline between 1972 and 1990 and a slight growth between 1990 and 2000. In the municipality of Alghero PD showed a continuous trend to decline, while in the municipalities of Stintino and Porto Torres a continuous trend to grow.

In figure 55 the Mean Patch Area is illustrated.

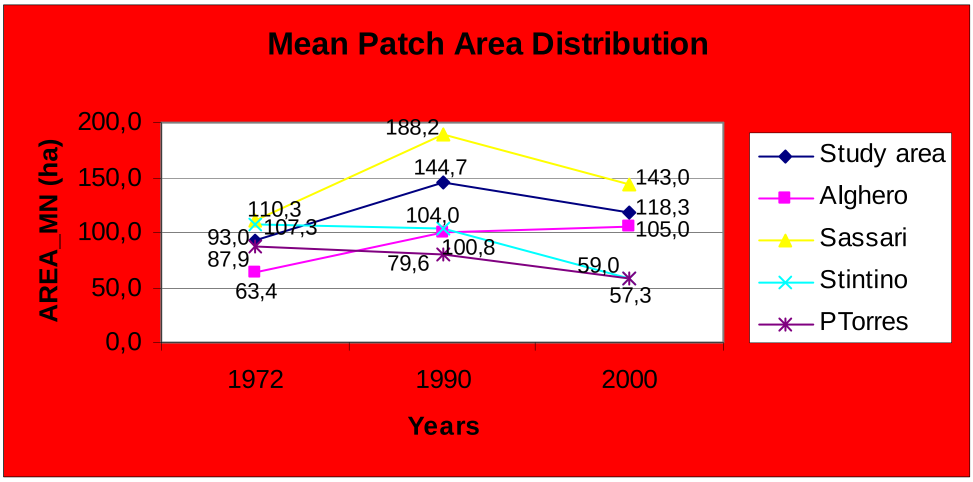

Figure 55 - Mean Patch Area Distribution in 1972, 1990 and 2000.

In the study area, and in the municipalities of Sassari, AREA_MN grew between 1972 and 1990 and dropped over the decade 1990-2000. A continuous trend to rise was assessed in the municipality of Alghero, while a continuous trend to fall was found in the municipalities of Stintino (107,3 ha in 1972, 104,0 ha 1990 and 59,0 ha in 2000) and Porto Torres (87,9 ha in 1972, 79,6 ha in 1990 and 57,3 ha in 2000).

In the following figure the Largest Patch Index is illustrated.

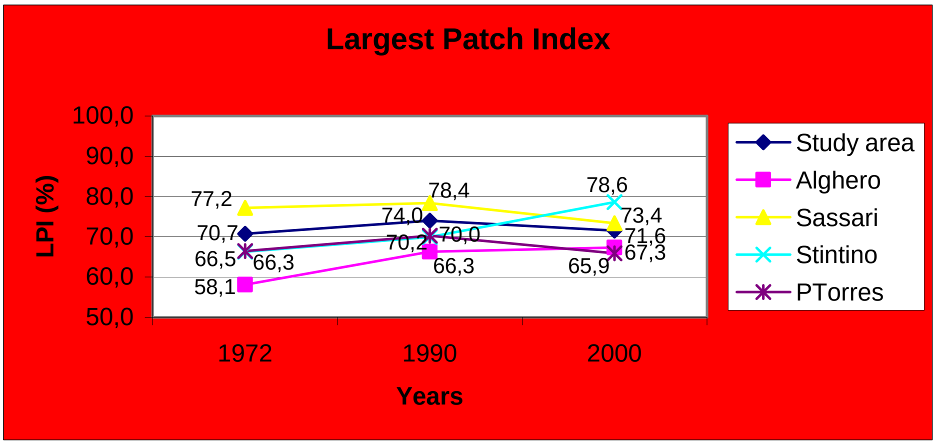

Figure 56 - Largest Patch Index in 1972, 1990 and 2000.

LPI showed a rise between 1972 and 1990 a fall over the decade 1990-2000 in the study area and in the municipalities of Sassari and Porto Torres. In the municipalities of Alghero and Stintino LPI showed a continuous trend to increase (58,1% in 1972, 66,3% in 1990, 65,9% in 2000 and 66,3% in 1972, 70,0% in 1990 and 78,6% in 2000).

In figure 57 the Shannon's Diversity Index is represented.

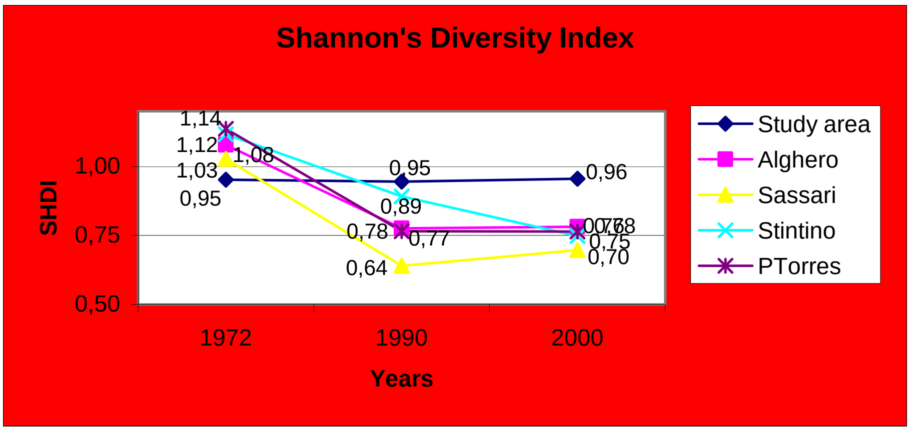

Figure 57 - SHannon's Diversity Index in 1972, 1990 and 2000.

SHDI showed rather constant values in the study area (1,03 in 1972, 0,95 in 1990 and 0,96 in 2000). In the municipalities of Alghero, Sassari and Porto Torres the index decreased significantly between 1972 and 1990 and then continued to be constant. The municipality of Stintino was the only municipality in which the index showed a constant decrease over time (1,14 in 1972, 0,89 in 1990 and 0,75 in 2000).

5.5 Landscape configuration at landscape level

Landscape configuration at landscape level was investigated through the following metrics: Landscape Shape Index (LSI), Mean Euclidean Nearest Neighbor Distance (ENN_MN) and Interspersion and Juxtaposition Index (IJI).

Landscape Shape Index is illustrated in the following figure.

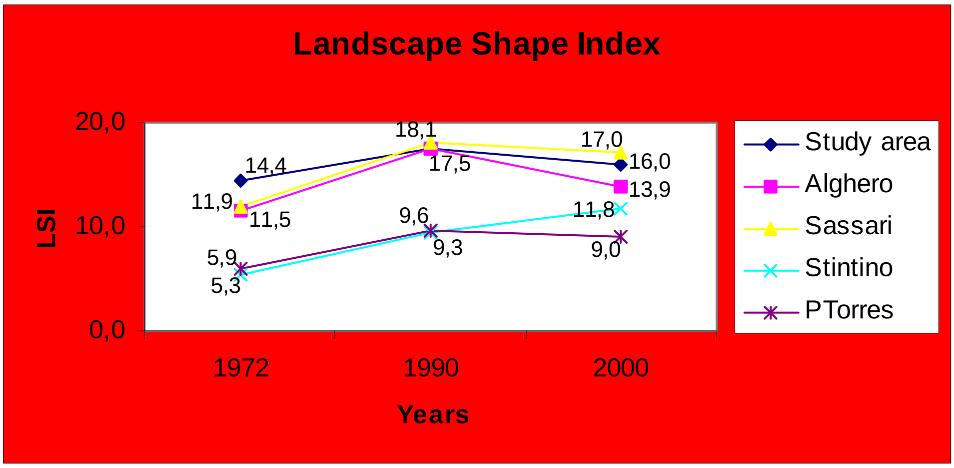

Figure 58 - Landscape Shape Index in 1972, 1990 and 2000.

LSI showed an increase between 1972 and 1990 and a slight decline between 1990 and 2000 in the study area and in the municipalities Alghero, Sassari and Porto Torres. Only in the municipality of Stintino did the index increase continuously over time (from 5,3 in 1972 to 11,8 in 2000).

In the following figure the Mean Euclidean Nearest Neighbor Distance is illustrated.

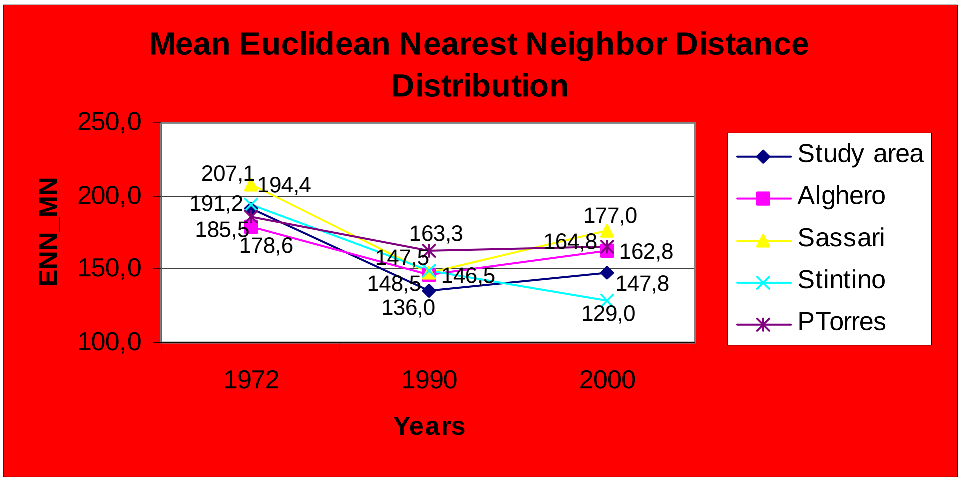

Figure 59 - Mean Euclidean Nearest Neighbor Distance in 1972, 1990 and 2000.

ENN_MN showed the same behavior in the study area and in the municipalities of Alghero, Sassari and Porto Torres, with a strong lowering between 1972 and 1990 and a slight growth between 1990 and 2000. Only in the municipality of Stintino the index showed a continous trend to decline (from 194,4 m in 1972 to 129,0 m in 2000).

In the following figure the Interspersion and Juxtaposition Index is illustrated.

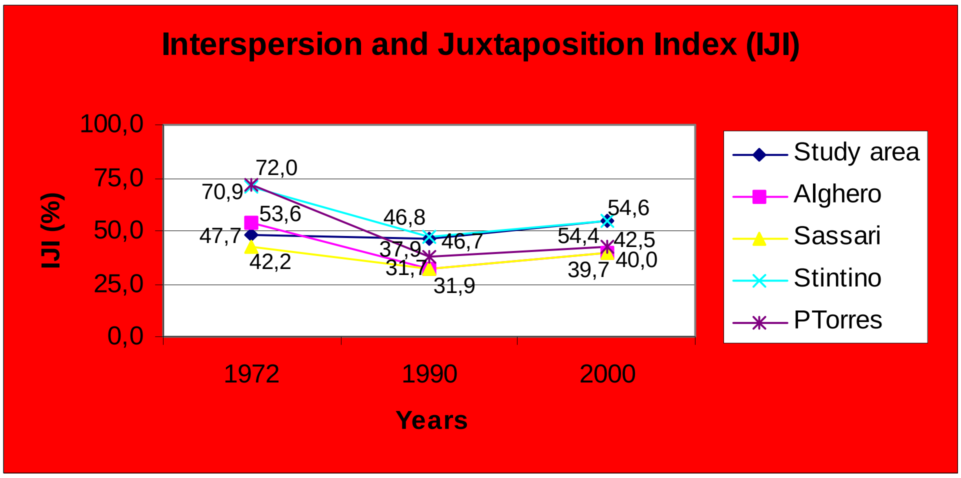

Figure 60 - Interspersion and Juxtaposition Index in 1972, 1990 and 2000.

IJI showed the same behavior in the study area and in the four municipalities, with a decline between 1972 and 1990 and a growth over the period 1990-2000.

5.6 Synthetic indexes for the monitoring of forest fragmentation, urbanization and landscape structure change

At class level we analyzed the change of urbanization and forest fragmentation spatial patterns and at landscape level the change of landscape structure, by means of specific sets of metrics selected in order to reinforce our interpretation.

Furthermore, we set up a classification system for each landscape metrics in order to combine them and to obtain synthetic indexes.

In the following figures the maps of the synthetic indexes are illustrated.

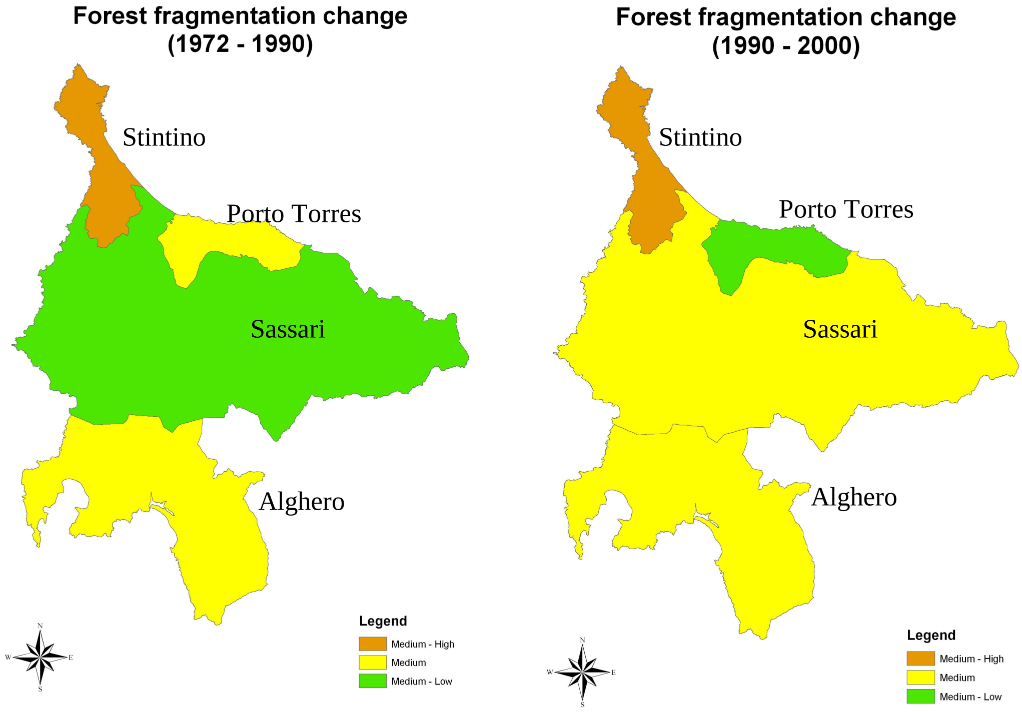

Figure 61 - Synthetic index of forest fragmentation change (1972 – 1990; 1990 – 2000).

Figure 61 illustrates the synthetic index of forest fragmentation for the two periods investigated. The synthetic index of forest fragmentation change was obtained by the combination of five landscape metrics: Number of Patches, Mean Patch Area, Largest Patch Index, Mean Euclidean Nearest Neighbor and Cohesion.

As seen in the figures both the maps indicate the municipality of Stintino as the area in which the process of forest fragmentation was found to be the highest. Here, in fact, a very clear trend toward forest fragmentation was observed with a continuous trend over time toward an increase in the number of forest patches, a decreasing mean patch area and a reduction in the largest forest patch, connected to an increase in the isolation of forest patch and a decline in the forest connectivity.

The high values of the index found in the municipality of Stintino clearly reflect a persistent process over time, in which all the landscape metrics experimented negative trends.

In figure 62 the change of urbanization level that occurred in the area over time is illustrated.

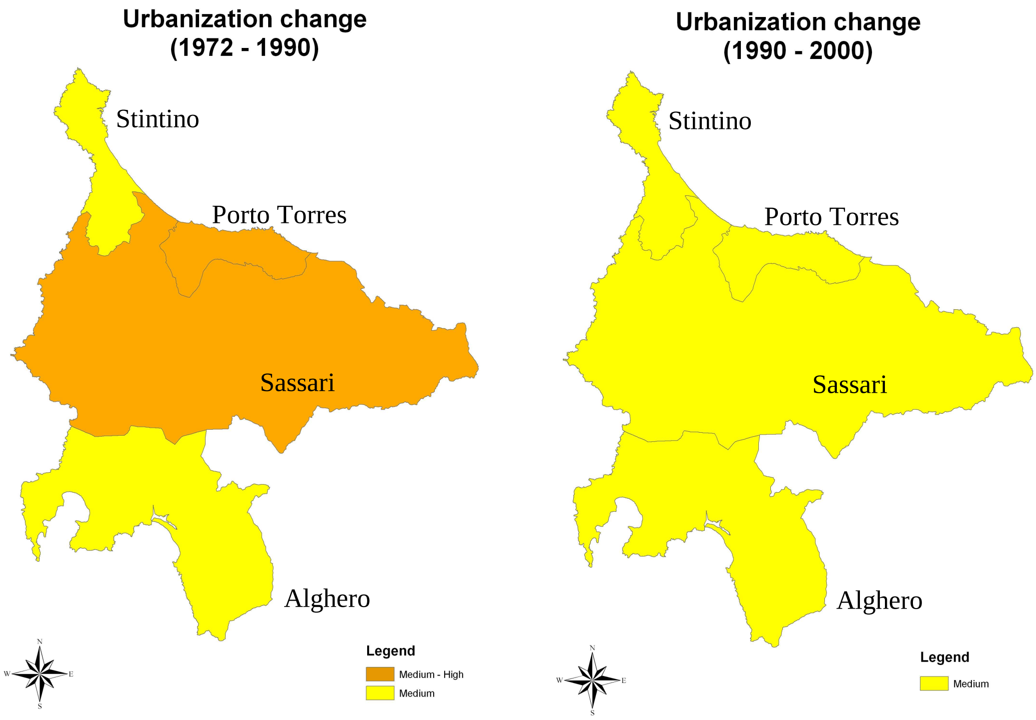

Figure 62 - Synthetic index of urbanization change (1972 – 1990; 1990 – 2000).

The synthetic index of urbanization change was calculated by the combination of the following four landscape metrics: Patch Density, Mean Patch Area, Mean Euclidean Nearest Neighbor and Largest Patch Index. The index does not reflect only the enlargement of urban areas, but the way how it took place over time.

As illustrated in figure 62 the municipalities of Porto Torres and Sassari showed a medium – high level of urbanization between 1972 and 1990. As enlightened in

Weng (2007), the degree of fragmentation of urban areas is positively related to the degree of urbanization.

In these areas, the fragmentation of urban landscape is clearly linked to the strong increase in the urban density in the area and the strong reduction in the mean urban areas. New small urban areas are in some way dispersed in the landscape and not adjacent to each other, thus leading to an increase in the habitat fragmentation and to more severe impacts (Gonzalez-Abraham et al., 2007).

In figure 63 the synthetic index of landscape structure change is represented.

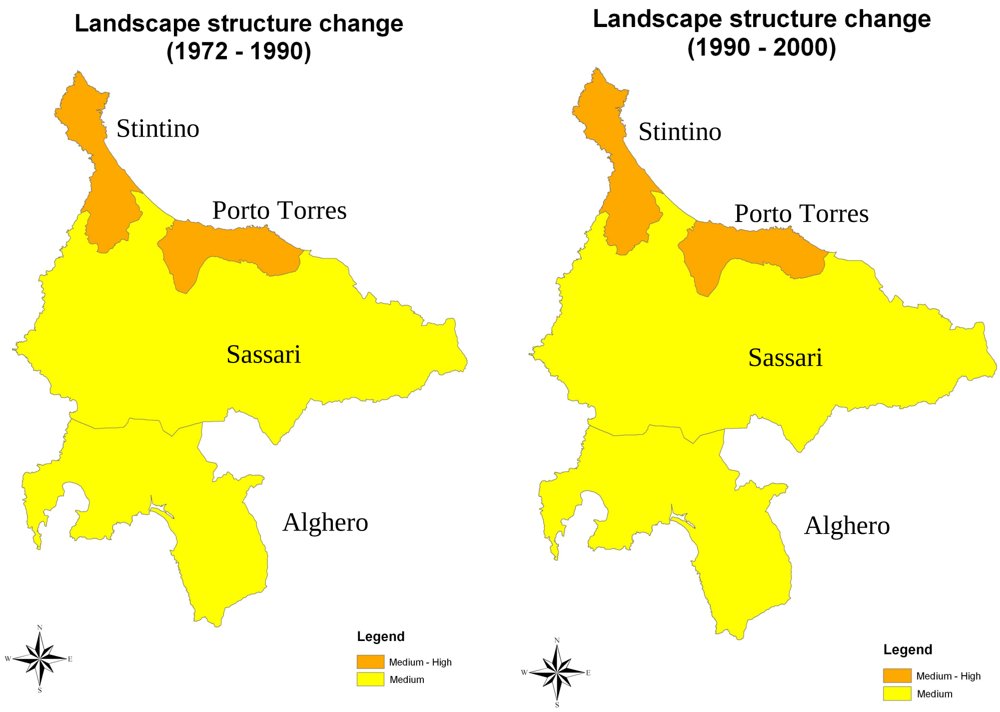

Figure 63 - Synthetic index of landscape structure change (1972 – 1990; 1990 – 2000).

The synthetic index of landscape structure change was calculated by means of the combination of the following five landscape metrics: Number of Patches, Mean Patch Area, SHannon's Diversity Index, Landscape Shape Index, Mean Euclidean Nearest Neighbor Distance.

As seen in the figure 63 the municipalities of Stintino and Porto Torres showed the highest level of change in the landscape structure toward a more fragmented landscape characterized by increasingly smaller and contiguous patches per unit area, decreasingly heterogeneous land cover structure, more irregular patches and closer links with each other. These results were found to be in accordance with the research findings found in literature for areas prone to desertification and land degradation (Li et al., 2004; Herzog et al., 2001).

In particular, the municipality of Stintino was the only municipality in which the diversity index continuously decreased over time, according to the assumption that the greater land use diversity is, in terms of small and contiguous plots of different land uses, the smaller the risk of land degradation and the higher biodiversity (Desertlinks, 2005).

6. DISCUSSION AND CONCLUSION

Key concept: *when dynamic processes are investigated, it is not only important to assess the location, the magnitude and the direction of changes, but also to investigate the way how the changes took place.*

Chapter VI is subdivided into two parts: the discussion and the conclusions. The discussion is, in turn, subdivided into two parts: methodology and results.

In the first part of the discussion the main technical and methodological aspects of the procedure are focused on and analysed, in order to give the most correct interpretation of the results and to point out possible further improvements of the approach proposed.

In the second part, all the results described in the Chapter V are compared, synthesized and commented on, taking into account the main findings of the MEDALUS methodology.

Finally the conclusions summarize the main findings of the research and set the basis for further development in the field of landscape ecology for the monitoring of desertification processes.

6.1 Discussion

6.1.1 Methodology

A technical analysis of the methodology implemented was required in order to give the most correct interpretation of the results obtained. Otherwise, the risk of an incorrect interpretation could be probable. Weak and strong points were therefore recognized and pointed out.

Weak points

The weak points of the methodology were mainly related to the technical characteristics of the satellite images set and to the theoretic background required before performing a landscape analysis.

The use of Landsat MSS 1972 implied a series of technical problems.

First of all, the lack of ground truth dating back to 1972 limited the performance of the classification procedure and the evaluation of its accuracy, which was therefore limited to few known and unchanged ground points.

Overlaying images with different spatial resolution required the resampling procedure in order to overlay images with pixel of similar dimensions, without enhancing the informative content of the image. Given the study scale of the present research and the dimension of the minimum mapping unit (5 ha) this operation did not affect the correctness of our analysis but it represents an important issue in case of more detailed analysis.

Before implementing the post-classification comparison, we focused on some possible sources of uncertainty. This approach, in fact, required very good accuracy in both classifications because the accuracy of the change map is the product of the accuracies of the individual classifications (Singh, 1989; Lambin and Strahler, 1994). The importance of accurate spatial registration of multi-temporal imagery is also self evident because spurious results of change detection will be produced if there is misregistration. Furthermore, misregistration of the polygon boundaries in the different classifications could lead to the presence of border pixels with false positive or negative changes.

Another unavoidable weak point was determined by the use of images dating back to different periods of the year: August (1972), May (1990) and June (2000). In fact, different periods could imply different phenological phases, different spectral responses, different water bodies volumes and therefore possible misleading interpretations. This is true in particular when the distinction between forestlands and croplands is performed. Of course, this problem could be magnified in case a more detailed classification and the distinction between different species of forests are required.

Once the analysis of satellite images had been performed, we took into consideration further technical aspects. Among these, the basic concepts related to landscape analysis were of primary importance.

The first point regarded the definition of the landscape, its units and the scale of the analysis (extent and grain): the meaning of the results, in fact, strictly depends on these definitions. A preliminary description of these concepts and the patterns to be investigated was therefore required in order to avoid wrong interpretations. Hence, the computed value of any metric is merely a function of how the investigator chose to define and scale the landscape.

In addition, current use of landscape metrics is constrained by the lack of a proper theoretical understanding of metric behavior. The interpretation of a landscape metric is contingent upon having an adequate understanding of how it responds to variations in landscape patterns. Failure to understand the theoretical behavior of the metric can lead to erroneous interpretations (McGarigal et al., 2002).

Furthermore, although the literature is replete with metrics now available to describe landscape patterns, there is seldom a one-to-one relationship between metric values and spatial patterns. Most of the metrics are, in fact, correlated among themselves as they measure a similar or identical aspect of landscape pattern. It is, however, unlikely that a single landscape metric set exists and explicitly reflects specific patterns.

We therefore adequately selected and defined appropriate landscape metric sets, reflecting some hypothesis found in literature about the observed landscape pattern and what processes or constraints might be responsible for that pattern. In this context, we combined specific set of metrics together in order to better understand and capture the spatial pattern change of urbanization and forest fragmentation at class level and landscape structure at landscape level.

In this context, the scarcity in literature of landscape metrics adequately set up and applied in the monitoring of desertification sometimes made it difficult to reinforce our interpretations.

Finally, our approach investigated only one aspect of the wide and interdisciplinary issue that is desertification. An exhaustive approach to the monitoring of desertification, including further environmental investigations on geomorphologic, climatologic and socio-economic aspects, was in fact out of the scope of the present thesis.

Strong points

One main advantage of remote sensing techniques is their ability to provide a synoptic view of a wide area in a single frame. Remote sensing systems can provide

data and information in areas where access is difficult and, together with GIS techniques, can integrate multiple, interrelated data sources and analysis procedures.
It could also be a multispectral sensing wherein data on the same site is acquired in different spectral bands, thus providing different information. Or, it could be a multitemporal sensing whereby data is collected on the same site on different dates, thus allowing a multitemporal dynamic analysis in large areas.
This is a prerequisite when the monitoring of desertification processes is required.

Furthermore, the methodology proposed requires a limited amount of data, thus avoiding problems related to the collection and the elaboration of different data, coming from different sources and, often, dating back to different periods.
The main source of the methodology is, in fact, land cover which is a familiar attribute in landscape descriptions and relatively easy to collect and quick to interpret from remote-sensing imagery. While reflecting the interaction of biophysical factors and socio-economic conditions at specific points in time, it represents an invaluable summary of the physical and socio-economic environment of an area.
In this context the procedure described, if appropriately implemented, has the potential to perform semiautomatic analysis and, therefore, to be at any rate exportable in broader areas.

Finally, the landscape indicators investigated and set up in the present research have the potential to represent important tools able to integrate the standard approach commonly used until now for the monitoring of desertification.
Compared to the state indicators of the MEDALUS methodology (Kosmas et al., 1999), in fact, they represent dynamic indicators as they reflect variations occurred over time. Furthermore, they represent rather new indicators able to provide additional and complementary information to those provided by the common indicators used up to now: compared to the simple land cover analysis commonly used to assess the location, the magnitude and the direction of changes, the landscape approach allowed to investigate the way how the changes took place. This is very important, in particular when dynamic processes are investigated.
In this sense, the landscape indicators could provide the basis for a better understanding and quantifying of the processes under investigation.

The classification scheme of the landscape metrics set up in the present research, in order to combine the various landscape indicators into synthetic indexes for each spatial pattern under investigation, needs of course to be further improved and tested, but the results obtained demonstrated to be in line with the main findings derived from the MEDALUS analysis.

6.1.2 Results

The analysis of the results obtained started and took into account the main findings derived from the MEDALUS methodology applied in the study area (Motroni et al., 2004), according to which the municipalities of Porto Torres (Pt) and Stintino (St) resulted the most sensitive municipalities to desertification.

The municipality of Alghero (Al) showed a relevant part of the territory belonging to less critical classes (F) and some small areas classified as potential or non-threatened, thus having the most well-balanced territory between more and less sensitive areas to desertification. The municipality of Sassari could be placed in an intermediate level of a scheme to represent the relative sensitivity to desertification of each municipality (fig. 64).

Figure 64 - Scheme representing the relative sensitivity to desertification of each municipality in the study area. St = Stintino; Pt = Porto Torres; Ss = Sassari; Al = Alghero.

Study area

By means of the methodology implemented we assessed and characterised the spatial patterns as they occurred in the study area over the twenty-eight years period investigated. Croplands were found to be the dominant land cover class in the study area (matrix of the landscape) and, together with forestlands and urban areas, affected the functioning of the landscape and its evolution over time.

The landscape dynamic in this area was therefore strictly the consequence of the interrelation between croplands, forestlands and urban areas over time. Forest cover change identified in the study area was linked in particular to urban sprawl and expansion of croplands, thus representing one of the degradation factors within the area investigated.

Barren areas played a minor role, showing, however, a slight trend towards an enlargement due, in particular, to the persistent and recurrent problem of fires in Sardinia.

The dynamics of croplands and forestlands were strictly linked: the expansion of croplands took place mainly to the detriment of forestlands and viceversa.

We pointed out a reversal trend in 1990. Croplands showed, in fact, the same temporal trend in all the municipalities with a rise between 1972 and 1990 and a decline over the decade 1990-2000.

Furthermore, we demonstrated and quantified the occurrence of a clear and continuous process of urban expansion in the four areas over the period 1972-2000.

This process was particularly significant in the municipalities of Sassari and Stintino, where the net increase of urban areas was higher than the average estimated in the study area (1,9% and 2,7%, respectively). The driving forces leading to this increase were probably different in the two areas, as explained below.

An enlargement over time of barren areas was identified along the western coast, in a continuous way, and was mostly linked to the widespread forest fires that frequently affected the area.

The changes that occurred in the study area between 1990 and 2000 (4,9%) were slightly higher than the changes that occurred between 1972 and 1990 (3,7%). The values obtained indicated that the rate by which the territory was transformed consistently increased, thus revealing an accelerating trend over the last decade.

Forestlands to croplands (FS to CP) and croplands to forestlands (CP to FS) represented the two major types of transformation which took place in the study area over the two periods: FS to CP was the prevailing transformation over the first period, while CP to FS dominated the changes over the second period.

Urban driven transformations were different: between 1972 and 1990 urban areas were built mainly to the detriment of forestlands, while between 1990 and 2000 new urban areas took place to the detriment of croplands. Particularly over the first period, changes were negative and led to the loss of a large amount of forests, which were partially recovered over the second period investigated.

In Sardinia, the choice of the species to be used for reforestation is strictly linked to economic requirements or, in some cases, to touristic, recreational and environmental reasons.

Until the sixties reforestation was realised in the more degraded soils with conifers (*pinus pinea*, *pinus pinaster*, *pinus halepensis*, *cupressus sempervirens* and exotic species), such as the littoral pinewood in the area of Alghero. As far back as the seventies, the considerable public funds and the private and public contributions allowed the plantation of fast-growing species such as *pinus radiata* but fires, in particular, reduced in a considerable way this kind of forests.

The majority of changes that have occurred in the area investigated should be classified as negative from the perspective of the sensitivity to desertification, leading to a considerable loss of forests and a significant gain in croplands, urban areas and barren areas.

In this context, these findings were in line with the results of the MEDALUS methodology (Motroni et al., 2004) and explained, at least in part, the environmental sensitivity of the area.

At the municipality level, the conversion from forestlands to croplands dominated the dynamic changes that occurred in the areas over the first period and the transformation from croplands to forestlands represented the prevailing transformation over the second period investigated, with the exception being the municipality of Stintino.

On the basis of the analysis and comparison of the landscape metrics at different levels, and by means of an appropriate combination of landscape metrics into synthetic indexes, we identified areas in which specific spatial patterns related to land degradation occurred in a more intense way. In particular, the analysis of forestlands and urban areas and the use of indicators related to forest fragmentation, urbanization and landscape structure allowed us to identify noteworthy differences among the municipalities.

Based on the land cover and landscape evolution patterns, thus we distinguished the four municipalities into two different classes: the first class includes the municipalities of Alghero and Sassari, where the landscape evolution was found to be similar to the evolution assessed in the overall study area; the second one comprises the municipalities of Stintino and Porto Torres, where the land cover classes distribution and the landscape evolution were found to be different, compared to the overall study area.

Alghero and Sassari

Percentage-wise, compared to the values observed in the study area, in the municipality of Alghero a larger extension of forestlands was assessed.

Here, the large forest patches showed a constant high degree of connectivity, with the highest percentage of forest recovery from croplands in the decade 1990-2000 and an enlargement of the largest forest patch which could, at least in part, explain the lower degree of environmental sensitivity of the area.

Land cover classes distribution indicated for this area the lower rate of urban sprawl, within the study area.

Compared to the values observed in the study area, percentage-wise, in the municipality of Sassari a larger extension of croplands was assessed.

The urban sprawl that occurred around the city of Sassari, which is the second city of Sardinia, was the obvious consequence of the process of urbanization from small rural villages to the urban centres. Urbanization has been quickening due to an increase in population and to migration from rural to urban areas, due to employment opportunities in the main urban center. As the city grew, the increasing concentration of population and economic activities demanded that more land be developed for public infrastructure, housing, industrial and commercial uses.

By means of appropriate combinations of landscape metrics, we pointed out that in the municipality of Sassari between 1972 and 1990 the new urban settlements grew in a sparse way, thus making the landscape more fragmented and denoting a high degree of urbanization with potential negative effects on the properties and functions of the ecosystem (Gonzalez-Abraham et al., 2007). This process was found to be similar to that occurred in the municipality of Porto Torres.

As regards water bodies, some signs of reduction in their extension over time, in particular in the area of the Baratz lake, where massive withdrawals for agricultural uses and scarcity of rainfall strongly threatened its survival, were identified.

Porto Torres

Compared to the values observed in the study area, the municipality of Porto Torres showed a significative higher extension of urban areas and a lower surface devoted to croplands and forestlands.

Here, urban areas represented the second land cover class in terms of extension, covering about 21% of the territory in 2000. The municipality of Porto Torres represented, in actuality, the most highly urbanized municipality within the study area because of the industrial pole and the related activities. Forestlands, on the other hand, showed the lowest values equal to about half that of the values assessed in the study area.

In this area, where the percentage of urban areas was already very high, urban sprawl was characterised by an increase in small urban patches per area, thus leading to a clear increase in the urban Patch Density and a decrease in the Mean urban Area.

By means of appropriate combinations of landscape metrics, we demonstrated that in the municipalities of Porto Torres between 1972 and 1990 the new urban settlements grew in a sparse way, thus making the landscape more fragmented and denoting a high degree of urbanization with potential negative effects on the properties and functions of the ecosystem (Gonzalez-Abraham et al., 2007).

Stintino

In terms of land cover change, the municipality of Stintino was characterised by an expansion of croplands and barren areas and a significative reduction in forestlands. As a matter of fact, land cover classes distribution showed a deeply different temporal dynamic, compared to the other municipalities: forestlands showed a continuous decreasing trend, in particular between 1972 and 1990, and a net loss in the study period of about 8%, corresponding to more than four times than the net loss that occurred in the study area. In this area the highest values of barren areas was also found.

Unlike the other municipalities, here almost all the transformations induced a considerable loss in the forest ecosystems, thus leading to a negative balance of forests for the period investigated.

In terms of landscape tranformations, in the municipality of Stintino did the small forest patches continuously increase in number over time and the only large patch (> 500 ha), found in 1972, totally disappeared over time, leading to the halving of LPI. At the same time the Patch Density increased and the Mean Patch Area decreased over time. In this region, the structure of forested areas was increasingly complex in shape and spatially interspersed. Cohesion of forest landscape showed a continuous trend towards decreasing over time.

The synthetic index performed for forest fragmentation analysis, clearly demonstrated that the forest landscape of the municipality of Stintino has moved into a more fragmented structure, with more small fragments of forests that are more isolated, more irregular and less spatially connected. Here, in fact, forested areas were broken-up into smaller, more fragile, more irregular and more isolated units in favour of urban and crop areas, thus reducing their ability to resist the desertification and to recover from disturbances. Larger and better connected ecosystems, in fact, are typically better at conserving biodiversity and preventing from soil erosion and land degradation than smaller and more isolated ones.

As regards the expansion of urban areas, the process of urban sprawl that occurred in the municipality of Stintino was characterised by a significative enlargement in the size of the urban area of the city of Stintino, in particular between 1972 and 1990, and by a constant increase in the complexity of urban shapes and a very high interspersion of urban areas within the landscape.

The tourist vocation of Stintino represented the main driving force behind the expansion of urban areas, as new tourist settlements were built mainly along the northern side of the coastal areas. Rapid development of urbanization and tourism thus increased the demand for proper infrastructure such as roads, water facilities and utilities. As a result, areas used for settlements have expanded in extreme proportions, as planned urbanization. The obvious consequence was that this kind of urbanization consumed areas of agricultural land and forested areas that could be the cause of many harmful impacts on ecosystem structure, function and dynamics with negative consequences on biodiversity, biogeochemical cycles and land resources.

The increase in the number of croplands, and in particular in the number of small crop patches, characterised the agricultural landscape of the municipalities of Stintino and Porto Torres. The largest cultivated area in the municipality of Stintino continuously increased in extension over time and the transformation that occurred in the landscape led to a more complex structure in the agricultural landscape.

In addition, we examined the structural changes that occurred at landscape level and we identified a dissimilar behavior in the municipalities of Stintino and Porto Torres, compared to the other municipalities.

In these areas the landscape was increasingly characterised by an increasing number of patches and a decreasing trend in the Mean Area of patches.

In particular, the municipality of Stintino was the only municipality in which the diversity index continuously decreased over time, thus being in line with the assumption that the greater land use diversity is, in terms of small and contiguous plots of different land uses, the smaller the risk of land degradation and the higher biodiversity (Desertlinks, 2005).

In both the municipalities LSI tended to increase and ENN_MN tended to decrease.

The final index performed for the analysis of landscape structure change provided useful information about the evolution of the territory toward a more fragmented landscape characterized by increasingly smaller and contiguous patches per unit area, decreasingly heterogeneous land cover structure, more irregular patches and closer links with each other. These results were found to be in line with the research findings found in literature related to desertification and land degradation (Li et al., 2004; Herzog et al., 2001).

6.2 Conclusions

In the present research study, we explored and tested the concepts and methodology of a landscape approach in areas prone to desertification, where this kind of investigation has not been experimented on up until now. Up to now, the key research topics in landscape ecology have focused on ecological flows and processes in landscape mosaics, but landscape ecology has been rarely combined with the issue of desertification, in particular in the Mediterranean region.

The land cover and the landscape change monitoring in an area prone to desertification in Sardinia, provided an example of the integration of remote sensing, the Geographical Information Systems and landscape analysis in order to monitor the environmental changes that took place over a period of twenty-eight years.

The methodology implemented and the indicators set up proved to be powerful tools in detecting the location, the direction, the magnitude of the changes and in characterising the spatio-temporal dynamic of landscape in an area prone to desertification.

Multi-temporal remotely sensed images, including Landsat MSS and TM, were used to analyse the land cover change trajectories and landscape change and to identify the environmental changes occurred.

The use of a landscape approach allowed for an assessment of specific spatial patterns related to land degradation and desertification that can be used in developing practicable application plans at the regional level in desertification prevention planning and decision-making.

The methodology showed several advantages, but also some limits.

Some technical limits have been pointed out, thus setting the scene for further future improvements in the procedure. The use of images with different spatial resolution and dating back to different periods of the year, could lead to misleading results and interpretations. Furthermore, low spatial resolution images limited the analysis to few land cover classes and, as a consequence, allowed for the investigation of few spatial processes related to desertification.

On the other side, multi-temporal series covering a large area, with relatively low costs, limited technical problems and a limited amount of data required, represent some examples of the technical strong points of the methodology.

Furthermore, the landscape indicators investigated and set up in the present research represent important tools able to integrate the standard approach commonly used until now for the monitoring of desertification, as they represent rather new indicators able to provide additional and complementary information to those provided by the most common approaches and indicators.

For the analysis of the results obtained, we started and took into consideration the main findings derived from the MEDALUS methodology applied in the study area, according to which the municipalities of Porto Torres (Pt) and Stintino (St) resulted the most sensitive municipalities to desertification within the study area and the municipality of Alghero (Al) showed the most well-balanced territory between more and less sensitive areas to desertification.

The study area showed a high sensitivity to desertification all over the territory, especially in the municipalities of Stintino and Porto Torres, where forest fragmentation, expansion of agriculture and urban sprawl represented some of the main degradation factors, thus explaining, at least in part, the causes of their sensitivity to desertification.

The landscape of the study area was dominated by croplands, followed by forestlands and urban areas and its evolution was dominated by the strict interrelation of the three land cover classes.

Urban sprawl was a clear and continuous process over the twenty-eight years period, in particular in the municipalities of Stintino, Sassari and Porto Torres. Here, the new settlements grew closer and more contiguous in distribution never returning the territory to natural areas in an irreversible way. Due to population increase and to migration from rural to urban areas, as a consequence of the availability of employment opportunities in the main urban centers, rapid development of tourism and urbanization increased the demand for proper infrastructure, thus consuming areas of agricultural land and forested areas with negative impacts on the structure of ecosystems, their functions and dynamics.

In the municipality of Porto Torres and Sassari, in particular between 1972 and 1990, new urban settlements grew in a sparse way, thus leading to a landscape fragmentation and potential negative consequences on the ecosystems.

The results obtained deserve to be taken into account for the future urban planning. In these areas, the adoption of specific plans aiming at the conservation of the existent and surrounding ecosystems should be recommended in order to prevent them from a further land degradation and desertification. New urban infrastructures should be structured in such a way as to make improvements without depleting natural resources, conceiving green spaces and wildlife corridors, and developed inside the urban structure instead of urban expansion in the periphery. Cities should have an equilibrium where various economic, social and environmental interests are in balance. A strong emphasis should be put on public transport and new road development should be limited to a minimum. Furthermore, initiatives promoting farm holidays, sustainable agriculture and the maintenance of the rural landscape, should be encouraged in order to link the economic profit to the conservation of the ecosystems.

In a future, a city together with its surrounding countryside will be more sustainable if it is relatively self-sufficient. That means that it is capable of meeting its basic needs. That does not preclude trade with other cities and even more distant places, but the local region should not be dependent on that trade for survival. Both the city and the countryside should be self-sufficient in the production of the energy they need to function. Smaller cities can achieve these goals better than huge ones. Where appropriate, new development contiguous to urban boundaries should be organized as neighborhoods and districts, while non contiguous development should be organized as towns and villages with their own urban edges, not as bedrooms suburbs.

At any rate, a sustainable land management should consider the soil vocation, in particular for agricultural purposes, before performing actions leading to the conversion from one land cover to another.

Forest landscape showed a significant trend in the municipality of Stintino. In this area almost all the transformations induced a loss in forests leading up to four times that of the net loss that occurred in the study area. A clear process of forest fragmentation led to a more fragmented forest structure, with small fragments, more isolated and less spatially connected, in favour of urban areas and croplands, thus reducing their ability to resist the desertification and to recover from disturbances.

Information on forest fragmentation can help in addressing political measures to recognize the loss of cover vegetation in a specific area and to organize efficient controls and successively reduce desertification.

Where forest fragmentation was found to be evident, a sustainable strategy for recovering the forest ecosystem is obviously urgent. In many cases, in fact, the ecological value and function of forest fragments can be improved through restoration activities. Promoting reforestation and encouraging natural regeneration can enhance the size and shape of forest patches, the linkages between isolated patches and, therefore, the resistance to external disturbances and to land degradation. Not only are current interventions needed in the most vulnerable areas, but a far-sighted land plan is also required in order to avoid the fragmentation of large contiguous forest patches, to protect or minimally disturb the well structured forests, to concentrate disturbances (i. e. buildings, roads) along the edges, and not within the interior of forestlands, and finally to preserve or restore even the smallest of forest fragments.

Water bodies also showed signs of reduction in their extension over time (but the different acquisition period must be taken into account), in particular as regards the Baratz lake, where massive withdrawals for agricultural uses and scarcity of rainfall strongly threatened its survival.

At the landscape level, the final index performed for the landscape structure analysis provided useful information about the evolution of the territory in the municipalities of Stintino and Porto Torres toward a more fragmented landscape characterized by increasingly smaller and contiguous patches per unit area, decreasingly heterogeneous land cover structure, more irregular patches and closer links with each other. These results were found to be in line with the research findings found in literature related to desertification and land degradation (Li et al., 2004; Herzog et al., 2001). This type of landscape structure did not facilitate the conservation of landscape, as larger and connected ecosystems are typically better at conserving biodiversity and at preventing from soil erosion and land degradation than smaller and more isolated ones (Desertlinks, 2005).

The results obtained, and in particular the information derived by the synthetic indexes set up and performed for the purpose of the present research, demonstrated to be able in identifying the areas in which specific spatial patterns occurred at some degree of intensity as degradation factors thus explaining, at least in part, the sensitivity to desertification of specific areas.

The quantification of the amount of land cover change and the landscape assessment allowed for a better understanding of the past and current environmental conditions in the study area, thus setting the basis for the prevention of future negative consequences and a better design of future management and environmental policies. From an ecological perspective, in fact, the effects of the change in land cover and landscape on desertification may be twofold, as negative and positive impacts could occur.

The results of the study that actually achieved analyses and monitoring of land cover and landscape change over time have, therefore, made an important step towards warning the authorities of the circumstances of the past and current land cover and landscape changes and their consequences.

In general, the necessity to find a balance between economic development and an increase in population along the coastal areas, while conserving and maintaining their unique scenic and environmental qualities, is required. The key objective should be a sustainable balance between tourism, urbanization, industrialization and environmental resources.

Concrete recommendations for managing the area should be better defined after a high resolution investigation, in order to better characterize the degradation factors of the area.

At the scale investigated, some general recommendations could be given anyway.

Where high degradation or sensitivity to desertification was identified, the closure of degraded forest areas could favour the natural vegetative recovery. In the areas in which forests were completely lost, reforestation interventions would be required. The main species to be used should be the native species, such as *Quercus suber*, *Quercus ilex*, *Quercus pubescens*, *Pinus pinaster*, *Pinus halepensis* or other species such as *Pinus pinea* and, where the pedo-climatic conditions are favorable, autochthonous and exotic species like *Castanea sativa*, *Prunus avium*, *Populus*, *Cedrus atlantica*, *Cedrus deodara*, *Pinus nigra* and others.

Better measures for fire prevention are required in the overall area investigated. Furthermore, the strengthening of the bodies charged of the fight against fires should be performed more and more by improving the techniques and adequately reinforcing the equipment.

Water management techniques and irrigation measures should be improved and integrated into water protection and management plans. The Nurra region needs to be prepared more and more to the effects of droughts and for this reason the development of plans for prevention, mitigation and adaptation is required.

As tourism activities are concentrated in vulnerable areas, such as the coastal areas, the reduction in pressure from tourism could be achieved by means of incentives for diversification of the offer, for example.

Finally, the development of new urban infrastructures should be strictly based on sustainable principles calling for the use of technologies aimed at the renewal and appropriate use of natural resources.

Future research perspectives

Although the results of this exploratory study are encouraging, much work remains to be done in order to strengthen our knowledge about the use of landscape ecology principles and methods for the monitoring of desertification.

Future research perspectives will significantly benefit from high resolution satellite analysis, which will allow for the investigation of the landscape at a more detailed scale and to assess more spatial patterns of interest for the monitoring of desertification.

The necessity to improve our understanding of desertification patterns requires further investigations into the behavior of landscape metrics in other areas prone to desertification in the Mediterranean environment, where scarce analysis have been conducted up to now. Also, further research towards similar environments, still not sensitive to desertification, will be useful in order to capture and to compare the possible differences between sensitive and non sensitive areas. Moreover, various landscape metrics still require thorough investigation in areas sensitive to desertification.

The development of new indicators of desertification, able to capture the landscape dynamic processes and to explain the way how changes come about in a territory, will greatly allow us to gain a better understanding of this environmental threat, thus laying the basis for setting appropriate management and restoration strategies.

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