Land cover change in a rural area of the forest-steppe ecotone of Andean Patagonia, Argentina: Utilizing Landsat data for the detection and analyzing the change

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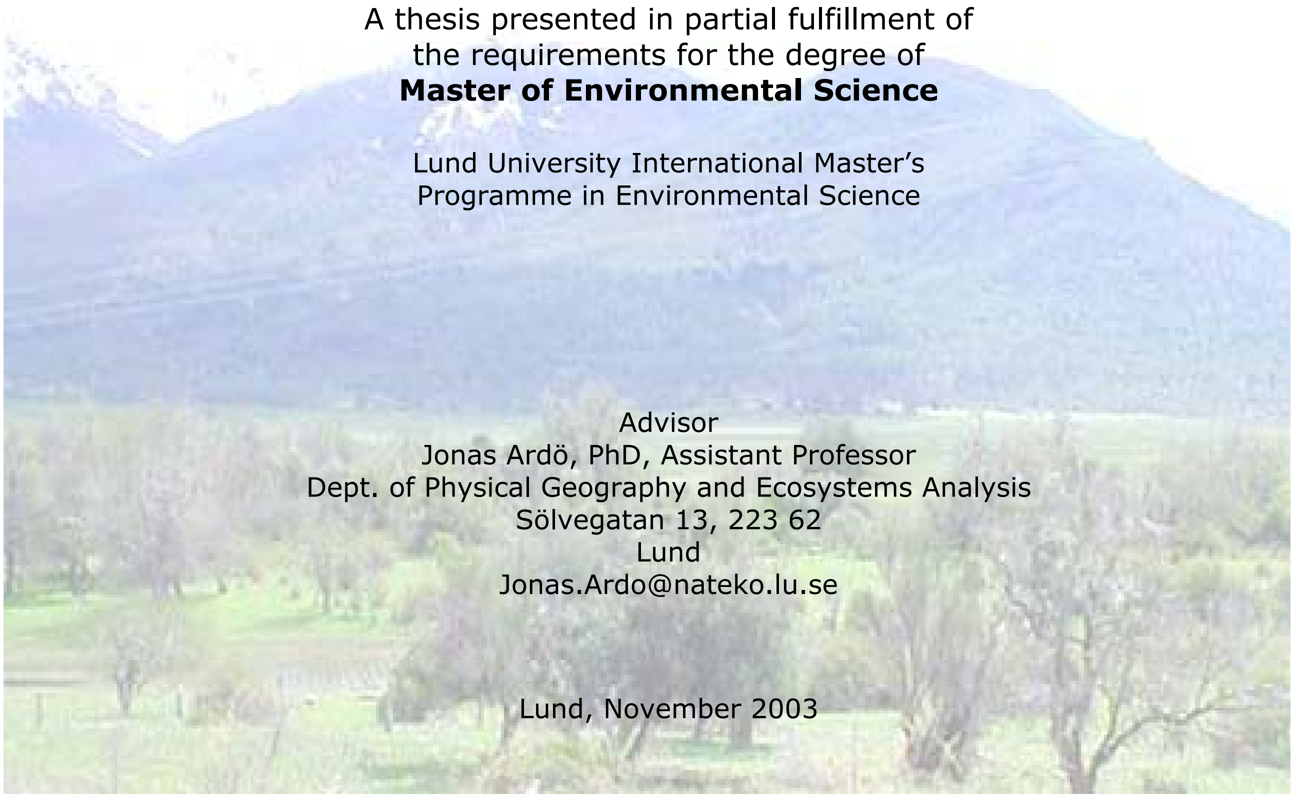

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Abstract

Changes in land cover at global level have been so large and rapid during the last century that they have constituted an abrupt shift in the human-environment condition. Land cover change must be understood in its complexity and nature, in order to comprehend the potential consequences, and the measures to be taken to avoid undesired outcomes and to enhance preferred effects. The identification of land cover changes in a region, coupled with documentation and monitoring, provides an observational base for raising awareness about the consequences of the activities developed, as well as the response of the land features to the natural events occurred in the considered period of time. This study concentrates on the detection of land cover change occurred between 1987 and 2003 in a rural area in the Argentinean Patagonia forest-steppe ecotone. The detection of directional change, and identification of its nature is considered to be relevant for the assessment of trends in the environmental conditions of the region, in order to make further considerations about sustainability in the area. Climate change, wildfires, overgrazing, introduction of foreign species, transition of economic activities, and the action of defoliating insects are analyzed as probable drivers of land cover change in the area. A remote sensing-based technique is used for the detection of changes. Results are given in the form of areal extent affected by land cover change, accounting for its negative or positive nature (i.e. decrease or increase of vegetation respectively). An overall increase in the amount of vegetation was found. Positive changes due to afforestation, and negative changes from the action of defoliating insects were identified. Positive vegetation changes in lowlands and grazing areas are likely to be described by a change in the composition of livestock, which increased the share of cattle and diminish the overall number of sheep. Invasion of sweetbriar rose in parts of the area has caused positive changes in the vegetation cover as well. The questionability of sustainability that is brought about by an increase in vegetation resulting from the introduction of exotic species is analyzed, as well as the possibilities they offer for increasing sustainability in the region. It is concluded that a detected increase in the vegetation cover cannot be translated immediately into an environmental improve and a parallel increase in sustainability before considering the nature of the land cover change and the potential consequences. In the case of this study, an overall increase in the vegetation cover does appear to indicate an increase in the sustainability of the area.

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"Most of the world's vegetation is in a state of permanent flux at a variety of temporal and spatial scales." The assertion made by Hobbs (1990) refers to the different processes vegetation is subjected to, which make land cover be in constant variation. Causes for land cover alterations are multiple, from seasonal variations and interannual variability, to directional changes (Hobbs, 1990). The latter group, *directional changes*, indicates a progressive or irreversible change in vegetation. Precisely due to those characteristics, it constitutes the central concern of this study.

During the past several thousand years, humans have taken an increasingly large role in the modification of the environment. As a matter of fact, changes in land cover are so large and rapid that they constitute an abrupt shift in the human-environment condition, surpassing the level of all past epoch-level events, since the raise of the human species (GCES)[1]. The abrupt increase observed in human population, more than fivefold to over 6 billion, and industrial activities that have busted atmospheric concentrations of carbon dioxide are considered to be major factors for land cover modification at the global level (Ojima *et al*, 1994). The human use of land is tightly related to land cover, and thus the latter cannot be considered independently; patterns and changes of land use profoundly affect the appearance of land cover. It has been estimated that, globally, the biotic function of 2.95 million km^2 of soils (equivalent to approximately the total area of Argentina) has been significantly disrupted by chemical and physical degradation human land use, occasioned especially by deforestation and grazing (GCES).

As it can be inferred, land cover changes are not simple processes; there are complex simultaneous patterns of land cover change, ranging from slight modifications to utter conversions. Land cover change has to be understood in its complexity and nature, in order to comprehend the potential consequences, and the measures to be taken to avoid undesired outcomes and to enhance preferred effects.

Even though global approaches have traditionally been the main focus of the land cover change realm (Lambin and Geist, 2001), a local and regional focus on land cover aspects is also needed. The recognition of drivers of land cover change and their effects could constitute an important step in the difficult path to sustainability, becoming the bases for decision making. Although the starting point is given by the detection of changes, which implies the identification of environmental features, they should be taken as "indicators" that allow for a holistic approach leading to addressing issues as sustainability and development. Thereafter, the pursuit of the well being of the involved community, should be oriented by the local community necessities, and driven by a sound land use plan coupled with a proper regional development program.

This study concentrates on the detection of land cover changes in a rural area in the Argentinean Patagonia forest-steppe ecotone. The detection of changes and identification of their nature is relevant for the assessment of trends in the environmental conditions of the region, which will also be explored, in order to make further considerations about sustainability in the area. The study will exploit the possibilities given by remote sensing to environmental research. Remote sensing has demonstrated great potential for detecting and analyzing land cover changes, and has been used successfully for that purpose in uncountable occasions during the last couple of decades (e.g. Singh, 1989; Hobbs, 1990; Collins and Woodcock, 1996; Coppin and Bauer, 1996).

The overall aim of this research is to identify land cover changes that occurred in a rural region of the forest-steppe ecotone of Patagonia, Argentina, between 1987 and 2003. Specifically, the objectives are:

- to identify directional vegetation change drivers in the region;

[1] Grand Challenges in Environmental Sciences.

- to detect possible vegetation changes occurred in the study area;
- to quantify the changes accounting for areal extent, and the nature of change accounting for positive and negative changes;
- to investigate the relationship between the detected changes and the identified potential driving forces;
- to assess the effects of the occurred land cover changes on the region's sustainability.

This thesis is presented in the form of six separate chapters. Chapter II "Study Area", presents a portrayal of the study site; chapter III "Theoretical framework", reviews the background of the study and its relevance; chapter IV "Materials and Methodology", describes the steps undertaken for the change detection; chapter V "Results and Discussion" elucidates the results and presents the correspondent discussion; and chapter VI "Conclusions" enumerates the conclusions deduced from the study.

Chapter II "Study Area"

This chapter describes the study area. A rendering of the environmental features, in addition to a description of the economic activities and demographic characteristics will enhance the interpretation of results, and enlighten the discussion about sustainability.

2.1 Location

The province of Chubut, in Patagonia (southern Argentina) is divided in 15 counties. The area of interest of the present study is situated in Cushamen County, located in the north-west of the province (see figure 1)[2]. The study area lies between 42°15' - 42°40' South and 71°39' - 71°01' West, and comprises 1,700 km^2 (170,000 hectares).

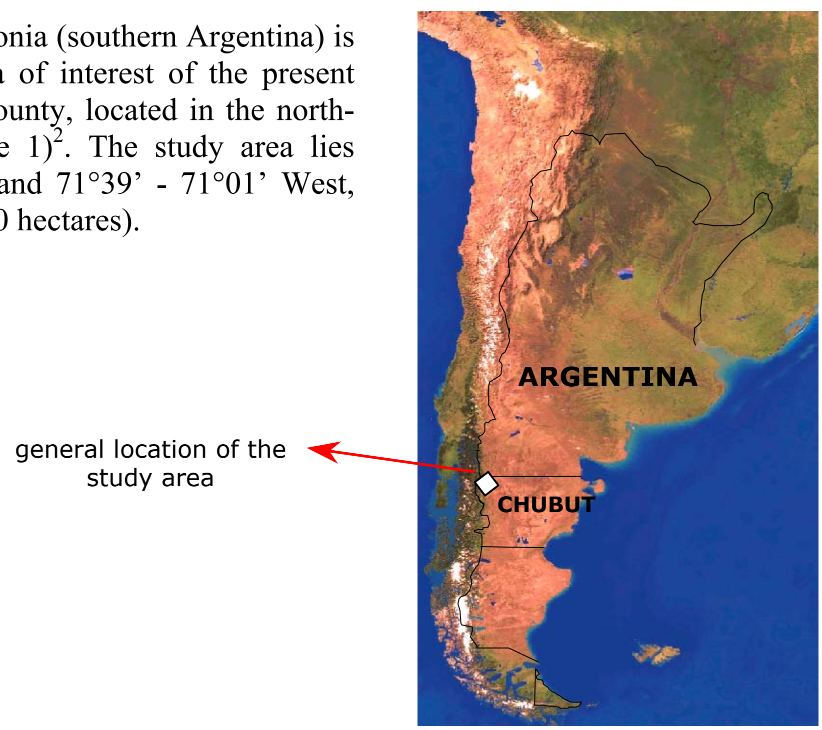

Figure 1. General location of the study area.

2.2 Physiography and general description

Ecotones between ecosystem types are areas of biome transition, where dramatic changes in vegetation occur over short distances (Risser, 1995). The study area is located in the forest-steppe ecotone of

[2] A detailed view of the study area is presented in section 2.2.1.

western Patagonia. Physiographically, from west to east the area is subdivided into the main Andean cordillera, the pre-cordillera of foothills and the Patagonian plains.

Overlaying the glacial topography, numerous layers of volcanic ash which, along with sediments from volcanic and pyroclastic rocks, constitutes the parent material throughout the region, in correspondence to the continuous volcanic activity (Veblen and Lorenz, 1988; Correa, 1998). Dominant soils are acid and alofanic (Andosols). Eastwards they are modified by transportation and mixed with sands and fluvial or colluvial limestone. (Laclau, 2003)

One of the world's most striking vegetation gradients is believed to be that occurring in this region, from the arid steppe to the temperate rain forests (Veblen and Lorenz, 1988). The strong vegetation gradient is a reflection of a steep rainfall gradient, from near 100 mm yr^{-1} in the steppe, to 4000-5000 mm yr^{-1} in the Andes (see figure 2). Prevalent winds blow from the west, and they leave most of their humidity in the western side of the Andes. In an east-west transect of less than 50 km bunch grasses are replaced by 30m tall *Nothofagus* forests.

2.2.1 Natural vegetation

Due to its position in the Patagonian forest-steppe ecotone, the study area shares the characteristics of two contiguous botanical units *floristic districts*, correspondent to the so-called Patagonian Province, a vegetation section identified and described by Soriano in a thoroughly descriptive study on Argentinean flora (1956).

In the western-most area, mountain slopes are dominated by deciduous forests of *Nothofagus pumilio* up to the timberline, situated approximately at 1800 m.a.s.l. Above the timberline, the highlands, are composed of subalpine grasses. At mid-slope altitudes, they may form mixed stands with tall forests of the evergreen *Nothofagus dombeyi*. It is common to find pure stands of the latter, with a dense understory of tall bamboo *Chusquea culeou*. Extending to the east, precipitation declines and *Nothofagus antarctica*, a tall shrub/small tree that reaches up to 10-12 m of height, is found in lower slopes and river creeks. Further continuing in that direction, *Austrocedrus chilensis* and *N. dombeyi* form extensive codominant stands. Eastward, towards more xeric conditions, *A. chilensis* forms pure dense stands, and then open woodlands codominated by sclerophyllous shrubs and small trees, such as *N. antarctica*, *Maitenus boaria*, *Lomatia hirsuta*, *Schinus patagonicus*, *Diostea juncea*, *Fabiana imbricate* and *Berberis buxifolia*. Further east, *A. chilensis* disappears and steppe elements such as spiny shrubs and bunch grasses emerge. Dominating species are *Festuca* spp., *Stipa speciosa, S. humilis, S. chrysophylla*, *Poa ligularis*, *Mulinum spinosum*, *Adesmia campestris*, *Senecio filaginoides* and *Nassauvia axilaris*, in the extreme east of the study area. (Soriano, 1956; Martinez Crovetto, 1980; Correa, 1998).

There is a very particular form of environment in the area, characteristic of the Patagonian forest-steppe ecotone, which consists in meadows locally called *mallines* (see figure 3). They are usually located along permanent or temporary water streams, or in low areas that permit accumulation of water. Waterline in *mallines* is generally near the surface, which generates very wet soils, or water accumulation. These higher levels of moisture are reflected in the determination of areas with very different vegetation communities than the surroundings. Production of high quality forage in *mallines* can reach up to 4 to 10 times that of the contiguous areas. (Martinez Crovetto, 1980; Lloyd, 2002)

The area is characterized by a mix of climate conditions of wet sub-Andean forests with more xeric conditions to the dryer east. It is markedly seasonal, and precipitation concentrates between May and September, whereas November to February is the dry season. Annual mean temperature is usually below 10°C, maximum annual mean temperature about 16-18°C and minimum annual means between 3-6°C (Laclau, 2003).

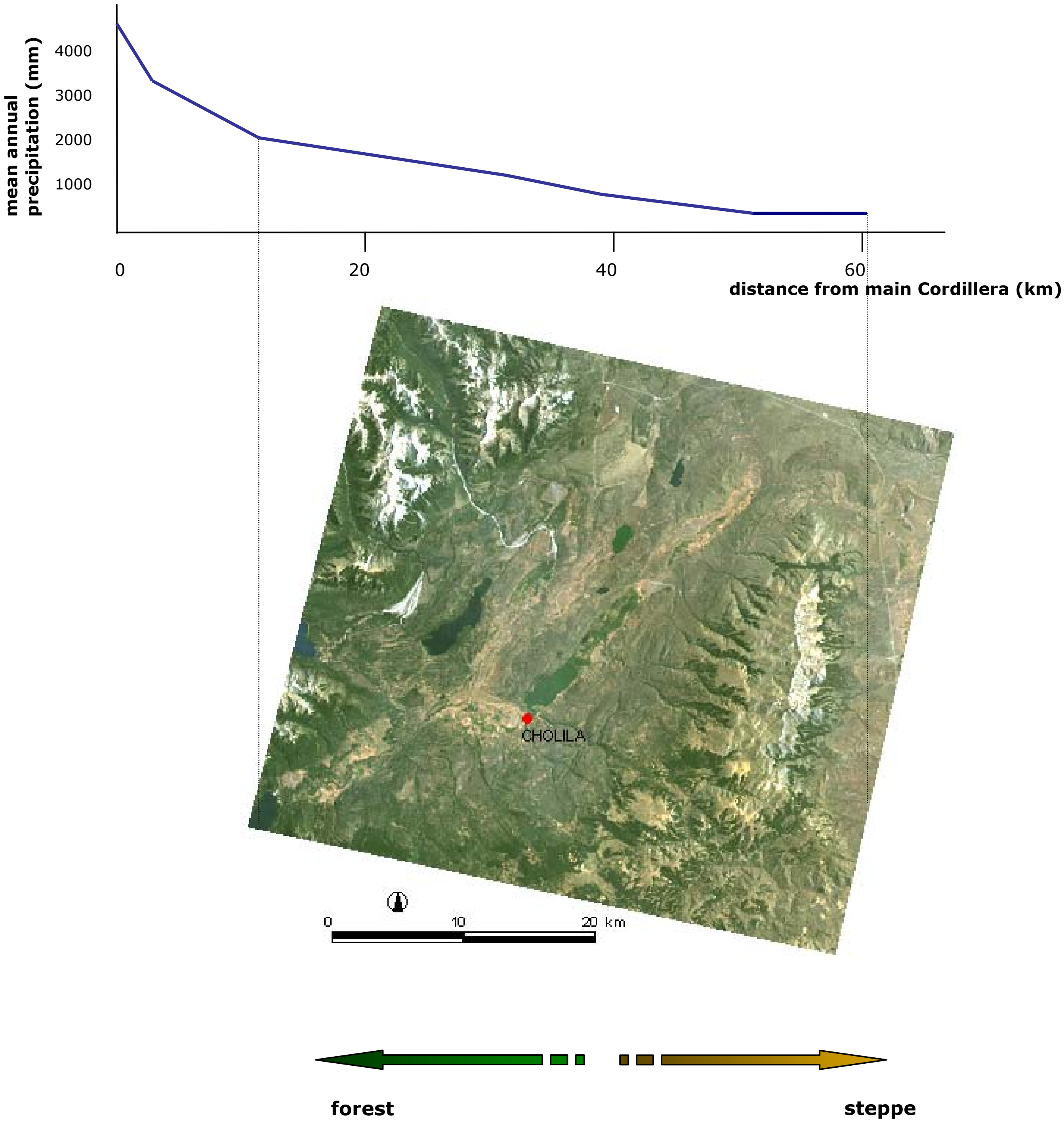

Figure 2. Physiography, climate and vegetation characteristics of the study area. The study area is comprised within the black rectangle superimposed to a Landsat TM subset, true color composite. The graph above (based on Veblen and Lorenz, 1988) represents the gradient in mean annual precipitation from the center of the Andean cordillera eastwards into the Patagonian steppe, for a transect at 40-41°S (1° north from the study area). Values of precipitation were projected from the precipitation transect to the image below, so that the gradient of annual rainfall can be appreciated over the image. The spatial scale of the image corresponds to that of the graph above, to facilitate comparison. Also, intensification of forest characteristics to the west (coupled with the presence of higher mountain ridges, some of them with snowy summits), and stepparian features to the east (related to a flatter topography), characterized by a lost of forest cover, have been represented.

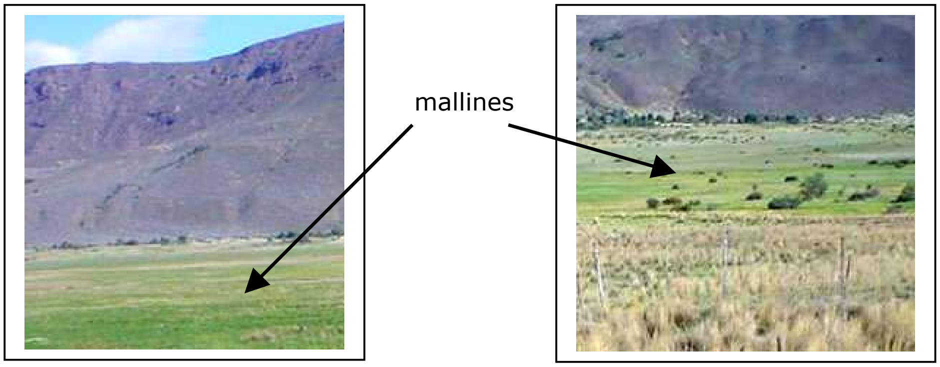

Figure 3. Typical *mallines* in the area (Photographs by D. Martinez).

2.3 Population

The study area is sparsely populated, and constitutes a rural area. Total population of Cushamen county has increased from 13,939 in 1991 to 15,765 inhabitants in year 2000. However, being Chubut's total population density very low (1.95 hab/km^2), the correspondent density for Cushamen is even lower, only 0.96 hab/km^2. (Statistical Yearbook 2000) Differing from the general trends in the province, the size of rural population keeps increasing in Cushamen. The annual growth rates of rural population have increased more in relation to those of total population, meaning that the phenomenon of rural migration to the cities is not taking place but, on the contrary, the share of rural population in Cushamen county has slightly increased from 1970 until 1991 (see tables 1 and 2).

Table 1. Dynamics of total population in Chubut province and Cushamen county during the recent past (1970-1980-1991) (Source: Statistics and Censuses Direction, Chubut Province)

Territory	Total population			Annual growth rate %	
	1970	***1980***	***1991***	***1970/80***	***1980/91***
Chubut	189,920	263,116	357,189	3.29	2.94
Cushamen	11,735	11,938	13,885	0.17	1.44

Table 2. Dynamics of rural population in Chubut province and Cushamen county during the recent past (1970-1980-1991) (Source: Statistics and Censuses Direction, Chubut Province)

Territory	Rural population			Annual growth rate %	
	1970	***1980***	***1991***	***1970/80***	***1980/91***
Chubut	57,740	49,067	43,497	- 1.60	-1.13
Cushamen	9,346	9,599	11,198	0.27	1.47

However, data must be considered with caution, since there were no available data for the most recent decade 1991-2001, when tendency for Cushamen county could have changed. As it can be observed from the figures, the relative annual growth rate of rural population to total population for Cushamen county declined, turning into nearly the same value (1.44 and 1.47) for the period 1980-91. That might indicate that for the following decade rural population could have decreased relatively to total population, according to the declining trend.

This rural area of Chubut province is rather poor. 57% of total homes in Cushamen county present some kind of deficiency, which can be either lack of tap water inside the house, absence of flush in the toilette, no synthetic floors, walls made of clay, or a combination of them. (Statistics and Censuses Direction, Chubut Province)

Education levels are quite low, 12% of population are illiterate, and only 56% of youth in age of attending mid-level school, go to school. This share rises up to 91% when considering children in elementary school age. (Statistics and Censuses Direction, Chubut Province) That would indicate a very basic level of education for people in the area.

The job market in the area is fairly precarious. Even though the unemployment rate for Cushamen indicates a low share of 4%, levels of unstable and occasional employment are high, since employment rate is only 62%, far from being the reflection of the low unemployment state (Statistics and Censuses Direction, Chubut Province).

The main town within the study area is Cholila (see figure 2), with a population of 1,767 inhabitants, as to year 2000.

2.4 Economy

Livestock breeding for the exportation of high quality wool and meat has been traditionally the foremost economic activity in the region (Soriano, 1956; Defossé and Robberecht, 1987). In the first decades of the twentieth century, regional economy was based almost entirely on the sheep industry, which expanded vigorously. The physiographic characteristics of the area, with extensive and productive *mallines* and abundant available water, have made of it an ideal spot for ranching. However, an enlargement of the economic activities spectrum has taken place in the past couple of decades.

Agriculture is hardly carried out in the area, only for local consumption. Otherwise, around 200-300 hectares of barley (*Hordeum vulgare*) are cultivated in areas adjacent to *mallines*. It is used as a supplement for livestock alimentation. (Fertig, personal communication)

Further comments on the economy of the area will be made throughout the following chapters.

2.5 Closing remarks

The study area is a "rural area in a rural area". Cushamen county has one of the highest percentages of rural population in the province and, at the same time, Patagonia can be considered as a rural region in Argentina. Rural areas in the country are characterized by lower standards in the economy and higher levels of unsatisfied necessities than in urban areas, which tend to centralize the attention and the means. This particular area, whose population highly relies on its natural resources, has shown nevertheless an improvement in the economic and social indicators over the last two decades (Statistics and Censuses Direction, Chubut Province). Rates of employment have raised, homes have improved their basic equipment (electricity and tap water) and educational levels are higher than years ago. However, indicators are still low if compared to those of urban areas, which are more developed and present higher living standards.

The great diversity and richness of natural resources that the area counts on is enormous. Forests, lakes, plentiful rivers, and vast grazing areas provide with a unique assortment of means to the improvement and further creation of opportunities for the rural population in the area to increase their well-being. Activities that could broaden regional economy opportunities of the region have been explored in the last years. Mixed livestock, cultivation of aromatic plants and berries, eco-tourism and afforestation appear to be great opportunities for impelling the development of the region.

This chapter reviews the background and the realm the study is embedded on. The relevance and the bases for the investigation will be duly presented.

3.1 Concept of land cover and land use

The concept of *land use* refers to the use of land by humans, often implying an economic activity connotation (Campbell, 1996; FAO, 1993). The impossibility of observing directly on the field its actual use, but only the physical implications of it, makes the concept be rather abstract. Conversely, *land cover* does designate the biophysical features of the earth surface. It is the result of the natural conditions prevalent in the area, such as climate, soils and topography, as well as it is a reflection of the use the land is subjected to. At the same time, the use of the land will depend on the natural features of the area, that is, the type of natural land cover. Both terms are then intimately associated, and depend on each other.

Both, land use patterns and land cover, share the characteristic of being functions of the society's interaction with the environment. However, whereas the concept of land use is abstract, land cover is concrete and therefore, possible to be observed directly (Campbell, 1996). The latter is the attribute that will be exploited in this study, since sizeable land cover changes occurred in the studied period of time are expected to serve as "hints" concerning the state of the environment, coalesced with other aspects of sustainability.

3.2 Land cover change: Possible causes in NW Chubut

Vegetation disturbances and other land cover changes may be the result of multiple causes, acting in isolation or simultaneously. As described by Hobbs (1990), changes in vegetation can be, among others, the result of *seasonality*, which are governed by differences in angle of illumination and atmospheric variations. This is expected to have neutral or minimal effect on the detection of changes in the present study (see Chapter IV "Materials and Methods"). The other causes of land cover change are grouped in *interannual variability*; and *directional change*. The latter constitutes the group of causal land cover change that this study focuses on, in the belief that directional changes might insinuate the actual trend on the state of vegetation, ultimately serving as an indicator of sustainability. Directional changes may be caused by *intrinsic vegetation processes* (e.g. succession), land use or other *human induced changes*, and alterations in *global climatic patterns* (e.g. global warming).

Human processes (e.g. economic, demographic, institutional and social factors) like agriculture, raising of livestock, resource exploitation, land clearing and other types of land use change, introduction of foreign animal and plant species, patterns and status of land tenure, rural migration and settlement, are examples of anthropogenic causes of land cover change. Even though constituting a rural area, many human activities have taken place in NW Chubut between years 1987-2003 that could have lead to land cover change. Some poverty-related factors could be the causes for environmentally harmful changes in vegetation as well, such as land degradation[3]. Lack of knowledge on proper management techniques, diminished possibilities of education, scarce resources from local research centers and low state budgets for carrying extension and education programs on range management, they all affect land cover; in this case, they have affected negatively the way ranchers have treated the land.

[3] The concept of land degradation will be defined in a subsequent section of this chapter, for being considered more appropriate to include it in the context of the discussion it arises.

Vegetation changes may take place at small scales, such as forest canopy gaps created by the death of old individuals or timber activities; or over large scales where vegetation responds to such disturbances as fires, floods or disease strikes. Changes in both small and large scale are expected to have occurred in the area.

It would seem natural to assume that if the tendency in the studied area is that of an increasing amount of vegetation over the years, an improvement in the state of the environment could be deduced. On the other hand, if a decrease in the amount of vegetation is detected, a degradation of the environment within the considered period of time could be claimed. This will be further analyzed accordingly with the acquisition of results, in order to get to a final agreement or disagreement with such assumptions.

Sorting out causes of land cover change in rigid categories is a very difficult task. There are some factors causing land cover change that are actually consequence of both natural and anthropogenic actions; whereas there are others whose causes cannot be established precisely without the execution of an extensive study. The limitation between different causes for land cover change turns therefore into a blurry zone of transition, where components of different nature are combined to derive in vegetation cover modifications. Nevertheless, an attempt of classification of possible land cover change drivers in NW Chubut is made in the following sub-sections.

3.2.1 Climate change

The phenomenon of climate change could be considered, however arguably, as a mixed result of both natural and anthropogenic causes. Large and widespread climate changes have occurred naturally and repeatedly in the past, as a result of trespassing earth system thresholds, bringing about major impacts (Alley *et al*., 2003). Twentieth century has not been an exception regarding climate differences. Yet, several studies point out that climate during twentieth century has been substantially different from that in the previous centuries (Bradley and Jones, 1992). As exposed by Villalba and others (1998) *"it is quite possible that climate change during the past century has been biased by anthropogenic related factors that were unimportant in earlier centuries"*. In fact, the Earth's climate has warmed by approximately 0.6°C over the past 100 years, especially between 1910 and 1945, and from 1976 onwards (Walther *et al*., 2002).

As stated at the beginning of this section, land cover is a function of climate, among other factors. Therefore, if climate changes, chances are fair that land cover will change as well.

Studies carried out by Dr. Villalba and colleagues (1998) on the reconstruction of precipitation since AD 1600 in northern Patagonia, indicate that precipitation variations during the twentieth century have been comparatively anomalous in the context of the past 400 years. The investigation was based on the dendrocronological analysis of tree rings from samples of *Austrocedrus chilensis*, a moisture-sensitive tree and one of most representative tree species of the forest-steppe Patagonian ecotone, and it sheds two remarkable and concluding facts. One refers to the long term variation considerations (periods of 5, 25 and 50 years), which show that both the driest, but especially the wettest periods have occurred along the twentieth century. The other interesting feature in the precipitation reconstructions is the increase in inter-annual variability during the twentieth century. Precipitation variability decreased from 1650 to 1730; it was slightly above the long term mean from 1800 to 1880; and significantly increased between 1910 and 1998. It is reported in the study that analyses of the relationship between *El Niño Southern Oscillation* (ENSO) events and the precipitation reconstructions reveal no clear ENSO modulation of precipitation in this region. That would emphasize the possibility of a non-completely natural origin of such changes in precipitation patterns. However, it is stated that *"although the occurrence of uncommon dry or wet conditions in northern Patagonia may not depend entirely on ENSO, they may be intensified by the occurrence of ENSO events."*

In another study, long term trends of temperature variations across the southern Andes (37-55° South) are determined through the combination of instrumental and *Nothofagus pumilio* (a dominant subalpine species) tree-ring chronology records (Villalba *et al*., 2003). The reconstructions extend back to year 1640, and result in the identification of the twentieth century as the warmest within the period considered.

Supporting evidence for the reliability of those temperature estimates comes from comparison with glacier records. Generalized glacier retreat has been observed in the twentieth century across the southern Andes, partly in response to climate changes (increasing temperatures and drier conditions). During the period 1968-1975, glaciers lost ice at a rate equivalent to a sea level rise of 0.042 ±0.002 mm yr^{-1}; furthermore, in the more recent years 1995-2000, average ice thinning rates have increased more than two-fold, to a sea-level rise of 0.105 ± 0.011 mm yr^{-1} (Rignot *et al*., 2003).

From the above exposed facts, it can be concluded that the occurrence of unexpected climate change is a fact in Argentinean Patagonian Andes, which has experienced an exceptional intensification during the last century.

Ecotones between biomes are predicted to be especially sensitive areas to climate change (Peters, 2002), therefore, the physical and biological systems of forest-steppe ecotone environments in Andean Patagonia are highly sensitive to climatic variations. Accumulation of water, tree mortality (Villalba and Veblen, 1998), fire occurrence (Veblen *et al*., 1999; Markgraf *et al*., 2000), and tree seedling establishment (Kitzberger *et al*., 2000) have been influenced by climate and climate fluctuations in northern Andean Patagonia. As vegetation dynamic processes are linked with variations in climatic conditions, it is reasonable to suggest that land cover of the study area might have changed accordingly.

3.2.2 Wildfires

Across a temporal and spatial range of scales, fire occurrence is dictated by the effects on ignition sources and fuel characteristics of climatic variation, the type of land use, and other human activities.

Fire, both natural and anthropogenic, has been shown to have a major influence on vegetation patterns in the forest-steppe ecotone of northern Patagonia (Veblen and Lorenz, 1988).

Fires of natural origin are those that occur generally from lightning, which actually play a relevant role in the dynamic of ecosystems. Occurrence of natural fires can be favored by a drier season than normal, and this, at the same time, can be promoted by climate change. In northern Patagonia, it is interannual climatic variability rather than variations in average climate conditions over long periods that strongly influences fire regimes, through its effect on fuel characteristics (desiccation) and frequency of lightning. It was found that at interannual scales, climatic variability overrides human influences on fire regimes (Veblen *et al*., 1999). About 90% of fires in the region occur between October and March, during the dry warm season, in opposition to the rain season which takes place between May and September.

Unpublished data from National Parks Administration[4] indicate that between 1938 and 1996, as much as 8% of the total number of fires in north Andean Patagonia, which accounted for 16.4% of the burned area, was due to lightning. Data correspond to four National Parks (Lanín, Nahuel Huapi, Lago Puelo and Los Alerces National Parks), and it representative of the study area, as it is found precisely in between of the last two aforementioned Parks.

According to a study by Veblen and Lorenz (1988), fire frequency increased in Andean Patagonia during the second half of nineteenth century, coinciding with greater use of the area by native hunters, and their fire-induced techniques to hunt the *guanaco* (*Lama guanicoe*). Increased burning, especially in the ecotone area, was related to the settlement of Europeans, who cleared forests

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[4] Official name: Administración de Parques Nacionales. National Institution in charge of the management of National Parks.

for agriculture and range practices. Afterwards, and up to 1930's, a marked decline in fire occurrence took place, correspondingly with natives' demise and fire exclosure due to the creation of protected areas.

Nowadays, fires from anthropogenic nature have different causes from the past, which could be accidental or intentional. The most widespread causes in NW Chubut are negligence (e.g. cigarette pits), forestry and range operations, falling electric lines, weed and forestry waste burning, small fires from campers that were not properly put out, and intentional fires caused by pyromaniacs. Some fires would stay as caused by unknown reasons.

3.2.3 Overgrazing conducing to land degradation

Land degradation processes, such as soil degradation and accelerated erosion, or reduction of the amount and diversity of natural vegetation, imply a reduction of the potential productivity of the land (Sommer *et al*., 1998). As understood from the former definition, land degradation leads to land cover change.

Land deterioration, or degradation, is partly the result of pressure posed by natural processes, such as fluctuations in precipitation rates. However, land degradation in NW Chubut is believed to be particularly the consequence of anthropogenic influences in the area and, for that reason, some considerations relevant to the context of this study are included in this section.

Grazing can alter the spatial heterogeneity of vegetation, thus influencing ecosystem processes and biodiversity (Adler *et al*., 2001). Accounting for that, Patagonian grasslands are considered to be especially sensitive to grazing, given their short evolutionary history of grazing (Markgraf, 1985 cited in Oliva *et al*., 1998). Overgrazing has been defined as an intensity of grazing that modifies the plant cover in such a way that its productive capacity is seriously impaired (Bharucha and Shankarnarayan, 1958). Particularly in Chubut Province, overgrazing has been highlighted as a major cause of land degradation (Soriano, 1956; Defossé and Robberetch, 1987; Soriano and Paruelo, 1990; Ares *et al*., 1991; Saba *et al*., 1999).

In a study carried out in Chubut Province by Ares and colleagues (1990), it has been found out that there is a spatial correlation between the intensity of land deterioration, and the distribution of major climatic factors, particularly the variability in precipitation. In that context, it is suggested that there is maladjustment of grazing stocks in accordance with interannual rainfall variability. That means that during humid years, livestock is increased, given the chance to feed more animals due to a suddenly increased productivity; and afterwards, high rates of land occupation persist during the following drier seasons, with the hope that years with high rainfall rates will eventually come.

The effects of land degradation are shown in changes in vegetation, serious depletion of the vegetation cover, soil compaction and an increasing proportion of bare soil, which result in soil instability and soil erosion. It has been proved that the vegetation composition of Chubut's rangelands would be different in the absence of overgrazing, with an overall increase in vegetation cover and diversity of the community (Soriano *et al*., 1980; Soriano and Paruelo, 1990; Oliva *et al*., 1998).

3.2.4 Introduction of foreign species

The introduction of foreign species also modifies the vegetation cover. Both animal and plant species have been introduced in Andean Patagonia.

Maybe the most representative introduced animal species in the NW of Chubut are the European hare *Lepus europaeus* and the red deer *Cervus elaphus*, both introduced from Europe by late 19^{th} century, following the large European immigration to Argentina. Among other ecological effects that are beyond the scope of this study, they affect the regeneration of native plant species, producing death of seedlings or problems in their normal growth. The European hare introduced in Patagonia damages vegetation regeneration, both in native forests and implanted ones (Rodriguez, 1997).

Browsing of tree species *Austrocedrus chilensis* by the introduced red deer can impede juvenile height growth and dramatically alter the form of saplings and small trees in a range of habitats from the forest-steppe Patagonian ecotone (Relva and Veblen, 1997; Kitzberger *et al*., 2000). Red deer browsing also diminishes the abundance of the preferred browse species in the area, the native endemic woody shrub *Schinus patagonicus* (Relva and Veblen, 1997).

Among the exotic plant species, the sweetbriar rose, *Rosa eglanteria*, a spiny shrub introduced from Europe, has become a large invader in the forest-steppe ecotone of northern Patagonia (see figure 4). It constitutes somehow an appreciated species in the region due to the possibility of preparation of jam and tea from the fruit; and the extraction of oil from the seeds which is beneficial for health and used for cosmetic applications. However, it does not constitute a noteworthy economic activity in the region. Furthermore, it has taken over so large portions of land, that it impedes the development of agriculture and even range activities, since it is not palatable. Nevertheless, the worse threat that sweetbriar rose imposes in the region is that of constituting a suitable habitat for the rodents that transmit a lethal disease. *Hantavirus Pulmonary Syndrome* (HPS) is a deadly disease transmitted by infected rodents through urine droppings or saliva. Humans can contract the disease when they breathe in the aerosolized virus. The east border of the southern Andean range constitutes one of the three geographically and ecologically distinct HPS endemic areas in Argentina, where several human fatalities have occurred in the last decade (Lopez *et al*., 1996; Pini and Resa, 1998; Cantoni *et al*., 2001). The presence of hantavirus reservoir species in peridomestic environments is commonly found. The current primary measure for reducing the risk, which consists on preventing access of rodents to homes (Calderón and Pini, 1999), constitutes an “end-of-pipe” solution, and the eradication of its habitat, or at least control measures against the spread of the sweetbriar rose should be undertaken. Hence the importance of its mapping and monitoring. Current treatments to eradicate the sweetbriar rose, even at small spatial scales, are expensive and time consuming, let alone the possibility of eradication to large scales. Moreover, it is a species that grows with renewed intensity after fires, which is negative for the eradication in two ways: it is quite useless to try to eliminate it with fire; and, after the occurrence of wildfires the sweetbriar rose is a pioneer in the colonization of the burnt area.

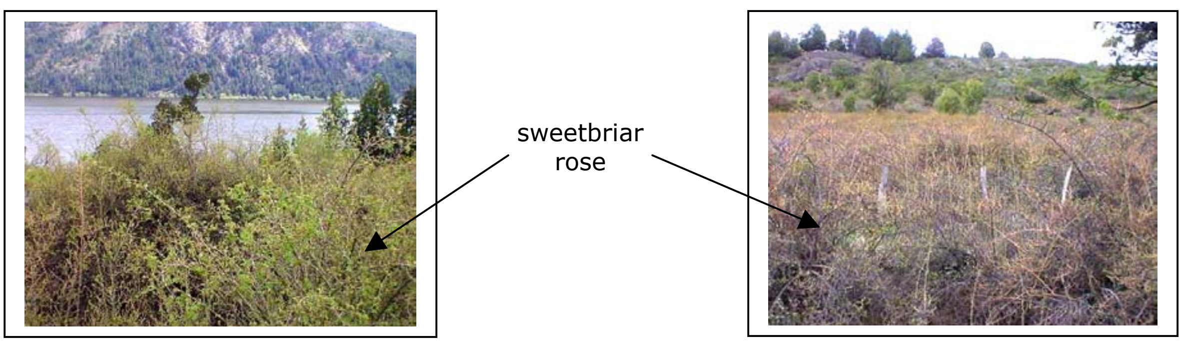

Figure 4. Sweetbriar rose invading the area (photographs by D. Martinez).

3.2.5 Transition of economic activities

In recent years, depressed wool prices in international markets, coupled with a stronger presence of scientific and educational centers that could advice on sensible agricultural and range practices, plus the realization of the potential of the area for tourism, have caused other economic activities to boost, causing the traditional sheep industry to decline, and the likelihood occurrence of land cover change.

3.2.5.1 From a sheep oriented industry towards a mixed livestock breeding

A shift from sheep ranching towards a larger share of cattle ranching has been a notable change in the economic activities of NW Chubut. Reasons do not involve solely the depressed wool market, but also the growing markets for beef in the coastal cities, rangeland deterioration due to overgrazing and the characteristic small ranch size in the area, which has resulted economically nonviable (Defossé and Robberecht, 1995). In addition, in early 1990's decade, Patagonia was declared to be a FMD-clear[5] area, thus promoting cattle breeding. Another fact that makes ranchers consider the breeding of cattle is the difficulty it poses to be stolen (Loguercio, personal communication). In simple words, it is easier to steal a sheep than to steal a cow, and that is appreciated by ranchers, who have often suffered from livestock subtraction. Table 3 and figure 5 depict the number of heads of sheep and cattle in the region for years 1995, 1999 and 2003. Even though data were not available for the earliest time period of the study, the trend illustrated is a steep diminution of the number of sheep, as well as an increase in the number of heads of cattle. Both phenomena have not occurred simultaneously, but a delay is observed between the steep diminution of sheep that took place in the period 1995-1999, and the increase in the number of cattle heads that followed, during the period 1999-2003.

Cattle and sheep cause different effects on vegetation, due to the differences in the botanical composition of their diets; therefore, the manipulation in the composition of livestock may result in vegetation changes. Especially if under overgrazing, sheep may induce severe negative effects and significant changes to the vegetation, whereas cattle impact is lower. (Araújo Filho and Araújo Crispim, 2002; Fertig, personal communication; Guitart, personal communication).

Table 3. Number of sheep and cattle heads in the region, in 1995, 1999 and 2003. (Source: Court of Chubut Province at Cholila).

	1995	1999	2003
N° sheep	14,496	8,906	7,108
N° cattle	7,604	7,898	9,165

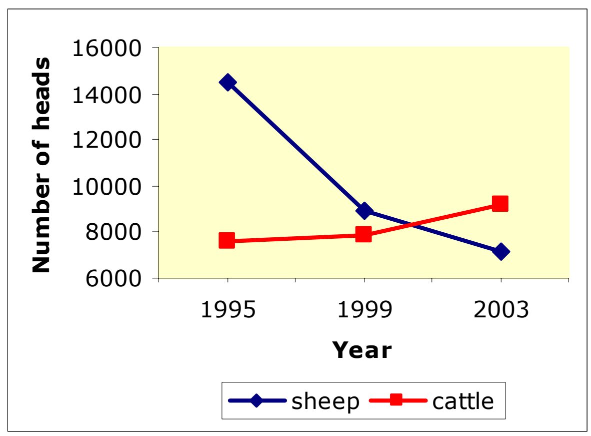

Figure 5. Representation of the change in composition of livestock in the area, for years 1995, 1999 and 2003. (Source: Court of Chubut Province at Cholila, unpublished data)

3.2.5.2 From exclusively native forests logging to the addition of afforestation with exotics

Timber activities in native forests have begun in the region by the end of nineteenth century. In spite of being a mature activity in the region, it contributes with a minimum share to the provincial economy (Jovanovski, personal communication). Nowadays, timber activities are controlled by DGByP (Chubut's General Directorate of Forest and Parks)[6], and it is only carried out in authorized sites and

[5] FMD: The Foot ad Mouth Disease is an infectious disease affecting cloven-hoofed animals. The disease is serious for animal health and for the economics of livestock industry, causing sensible economic losses.

[6] Official name: Dirección General de Bosques y Parques del Chubut (DGByP)

under close inspection. 12,7% of native forests in Chubut Province are commercially suitable, composed of *Nothofagus pumilio*, *N. dombeyi* and *Austrocedrus chilensis*. Presently there are five sawmills that process A. chilensis at small scales, extracting around 1,000 m^3 yr^{-1}; and seven sawmills that process N. pumilio, reaching a total of 20,000-25,000 m^3 yr^{-1} (Jovanovski, personal communication). In Cushamen county *A. chilensis* has been the foremost native species accounting for timber activities, taking over the great majority of this species logging in the province (see table 4). The traditional timber extraction system in the region has been selective logging (*"floreo selectivo"*), which is based in the selection of the best commercial trees of a stand and their following felling. This leads to the opening of gaps within the stand, a decrease in the overall biomass of the stand, and a vegetation cover change.

Logging permits are given for an interval of five years each time, thus not encouraging long term investments in the area, and preventing this activity to play a major role in the regional economy.

An activity that has gained popularity in the region is afforestation. According to the definition adopted by the Intergovernmental Panel on Climate Change (IPCC), afforestation refers to the *"artificial establishment of forests by planting on lands which, historically, have not contained forests"*. A provincial law passed in year 1993 provides the legal framework for promoting afforestation and provides funds to partly subsidize the activity (Defossé and Roberecht, 1995). The area presents the adequate climatic and edaphic conditions to allow some tree species grow fast and well (Gonda, 1998; Godoy *et al.*, *in press*), being particularly suitable for the establishment of plantations of the genus *Pinus (P. ponderosa,* but also *P. contorta var. latifolia* and *P. radiata)* and *Pseudotsuga mensiezii* (Davel and Ortega, 2001). Especially, *Pinus ponderosa* has demonstrated to be the most adaptable species, with very satisfactory results in growth rate.

As to year 1995, there were approximately 18,000 hectares of implanted forests in Chubut (Defossé, 1995). In the period 1993-2003, another 19,580 hectares were added (Defossé, personal communication). Therefore, nearly 40,000 hectares totalize the afforested area in the province. Calculations based on soils aptitude and climate conditions reveal that the potential of Chubut's ecotone and irrigated lands be 800,000 hectares (Irisarri *et al.*, 1995), so it seems that has the potential to become a further driver of land cover change. Especially Cushamen county accounts for a large proportion of the total afforested area in the province, 35% of the total implanted area in the province occurs in this county (see also table 4, which indicates the volumetric share of timber production of Cushamen county in comparison with the provincial totals).

Land cover change, in the case of afforestation, is the result of an increased plant cover and photosynthetic activity, which is the detectable feature by the satellite's sensor.

Table 4. Commercial timber production in Cushamen county according to species, and relative to the provincial total, for year 1999 (Source: DGByP).

Species	*Status*	*Cushamen county*(m^3)	*Chubut province*(m^3)
Austrocedrus chilensis	native	10,474	13,236
Nothofagus pumilio	native	23.97	25,829
Nothofagus dombeyi	native	79.50	82
Pinus spp.	exotic	5,555	6,809

3.2.5.3 The development of eco-tourism

Incipient eco-tourist and recreational activities in the area are not expected to cause significant land cover change as such, since they are based on the highly scenic value of the region, and they necessitate the "pristine and untouched" image of Patagonian Andes for the continuation and increase of this kind of activities. However, an important factor concerning the change of land cover could be the increase in the frequency of fires due to anthropogenic causes.

3.3 Land cover change impact

Usually, land cover changes are associated with a negative influence on the environment. There is abundant evidence of being this the case, especially when they are aggregated globally. Alterations of the earth's surface are currently of unprecedented magnitude and reach. They have attained such relevance that they affect significantly key aspects of the Earth system functioning. They contribute to changes in biogeochemical cycles, alter hydrological cycles, impact on biodiversity, contribute to local and global climate change, are the primary source of soil degradation, and, by altering ecosystem services, they affect the ability of ecosystems of providing for human needs. (Lambin *et al*., 2001; IIASA[7]; GCES). Land use and land cover changes also contribute to increase the vulnerability of regions to environmental perturbations (Kasperson *et al*., 1995).

Land use activities change landscape structure by altering the relative abundance of natural habitats and introducing new land cover types. As a result, biodiversity may increase, due to the provision of new habitats. However, natural habitats are often reduced or fragmented, producing a decline of natural biodiversity.

Some studies have nevertheless demonstrated to prove challenging to conventional wisdom. (GCES). Especially if considered to smaller temporal and spatial scale, changes in practices that in turn have led to land cover changes, might result in improved or restored environments, increasing economies and a better state of welfare. The causes leading shifts in practices, and resulting in changes in land cover are numerous and from multiple origins (social, economic, political, etc), as reviewed above. Improved information and understanding of land use and land cover dynamics are essential for society to respond effectively to environmental changes, and to manage human impacts on environmental systems.

The identification of land cover changes in a region, coupled with documentation and monitoring, provide an observational base for raising awareness about the consequences of the activities developed, as well as the response of the land features to the natural events occurred in the considered period of time. That way, the ground is paved for a more effective land use planning; as well as decision making is sustained by solid bases.

3.4 Sustainability in the context of the study

Sustainable development refers to the reconciliation between the meetings of human needs with economic progress, within the bounds of environmental conservation, whereas preserving options for future generations (ESD)[8]. Sound and efficient use of natural resources is therefore essential for the successful trade-off between levels of production and consumption. The definition of the concept may appear to be clear and straightforward, yet its practice seems to be quite more complicated. In essence, the concept of development implies change, and it is the sum of every factor causing that change that will determine its magnitude and direction. It will depend on the nature and concordance among those factors that the orientation of change be towards sustainability or not.

In the context of this study, the realm of sustainability is explored from two perspectives.

One accounts for the contribution of remote sensing as a discipline that has the potential to help increasing sustainability, as a tool to provide with bases for planning and decision making. During the past few decades remote sensing has increasingly become a practical tool for developing and understanding the global, physical processes affecting the earth; as well as monitoring the environment and assessing natural resources for different applications. The contribution of remote sensing to

[7] IIASA: International Institute for Applied Systems Analysis
[8] ESD: Encyclopedia of Sustainable Development

increasing sustainability comes from the capability of mapping and monitoring, both prerequisites for the definition and implementation of political decisions and development plans for the protection and sustained use of land resources (Sommer *et al*., 1998). The trail left by change on the earth's surface can thus be detected and measured. For that reason remote sensing makes it possible to put in practice a holistic approach towards the relationship between natural resources state, humans, and developed economic activities; hence providing tools for sound decision making. As argued by Blaschke (2001), the operationalisation of sustainable development needs spatial thinking and spatially explicit approaches, and he believes remote sensing covers a wide range of these needs.

The other reference to sustainable development will be made through the discussion of the obtained results, when considerations are to be made to assess their significance and implications for sustainability in the studied area. Changes in land cover have the potential to affect sustainability, either by undermining it, or conversely, by increasing it. They might as well serve as indicators of the environmental and social conditions in the area, since they are caused by the activities developed in the area, thus providing a means for an evaluation of their overall performance. An approach to analyze the results bearing this in mind is to be made.

3.5 Remote sensing

Many definitions of remote sensing have been suggested. However, they all share a common ground, which is that of consisting on the observation of an object at a distance, without establishing physical contact Campbell (1996).

Sensor digital data are formed as a multispectral satellite sensor records the incoming electromagnetic radiation, which has been either reflected or emitted from the landscape's physical features. Therefore, multispectral remote sensing depends on observed spectral differences in the energy reflected or emitted by those features; in other words, the detection of differences in brightness of objects (Campbell, 1996). Spatially, data is composed of discrete picture elements (*pixels*) and radiometrically, it is quantized into discrete brightness levels (Richards, 1993).

Multiple images of the same target object are acquired simultaneously by the sensor, each at different wavelengths. Each one of those multiple images represents a "spectral band". Each spectral band corresponds to a discrete portion of the electromagnetic (EM) spectrum; therefore, each band measures unique spectral characteristics about the target. The major EM spectrum ranges used for sensing earth's resources are between about 0.4 and 12 μm, considered as the "visible/infrared" range (Richards, 1993). In this range, the radiation recorded by the sensor will depend on properties such as vegetation pigmentation, moisture content and cellular structure of vegetation (Tucker and Sellers, 1986), the mineral and moisture content of soils, the level of sedimentation of water, heat capacity and thermal properties of the surface under observation (Richards, 1993).

3.5.1 Vegetation monitoring

For studies of land cover change it is of special relevance the understanding of spectral reflectance behavior of vegetation.

The performance in the visible portion of the spectrum is dictated by the pigments in the plant leaves. Chlorophyll, for instance, strongly absorbs energy in the wavelength bands centered at about 0.45 and 0.67 μm, which correspond to blue and red colors. That is the reason why our eyes perceive vegetation as green, simply because energy at this wavelength is not needed by the chlorophyll in the plant cells' chloroplasts to produce photosynthesis, and therefore it is not absorbed, but reflected. Moving along the spectrum towards the near-infrared portion at about 0.7 μm, the reflectance of healthy vegetation increases dramatically, and stabilizes until 1.3 μm. At that range of wavelengths, reflectance can be up to 40-50% of the incident energy, which is dependant on the leaf internal structure. Most of the remaining energy is transmitted, and only a very little proportion of the incoming energy is absorbed (about 5%). Therefore, multiple layers of leaves provide the chance for multiple transmittance and reflectance. Hence, the near-infrared increases with the number of layers of leaves in a canopy. Beyond 1.3 µm, incident energy is essentially absorbed or reflected, with little transmittance. Dips in reflectance occur at 1.4, 1.9 and 2.7 µm, because water in the leaves absorbs strongly at these wavelengths, therefore these portions of the spectrum are known as "water absorption bands." (Tucker and Sellers, 1986; Lillesand and Kiefer, 1987)

3.5.2 Remote sensing for change detection

According to the definition given by Singh (1989), change detection is *"the process of identifying differences in the state of an object or phenomenon by observing it at different times."*

Because of their synoptic and repetitive data acquisition capabilities, the ability of acquiring data from non-visible parts of the spectrum and the consistency of image quality, satellite based sensors have the potential to detect, identify and map land cover changes (Coppin and Bauer, 1996). Change detection is an important component in the process of monitoring and managing natural resources, since it provides quantitative analysis and invaluable information about the spatial distribution of the features of interest under observation. The detection of land cover changes is of particular importance to ecosystem managers and decision makers, given sustainability requirements of resource data that are accurate and continuously updated.

The fundamental assumption that rules the use of digital imagery for the detection of land cover changes is that changes in land cover must result in changes in radiance values. At the same time, changes in radiance values due to land cover change must be large compared to radiance changes caused by other factors, such as differences in atmospheric conditions or soil moisture (Singh, 1989).

There are three main aspects of change detection that will be explored within the scope of this study, a) detection of changes; b) identification of the character of the changes; and c) quantification of the spatial extent of the changes.

Many different change detection techniques have been developed over the last three decades. Singh (1989) and Coppin & Bauer (1996) provide comprehensive reviews of different methods for digital change detection. Even though there is ample evidence supporting the feasibility of detecting and monitoring changes by means of remote sensing, the application of different methods for the same environment may cast different results. It is still unclear which methods are most appropriate for a particular application (Singh, 1989; Collins and Woodcock, 1996; Coppin and Bauer, 1996).

A *vegetation index differencing* has been implemented in this change detection study, based on the assumption that consistent relationships exist between the amount of vegetation cover and the vegetation indices. Image differencing, methodology group that contains the method used in this study, is one of the most widely applied change detection algorithms for a variety of geographical environments (Singh, 1989). It appears to perform generally better than other methods for change detection, demonstrating particular suitability for the detection of changes of forest covers (Coppin and Bauer,1996). Further details are given in chapter IV "Materials & Methods".

3.5.3 Remote sensing for environmental research in Patagonia

The use of remote sensing as a tool for environmental studies in Patagonia is young, yet conspicuous, and some examples are cited below.

Especial concern about desertification status and processes has resulted in numerous works, especially since the 90's decade. In an ample study, pioneer in its kind as a consequence of the large spatial scale it encompassed, Del Valle and others (1998) evaluated and classified the status of desertification in Patagonia, primarily from NOAA/AVHRR[9] data. Roenick and Ayesa (1992); Ayesa

[9] National Oceanographic and Atmospheric Administration/Advanced Very High Resolution Radiometer

et al. (1993; 2000); Bran and others (1993; 2002); Paruelo and Aguiar (2003); and, investigated the use of satellite data for sustainable environmental management, monitoring of desertification, and evaluation of areas affected by fires in Patagonia. Paruelo and others (1993) studied the seasonal dynamics of the Normalized Difference Vegetation Index in extra-Andean Patagonia. In a very comprehensive approach, Lencinas (2001) studied the options for the sustainable management and multiple use of a watershed environment of the forest-steppe ecotone in Chubut province, mainly based on SPOT IV[10] data; whereas Siebert (2001) generated a DEM from the same type of data and compared it with DEMs generated from other sources, to conclude about the deficit of reliable topographic information in the Andean Patagonian region, necessary for the determination of potential afforestation sites.

However, detection of changes in land cover, aiming at identifying connections with human activities and other directional factors has not been an investigated issue among environmental research based in remote sensing in Chubut. This study intends to be the starting point for the development of such a resourceful and desirable discipline.

Chapter IV "Materials and Methods"

4.1 Software utilized and general overview of the applied methodology

The land cover change for the period 1987-2003, was derived from two Landsat images.

The processing of the satellite images employed in the study was conducted using image processing software from PCI Geomatics Enterprises Inc.®; Richmond Hill, Ontario, Canada. ImageWorks™, XPace™ and GCPWorks™ from Geomatica Version 8.2, and OrthoEngine™ from Geomatica Version 9.0 were used.

Area calculations, analysis of results, and portray and final hardcopy maps were produced in ArcView GIS® Version 3.3 software, released by ESRI Inc., Redlands, California, USA.

This section reviews the techniques undertaken to detect the areas of change occurred within the study site. Basically, four procedures were applied after acquiring the images: image to image registration, image normalization, generation of vegetation indices and vegetation indices differencing for change detection. Finally, statistical considerations were made to enhance interpretability of the areas of change (see figure 6).

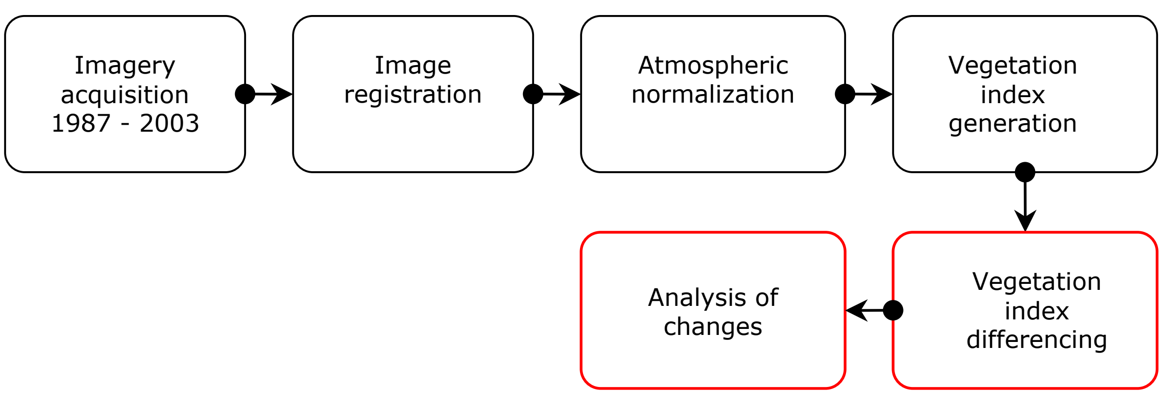

Figure 6. Data processing flow chart for change detection, showing the main steps undertaken.

[10] Systeme Pour L'Observation de la Terre.

4.2 Imagery acquisition

The satellite image data set was comprised of two Landsat images. Image from 1987 (*image 1*) was acquired by the satellite's Landsat 5 Thematic Mapper (TM) sensor, whereas image from 2003 (*image 2*) was obtained by Landsat 7 Enhanced Thematic Mapper (ETM+) sensor. Both satellites have similar properties and same resolutions for the features that were relevant to this study (see table 5). In a comparative study between Landsat sensors, Vogelman and others (2001) concluded that the two sensors behave in a very similar manner, and can be used to measure and monitor the same landscape with comparison or change detection purposes with no problems. If using *Vegetation Indices*, only a radiometric normalization is needed to make images reliably comparable.

Table 5. Properties of sensors Landsat 5TM and Landsat 7ETM+

Property		Landsat 5 TM	Landsat 7 ETM+
Spectral resolution (microns – μm)	Band 1 *(visible blue)*	0.45 – 0.52	0.45 – 0.52
	Band 2 *(visible green)*	0.52 – 0.60	0.52 – 0.60
	Band 3 *(visible red)*	0.63 – 0.69	0.63 – 0.69
	Band 4 *(near infrared)*	0.76 – 0.90	0.76 – 0.90
	Band 5 *(middle infrared)*	1.55 – 1.75	1.55 – 1.75
	Band 6 *(thermal infrared)*	10.4 – 12.5	10.4 – 12.5
	Band 7 *(middle infrared)*	2.08 – 2.35	2.08 – 2.35
	Band 8 panchromatic *(visible green and red, near infrared)*	N/A	0.52 – 0.90
Pixel size (spatial resolution)	Bands 1-5 & 7	30 * 30 m	30 * 30 m
	Band 6	120 * 120 m	60 * 60 m
	Band 8	N/A	18 * 18 m
Swath wide		185 km	185 km
Repeat coverage interval (temporal resolution)		16 days	16 days
Quantization (radiometric resolution)		8 bits (256 levels)	8 bits (256 levels)
Inclination		98.2°	98.2°

The appropriate selection of imagery acquisition dates is crucial to change detection. Anniversary dates or anniversary windows are desired, in order to minimize differences in reflectance caused by seasonal vegetation fluxes and sun angle. Summer and winter are the best seasons for detecting changes, due to their phenological stability[11]. Furthermore, selecting summer or the driest season of the year will enhance spectral differentiation, whilst minimize spectral similarity due to excessive surface wetness prevailing during other periods of the year. (Coppin and Bauer, 1996)

The aforementioned criteria were considered for the selection of available scenes, in addition to the lowest percent of cloud cover. The interval length was determined by the availability of satellite imagery of acceptable quality. The review of several studies concludes that longer periods of six to fifteen years between scenes performed better to monitor non-forest to successional shrubs stage, and also to detect human-induced and canopy disturbances in forests than a shorter periods of one or two years (Coppin and Bauer, 1996). The period of time considered in this study is sixteen years (see table 6), as the study was designed to investigate the occurrence of changes, which could have been

[11] Phenology refers to the timing of seasonal activities of animals and plants (Walther et al., 2002)

originated by a mix of diverse causes. In addition, a consideration for sustainability in the region will be made, and short periods of time would not be suitable to indicate significant trends.

The study area lies within the overlap region of two adjacent Landsat scenes, and only different nominal scenes that fulfilled the requisites for the change detection study were available for the area of interest; therefore, utilized scenes correspond to adjacent rows in the WRS[12].

Table 6. Landsat TM scenes utilized in the study.

Scene No.	Image acquisition date	Satellite sensor	WRS Path/Row
1	24 January 1987	Landsat 5 TM	232/89
2	10 March 2003	Landsat 7 ETM+	232/90

In both images, the six non-thermal bands were utilized for a preliminary visual appraisal. The thermal band (TM6) was excluded from the methodology because it has been demonstrated that, for identification of surface types, thermal information is not readily associated with that in the reflective part of the spectrum, which in turn may lead to misinterpretation (Coppin and Bauer, 1994).

4.3 Image Preprocessing

Preprocessing of satellite images refers to those operations that are preliminary to the main analysis. Preprocessing prior to actual change detection is essential. The purpose is to maximize the signal to noise ratio, that is, to establish a more direct relationship between the data and the biophysical features, as well as to eliminate of undesired scene fractions. It usually comprises a series of sequential operations, including image registration, atmospheric correction or normalization and masking (Campbell, 1996; Coppin and Bauer, 1996).

4.3.1 Subset of the study area

In order to minimize computer storage needs, as well as time consumed in the preprocessing steps, subsets (segments of full images) corresponding to the area of interest were extracted from both images. Further preprocessing was applied to the subsets.

4.3.2 Image registration

Correction of the various types of geometric distortions present in digital image data is necessary. Both images had been geometrically rectified and registered to different projections previously to their obtainment for this study. The most common approach to improve the geometry of images consists in establishing mathematical relationships between the addresses of pixels in an image and the corresponding coordinates of those points on the ground (via map, other corrected image or via field work). These relationships can be used to correct the image geometry irrespective of the analyst's knowledge of the source and type of distortion. (Richards, 1993)

Image 1 had been geometrically corrected and geocoded utilizing a topographic map at scale 1:100,000 as a reference for ground coordinates, projected to the Transverse Mercator grid and resampled through the nearest neighbor method with a first order transformation. On the other hand, *image 2* had been geometrically corrected based on an ortho-image[13], set to the Universal Transverse

[12] WRS: Worldwide Reference System is a global notation system for Landsat data, which designates each unique nominal scene by specific path and row numbers (GSFC, NASA).
[13] Ortho-image: Satellite image geometrically corrected accounting for topography distortions.

Mercator projection and resampled using the nearest neighbor method, with a first order transformation. No detailed information about the RMS error[14] from the geometric correction of the images could be obtained. Only a RMS error value below one pixel was certain for both scenes. Counting on already geometrically corrected images turned into a source of error for the change detection procedure. Both images had been corrected based on different sources as a reference, and none accounting for topography-induced distortion, what added an extra difficulty for the co-registration of the images.

Accurate spatial registration of the utilized imagery is absolutely essential to obtain reliable change detection results. That means that every pixel in both images must be representing exactly the same portion of the earth's surface. If a pixel to pixel comparison technique is to be used, misregistration of the images could lead to the degradation of the areal assessment of the change events and the detection of unreal changes, where correspondent pixels in both images are displaced. That is likely to occur especially at the change-no-change boundary (Coppin and Bauer, 1994). Even a small amount of RMS error has the potential to introduce some degradation to the change detection accuracy.

An image to image registration was applied. *Image 1* was used as a master, and *image 2* was registered to it, as the master was supposed to have a better geometry, inferred from the geometric correction technique previously applied.

Collection of ground control points (GCP's), a first order transformation, and nearest neighbor resampling of the slave image was performed. 43 GCP's were located, evenly distributed throughout the image. A first order transformation is a linear function that applies the standard linear equation ($y = ax + b$) to the X and Y coordinates of the GCP's. The nearest neighbor resampling method uses the value of the closest pixel to assign to the output pixel value, thus transferring the original digital values without averaging them as other methods do, thus not losing the original information. That is important to consider when change detection is being carried out, since modified pixel values in the images to be compared might result in unreliable produced information. For further details on geometric correction of satellite imagery refer to Lillesand and Kiefer, 1987; Richards, 1993; and Campbell, 1996.

The obtained overall RMS error for the procedure was 1 pixel (error in x = 1.36; error in y = 0.64). Even though the error was above the recommended 0.5 pixel value for change detection (Coppin and Bauer, 1994), that was the best match for the areas of major interest for the study, the lower lands where human activities take place. In those lower areas, displacement was generally below 1 pixel, whereas greater displacements of up to 4 pixels were found on the top of mountain ridges. Several attempts were previously made in order to lower the RMS error, but only to obtain greater relative errors in the lower areas and only slight improvements on the mountain tops, where error was still up to 3 or 4 pixels.

As the result of the traditional polynomial correction method was not fully satisfactory, an ortho-correction of *image 1* was performed. The polynomial transformation method does not reflect the geometric distortions due to image acquisition and relief displacements, but accounting for relief is essential in mountainous areas if an acceptable geometry is desired (Itten and Meyer, 1993). The software's Satellite Ortho Model reflect the physical reality of the complete viewing geometry and reflects all the distortions generated during the image formation: distortions due to platform (position, velocity and orientation); distortions due to sensor (orientation, integration time and field of view); distortions due to earth (geoid, ellipsoid and topography); and distortions due to cartographic projections (ellipsoid and cartographic reference) (GCPWorks™ User's Guide, 2001; OrthoEngine™ User's Guide, 2003). A digital elevation model (DEM) is required as an input, in order to get the information about elevation. A DEM provided by the Remote Sensing and GIS Laboratory at

[14] RMS error: The Root Mean Square error is a measure calculated when registering satellite images, which indicates the discrepancy between known point locations (reference) and their digitized locations. The lower the RMS error, the more accurate the transformation.

CIEFAP[15], Esquel, Argentina, was used. The DEM had a resolution of 30m, and was generated from ASTER[16] satellite images. For an ortho-rectification, the ephemeris data of the satellite at the moment of image acquisition is needed as well, in order for the model to calculate the position and orientation of the sensor for the acquisition time. This information is usually contained in the header file of the raw image. As the image used in the study was not the raw image, the header file was not available. Therefore, standard information for Landsat sensors ephemeris provided by the software was used. However, it must be noted that this is not the optimal situation, and detail from the actual sensor's position would have been preferable. The same set of ground control points previously applied was used, and *image 1* was ortho-rectified. The overall correspondence of pixels between the two images improved, both in the low-lands and in the higher mountain summits. Nevertheless, after applying visual assessment of the registration, it was noticed that the error in the mountain peaks was still up to two pixels, thus posing prospective inaccuracy in the detection of changes.

4.3.3 Image normalization

Proper atmospheric correction is critical for satellite derived change detection, because differences in the atmosphere for the two considered dates can cause either false indication of change or mask areas of real change (Coppin and Bauer, 1996; Liang *et al., in press*).

There have been reported several methods for atmospheric correction of Landsat TM data. All methods can be roughly classified into the following groups: invariant-object, histogram matching, dark object, and contrast reduction (Liang *et al*., 2001). The method applied in this study corresponds to the invariant-object group, which assumes that there are some elements in any given scene whose reflectances are nearly constant over time. A linear relation for each band based on the digital response of these "invariant objects" can be used to normalize images acquired at different times. This statistical method is simple and straightforward, and performs a relative correction. It is based on the assumption of a linear relationship between image bands across time (Song *et al*., 2001) and that the same digital number (DN) in corrected images represents the same reflectance, irrespective of what the actual reflectance value may be on the ground (Chavez and McKinnon, 1994). Moreover, this method does not need the considerable amount of ancillary information needed by other more sophisticated techniques, such as meteorological and/or atmospheric information, which is not readily available in rural remote areas as the study site; or sensor specific information. This information could not have been acquired in this study for being usually in the header file of the images, which was not available. Chavez (1996) considers that the optimum radiometric correction procedure is one based solely on the digital image and requiring no in-situ field measurements during the satellite overflight. Hall and others (1991) consider that this method constitutes a useful relative correction procedure when reliable atmospheric optical depth data or calibration coefficients are not available. Furthermore, according to Collins and Woodcock (1996) there is no evidence that a full detailed radiometric correction technique results in any improvement over a much simpler method, and concluded that the use of simple DN matching through the stable objects method is recommended for change detection studies.

Radiometric measurements of several invariant features were used to calibrate a regression equation. Fifteen stable features were used; two corresponding to dense mature forest stands, four were alluvial fans, six corresponded to rock outcrops, and three were gravel covered areas. The mean DN value was obtained for each stable feature represented by a polygon, in every band of the two images. The band by band average digital count values of the radiometric control sets were used to compute the

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[15] CIEFAP: Centro de Investigación y Extensión Forestal Andino Patagónico (Andean Patagonian Forest Research and Extension Center).

[16] ASTER: Advanced Spaceborne Thermal and Reflection Radiometer, is an imaging instrument flying on TERRA satellite, which was designed, among other purposes, to generate along-track stereo images. Stereo images provide with the possibility of DEM creation.

coefficients *a* and *b* of linear transformations relating all digital count values band by band between the two images. Finally, the linear regression model was applied to each band in order to predict time-2 digital numbers from time-1 DN's (eq. 1).

$$(DN_{\,time2})_{\lambda} = a + b * (DN_{\,time1})_{\lambda} \qquad \textbf{eq. 1}$$

λ denotes wavelength. DN accounts for digital number (pixel value).

The linear character of the relationship between band-specific target reflectances over time is illustrated in figure 7; and the model coefficients of the linear model and the R square values are given in table 7.

Table 7. Regression parameters used for the relative calibration of *image 2* to *image 1*, using 15 test areas. Only values for bands 3 and 4 are shown, as they were to be the bands of interest.

Band TM	*a* coefficient	*b* coefficient	R^2
3	4.1076	1.0574	0.995
4	13.689	0.7557	0.953

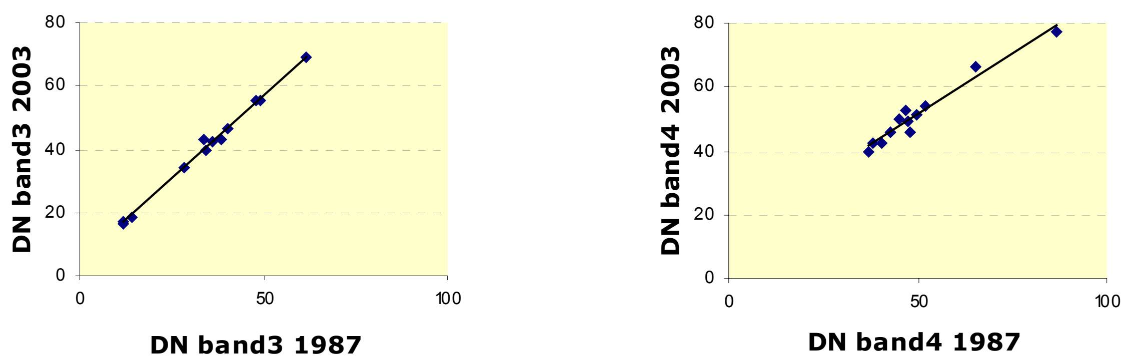


Figure 7. Representation of the linear relationship between mean pixel value of the stable targets for the two images, considering bands 3 and 4.

4.4 Change detection

According to Coppin and Bauer (1996), image differencing appears to perform generally better than other methods for change detection, demonstrating particular suitability for the detection of changes of forest covers. Singh (1989) reported the results of an objective evaluation of different change detection methods for forest ecosystems utilizing Landsat MSS[17] data. Normalized vegetation index differencing qualified within the best methods. He also concluded that simple techniques yielded better results over sophisticated ones, such as principal component analysis and post-classification comparison. As well, various pre-processing techniques such as image smoothing and edge enhancement did not improve the change detection accuracy. Another main advantage of the use of vegetation indices is that they reduce the amount of data to be processed and analyzed, in addition to their inherent capability to provide information not available in any single band (Coppin and Bauer, 1996). Furthermore, the fact that the ratio between image bands can minimize the topographic effects and normalized differences in radiance when using multidate imagery (Singh, 1989; Richards, 1993;

[17] Landsat MSS: Landsat MultiSpectral Scanner 1, 2 and 3. Were launched in 1972, 1975 and 1978 respectively. Images have different spectral and geometric resolution compared to the TM sensor.

Millette *et al*. 1995) was of great significance for the selection of the method to apply in this study. Other methodologies that do not account for topographic effects might not have been as appropriate for such a mountainous area, if considering that no other normalization technique was applied due to the lack of proper data.

4.4.1 Vegetation indices generation

Vegetation indices are quantitative measures based on digital values that attempt to measure vegetative vigor and abundance (Campbell, 1996). Usually, a vegetation index (VI) is formed by combinations of several spectral values that are subjected to mathematical operations to yield a single value, which indicates the amount of vigor of vegetation within one pixel. The simplest form of VI is a ratio between two digital values from separate spectral bands. For living vegetation, the ratioing strategy can be particularly effective due to the inverse relationship between vegetation brightness in the red and infrared regions.

One of the most widely used VI's is known as *Normalized Difference Vegetation Index* (NDVI; eq. 2).

$$NDVI = \frac{NIR - \mathrm{Re}\,d}{NIR + \mathrm{Re}\,d} \qquad \textbf{eq. 2}$$

The principle behind this vegetation index is that chlorophyll causes considerable absorption of incoming radiation in the red portion of the spectrum, whereas the spongy mesophyll tissue of leaves leads to considerably strong reflection of incoming energy in the near infrared region of the electromagnetic spectrum (NIR). (Tucker and Sellers, 1986; Campbell, 1996) The more leaves a healthy plant has, the more these wavelengths are affected. Thus the red and NIR values will be quite different, and the ratio IR/Red will be high. High values of the vegetation index indicate pixels with higher levels of photosynthetic capacity; consequently, the land surface that the pixel represents is likely to be covered by substantial proportions of healthy vegetation. In general, if there is much more reflected radiation in NIR wavelengths than in wavelength correspondent to red, the vegetation in that pixel is likely to be dense, and may involve the presence of forest. On the contrary, if there is little difference in the intensity of red and NIR wavelengths reflected, the vegetation is probably sparse and may consist of grassland or semi-desert compositions.

There are other vegetation indices, which intend to correct for undesired effects, like soil background reflectance in the case of the *Soil Adjusted Vegetation Index* (SAVI) (Huete, 1988), and the *Modified SAVI* (MSAVI). A difficulty about using vegetation indices that attempt to minimize the effect of soil backgrounds is an increase in the sensitivity to the atmospheric conditions. Consequently, there have been several approaches to develop indices that are less sensitive to the atmosphere, resulting in the *Atmospherically Resistant Vegetation Index* (ARVI) and the *Global Environmental Monitoring Index* (GEMI). However, these sort of vegetation indices designed to minimize the effect of the atmosphere have increased sensitivity to the soil (DES UV)[18]. As it can be concluded from this, selecting a vegetation index implies a trade-off among different factors. Purevdorj *et al.* (1998) studied the performance of different vegetation indices in estimating vegetation cover on grasslands in Mongolia. They found that the *Transformed SAVI* (TSAVI) and NDVI gave better estimates than the SAVI and MSAVI. Leprieur and others (2000) compared several vegetation indices for the monitoring of vegetation in semi-arid regions, and they found that for the detection of small amounts of green vegetation, the NDVI and GEMI performed better than the MSAVI; whereas NDVI and MSAVI proved to be better than GEMI when fractional vegetation cover increases. Therefore, in the overall assessment, NDVI performed relatively better than the other two indices.

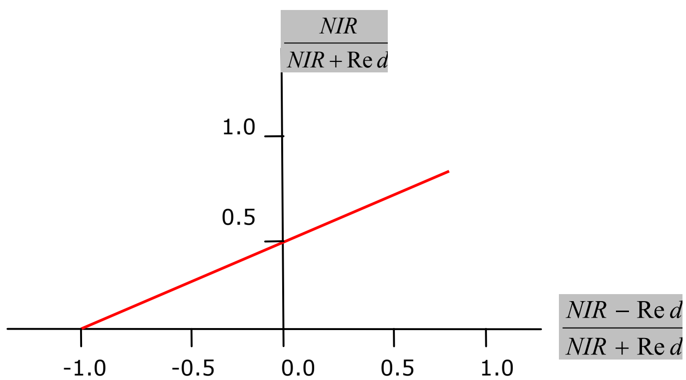
[18] Department of Environmental Sciences, University of Virginia.

The NDVI is preferred to the simple ratio based VI = IR/R for vegetation monitoring because it helps compensate for changing illumination conditions, surface slope, aspect, and other extraneous factors that act equally in all bands of analysis (Lillesand and Kiefer, 1987), and it has a closer functional linearity with measures of vegetation amount (Crippen, 1990). It has also the advantage of varying between -1 and 1, facilitating interpretability.

After consideration of the different possibilities and review of relative performance of different vegetation indices, a slight variation of the classic NDVI was chosen for the present study. Crippen (1990) noted that the subtraction of the red band radiance that is done in the calculation of the NDVI was irrelevant, and introduced the *Infrared Percentage Vegetation Index* (IPVI). Computationally, the proposed index differs from the NDVI only in that the subtraction of the red radiance is eliminated (eq. 3). Otherwise, it produces results that are functionally and linearly identical to normalized differences. Advantageously, it is both computationally faster and never negative (Crippen, 1990). Ray and others (1994) used this vegetation index successfully for multitemporal studies of land degradation in California.

$$IPVI = \frac{NIR}{NIR + \mathrm{Re}\,d} \qquad \textbf{eq. 3}$$

IPVI measures the percentage of near-infrared radiance in relation to the combined radiance in both the red and infrared bands, and ranges between 0 and 1. The linear relationship between this index and the NDVI is shown algebraically in eq. 4, and graphically in figure 8.



$$\frac{NIR}{NIR + \mathrm{Re}\,d} = \frac{1}{2}\left(\frac{NIR - \mathrm{Re}\,d}{NIR + \mathrm{Re}\,d} + 1\right) \qquad \textbf{eq. 4}$$

Figure 8. Linear relationship between the NDVI (abscissa) and the IPVI (ordinate).

Thus, the proposed index differs from the NDVI only by a gain 0.5 and an offset of 1.

If applying Landsat TM derived images the formula becomes as in eq. 5.

$$IPVI = \frac{TM\,4}{TM + TM\,3} * 100 \qquad \textbf{eq. 5}$$

Band TM 4 corresponds to the NIR portion of the spectrum, whilst band TM 3 comprises the red sector of the visible portion of the spectrum. A scaling factor of 100 was applied, in order to rescale the obtained IPVI values, and enhance the visual interpretation.

In the present study, the formula shown above was applied to both images, resulting in two IPVI images: $IPVI_1$ corresponding to the 1987 image, and $IPVI_2$ for the 2003 scene.

Since obtained pixel values were too small, ranging from 0 to 1, a scaling factor of 100 was used in order to facilitate the visualization of results.

4.4.2 Vegetation indices differencing

To identify the occurrence of changes in vegetation between the two considered dates, a subtraction of the vegetation indices was applied. $IPVI_1$ was subtracted from $IPVI_2$, to obtain a final *difference image* (DI), which contained the changes (see figure 9). The mathematical operation is shown in equation 6.

$$DI = IPVI_2 - IPVI_1 \qquad \textbf{eq. 6}$$

Where *DI*: pixel value for the difference image DI
$(IPVI_2)$: pixel value for $IPVI_2$
$(IPVI_1)$: pixel value for $IPVI_1$

Broadly speaking, any change occurred would take values different from 0, since this value would indicate no change between the two dates. Positive values would indicate increase in vegetation in the period considered, whereas negative values would indicate a vegetation decrease.

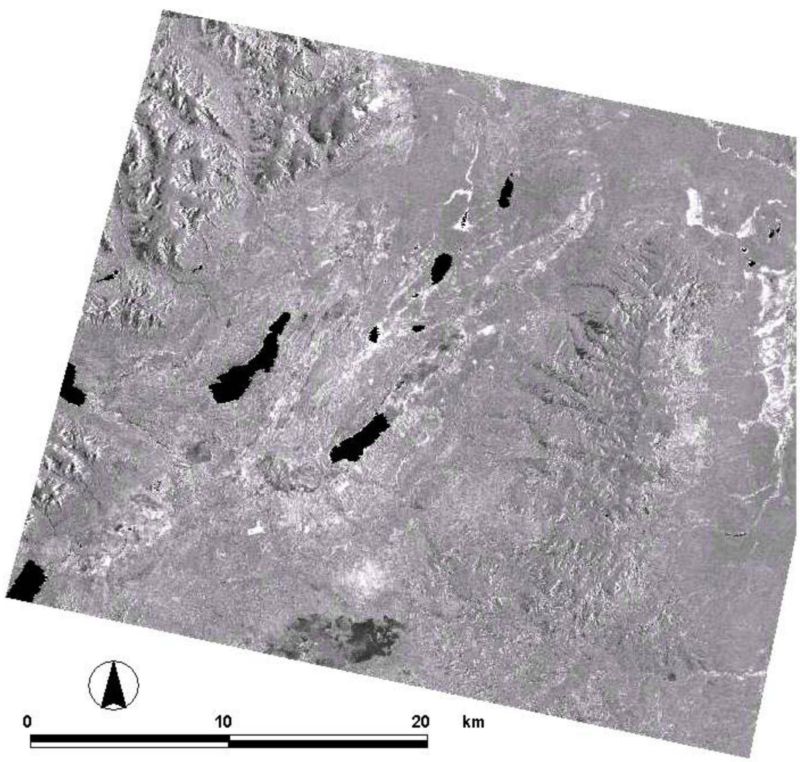


Figure 9. Difference image (DI) obtained from the subtraction of $IPVI_2$ to $IPVI_1$.

4.4.3 Masking out of undesired objects

After visual assessment of the resulting DI, a clear displacement of up to 2-3 pixels was noticed along the mountain ridges. Identified change in those areas resulted to be a misregistration effect. Consequently, these parts had to be eliminated from the study, since they could interfere with the results, producing a certain bias in the quantification of changed areas.

Sectors of DI corresponding to mountains were masked out. In order to do this, a bitmap mask comprising the undesired object was created and overlaid on the DI. The mountain mask acted as a virtual “cookie-cutter” and subset the area, saving the rest of the area, which was apt to be subjected to the further analysis of change detection. Lakes were eliminated from the area as well, as they were irrelevant for the aim of the study.

A *final difference image* (fDI) was thus obtained, with no lakes and no mountain ridges (see figure 10).

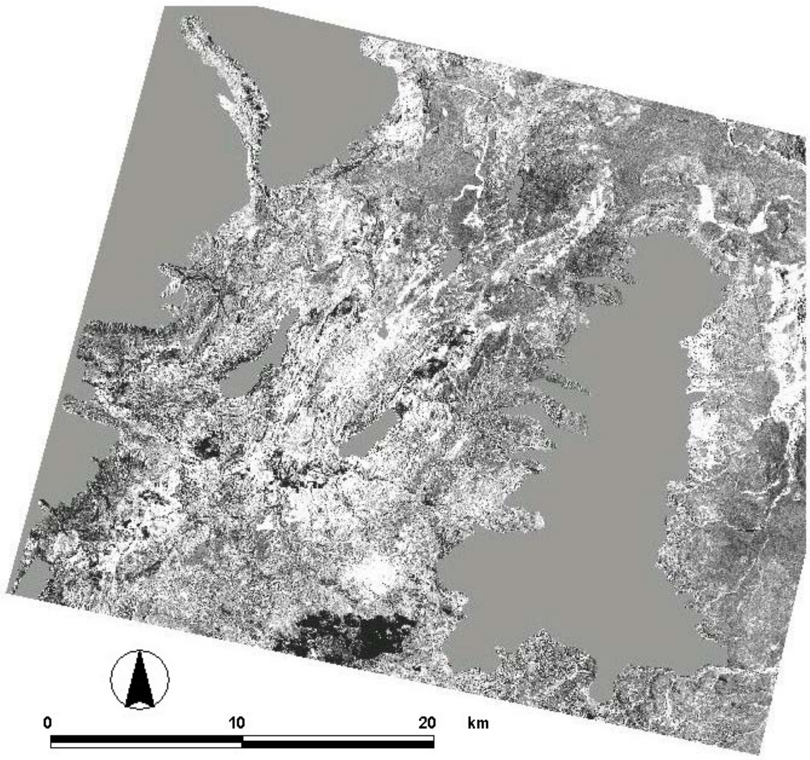


Figure 10. Final difference image (fDI) obtained after the application of masks to eliminate the undesired portions of the DI. Eliminated areas can be seen in plain grey.

4.4.4 Thresholding

The resulting fDI represents an image of continuous change, which indicates the degree of change in a gradual scale. Since the generation of a "change – no change" image was the aim, a threshold that would delimit the categories of "changed" and "stable" areas needed to be indicated. The problem of placing threshold boundaries has different solutions and, once again, no fixed criteria of general applicability have been determined (Singh, 1989; Chuvieco, 1998).

After study of the fDI's histogram[19], which indicated a normal distribution a statistical approach was deemed suitable to the determination of the thresholds to be used. To account for the uncertainty of the change detection, results can be given for a range of threshold levels, as done by Washington-Allen *et al.* (1998). Thresholds would be given by a number of standard deviations from the mean pixel value. Pixel values comprised within the standard deviation (σ) limits would be considered as "no change" pixels, whereas values outside the standard deviation region/s would be labeled as "change" areas, differentiating between positive and negative change, according to the sign of pixel value. Three different thresholds on the basis of the number of standard deviations from the mean were determined: $\pm 1\sigma$, $\pm 2\sigma$ and the more conservative $\pm 3\sigma$, which would consider almost all pixels as "no change" areas (see figure 11). Three "change images" were thus obtained, each one indicating a different degree of change.

[19] In digital image processing, a histogram depicts the number of pixels corresponding to each grey value.

The probabilities of a normal distribution could be translated in the context of this study as follows:

p(-1σ < μ < 1σ) = 0.683 for thresholds set at ±1σ; which means that there is 68.3% of probabilities of observing a value comprised by the interval (μ – 1σ; μ + 1σ); that is, a pixel has 68.3% of chances of not observing a change;

p(-2σ < μ < 2σ) = 0.954 for thresholds set at ±2σ; or its equivalent, there is 95.4% of probabilities of observing a value comprised in the interval (μ – 2σ; μ + 2σ). In this change image, any pixel has 95.4% of probabilities of remaining stable;

p(-3σ < μ < 3σ) = 0.997 for thresholds set at ±3σ; which means that there is 99.7% of chances for a pixel to be within the interval (μ – 3σ; μ + 3σ) and therefore not to observe any change. In this change image, the possibility of any pixel to be a “change” pixel is only 0.3%.

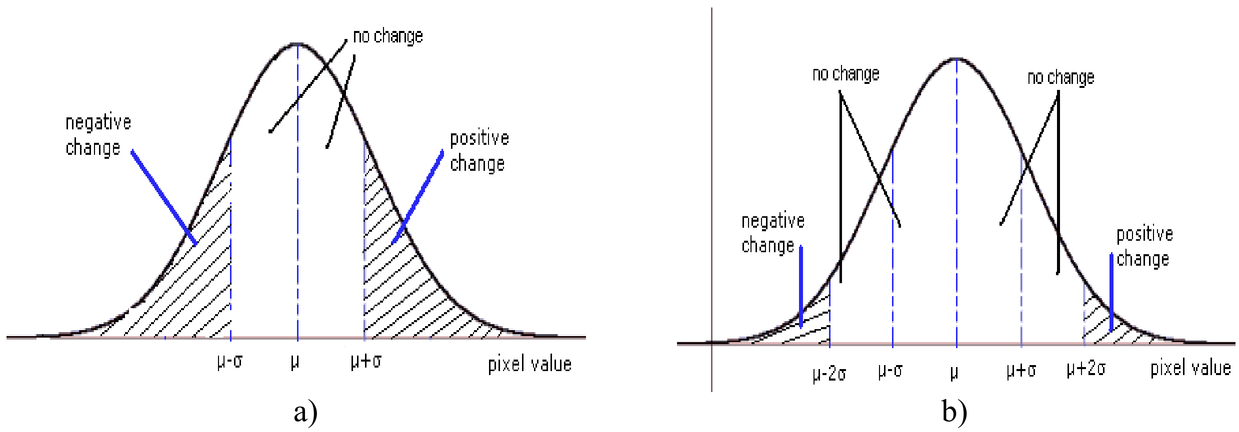


Figure11. a) Normal distribution showing the thresholds set at ±1σ, indicating the area under the curve that will show change. b) Normal distribution showing the threshold set at ±2σ, note that the area under the curve that will determine change is smaller than in a), what will result in less detected change. Areas indicating change in ±3σ would be even smaller, almost not appearing at all.

4.5 Analysis of results

The quantification of change and no change areas, as well as the calculation of proportions, was done by means of the powerful vector capabilities of ArcView® v3.3.

The information of change and no change obtained after the processing of the images was exported from PCI® as vector files, and a Geographic Information System (GIS) was created. Information in the form of shape files (vectors) was added as layers to the GIS. Some data were provided by DGByP, such as point locations for fires occurred since year 1999 and the location of plantations since year 1995, whereas information about the areas covered by sweetbriar rose and *Nothofagus pumilio*, was supplied by CIEFAP. Complementary vector files had to be created in order to analyze the detected changes. Those corresponded to mature plantations, and the location of the main town in the area, which were digitized on the screen.

In order to account for the contribution in percentage of identified features to each category of change, operations to combine the attributes of different layers had to be applied in the GIS. Afterwards, mathematical calculations would give the definite numbers.

This chapter aims to review the findings of the study. They will be discussed in the light of the anticipated objectives, and the implications to the understanding of the land cover change situation in the study area.

5.1 Imagery pre-processing and data availability

For it being an essential part of the study and a determinant factor of the results of the study, consideration must be taken on the outcome of the preprocessing of the imagery, prior to the assessment of the results of the study as such.

As previously exposed, the registration of the images was not completely satisfactory in the mountain ridges of the area, consequence of geometric distortions due to image acquisition and relief displacements, and an ortho-correction had to be applied to improve the registration. However, it is not recommended to apply the ortho-correction when the image has been previously geometrically processed, or when not counting on the original orbit information. Therefore, it cannot be stated that *image 2* is now a proper “ortho-rectified” image, since it did not comply with the requisites. The model was nevertheless applied, as it improved the co-registration between images, which was the aim of the procedure.

Based on the difficulties experienced during the pre-processing of imagery, it is hereby argued that availability of raw images is very important for the successful outcome of a change detection procedure. It gives the possibility of relying on original data avoiding the existence of external sources of error, plus the existence of the header files, which contain relevant information. For the same purpose, it would be also essential the possibility of DEM’s generation.

Insufficiency of ancillary information represented a drawback for the study. Available information was scarce, and spread over different local, provincial and regional institutions, therefore presenting difficulties for data gathering. Collected information varies in spatial scale, referring to regional, county or individual ranches level, depending on the source and nature of the information. Time scales among data also differs, as existence of information for rural areas in Patagonia is subjected to specific needs and availability of funds, thus preventing the development of thorough data bases. Nevertheless, existing information added to accumulated knowledge about the region, made it feasible to attribute some of the observed changes to possible causes, which will be reviewed in the following sections.

5.2 Change detection

Results from the change detection procedure are shown in table 8 and figure 12. Table 8 lists the corresponding percentage areas of change for the three different threshold levels. The information is depicted graphically in figure 12, which shows a categorization of the change (positive and negative), and no change areas for each of the three change images. That way, the visual interpretation of the results is enhanced, and allows for disclosure of the location of change within the area.

Table 8. Percentage of the study area changed and unchanged in the IPVI difference image, at different standard deviation threshold levels (i.e., $\pm 1\sigma$, $\pm 2\sigma$, and $\pm 3\sigma$). The symbol 0 in column headings indicates no change, + shows positive change, and – means negative change.

Years difference	± 1σ % 0	± 1σ % +	± 1σ % -	± 2σ % 0	± 2σ % +	± 2σ % -	± 3σ % 0	± 3σ % +	± 3σ % -
2003 - 1987	79.7	11.9	8.4	94.8	3.4	1.8	98.4	1.0	0.6

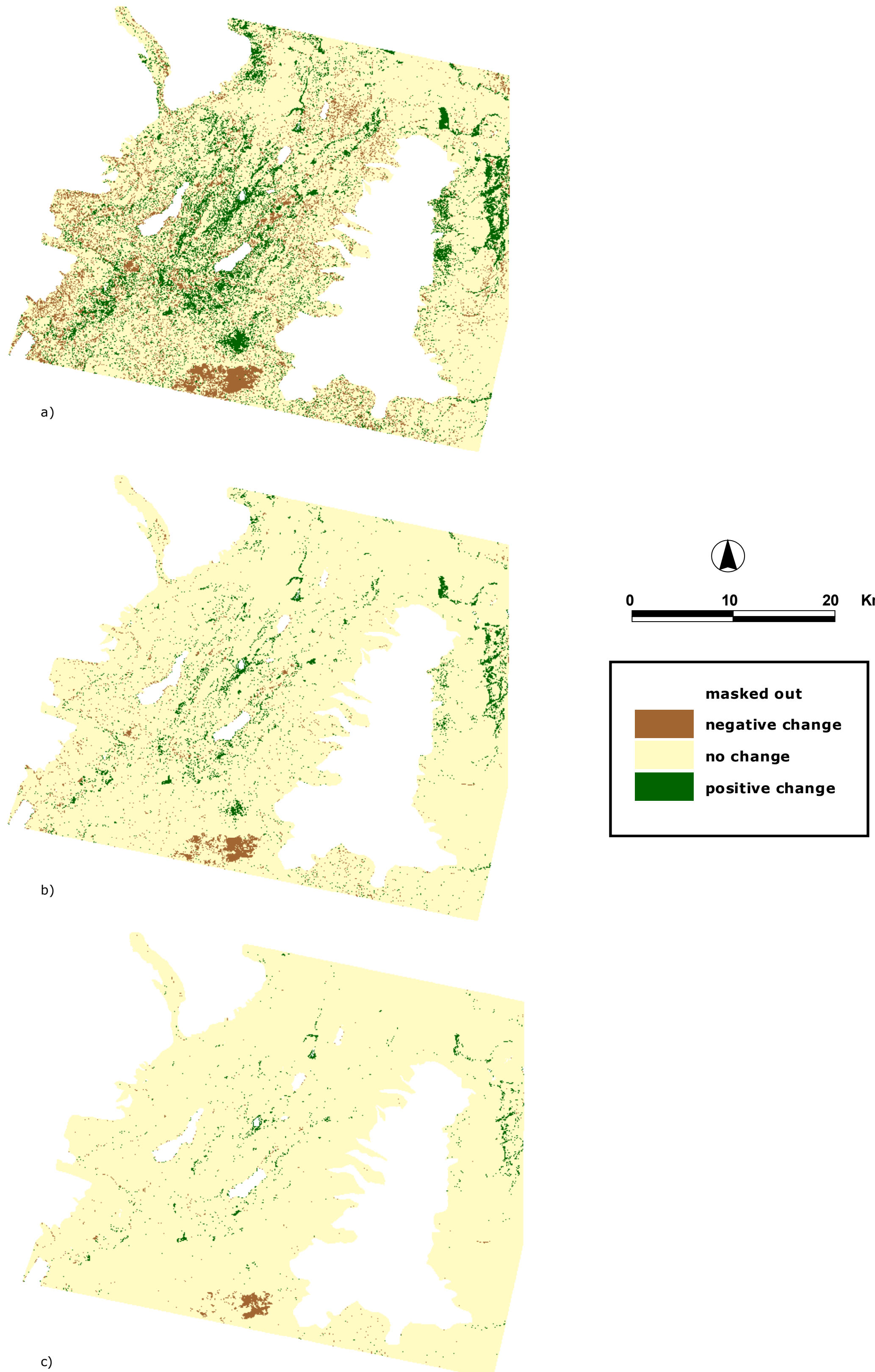


Figure 12. Map of the area showing the categorization of change from the IPVI difference image, considering the three different threshold levels: a) ±1σ; b) ±2σ; and c) ±3σ.

Positive changes indicate an increased photosynthetic activity in the moment the image was taken in year 2003 respect to the image from year 1987. Conversely, negative changes reflect a decrease in photosynthetic activity in year 2003 respect to year 1987. Within the frame of this study it is assumed that an increase or decrease in photosynthetic activity indicates an augment or diminution of the amount of vegetation accordingly. As expected, the area considered as *change* is larger in the change image with thresholds at ±1σ than in the image with thresholds set at ±2σ; being the image with limits at ±3σ the one that shows the least change.

An overall assessment indicates a larger share of positive changes than negative changes in the three considered situations. At a first glance it might seem possible to assert an improvement in the environmental situation of the area, which in turn could be translated into an increase in the sustainability of the region. Still, some considerations prior to a conclusion must be made. In the following sections an attempt to link the found changes to the possible causes previously reviewed is made.

5.2.1 Rainfall pattern and phenology

Information about precipitation patterns in the area when a change detection study is carried out is of crucial importance, given the natural response of vegetation to rainfall, or the lack thereof.

Historical climatic data for precipitation was available since year 1957, for a weather station located within the study area, at 42°29'59''S and 71°32'19''W. That station was the only one situated within the study area counting on a reasonable amount of data. The use of one meteorological station might be enough and representative to the conditions within the study area; according to Villalba and Veblen (1997), *"the environmental conditions along the forest-steppe ecotone are uniform, and the climatic conditions are relatively homogeneous in Patagonia east of the Andes at about 37-44 degrees south."* Precipitation average for the station is 999 mm yr^{-1}. Figure 13 depicts the yearly rainfall in the area, which shows a tendency towards "dry" (below the average line) and "humid" (above the average line) cycles. Notoriously, dry cycles have become increasingly intense with time.

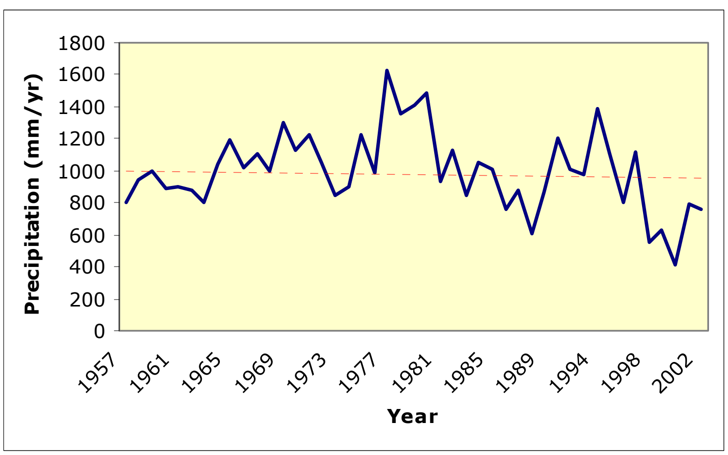


Figure 13. Yearly rainfall in the area for the period 1957-2002. A running average line for the meteorological station is superimposed, to facilitate the identification of "humid" and "dry" cycles. (Source: Hydrological Resources National Office database)

Conditions regarding precipitation for the moment each image was acquired are reasonably comparable between the two scenes. Accumulated rainfall for the previous year to image acquisition was 758.9 mm and 763.5 mm for 1986 and 2002 respectively, both below the station average. As images do not correspond to the same Julian Day[20] however, accumulated rainfall for a time frame corresponding to the twelve immediate previous months to each image acquisition was compared. It

[20] Julian Day: day number of the year.

resulted in 755.9 mm of rainfall for the period 24th Jan 1986-24th Jan 1987; whereas the result was 745 mm for the segment 10th Mar 2002 – 10th Mar 2003. A slight difference of 10.9 mm of rain between both 12-month periods could hardly explain any difference in land cover change. Furthermore, the last rain event for scenes 1 and 2 was 54 and 20 days ahead of image acquisition respectively. Evaporative losses in the characteristically dry summer season make soil moisture comparable between scenes, thus eliminating the potential effect of greater/lower moisture in soil reflectance, and making both scenes further comparable. Nevertheless, some difference in the distribution of rainfall within the previous year to image acquisition might be worth a comment. Rainfall was delayed in year 2002, the bulk of yearly precipitation fell between August and October; conversely, year 1986 followed the rule, and experienced a normal pattern of winter rains, between June and August. However, this might be partly compensated by the 45-day difference in acquisition between the 1987 and 2003 images (see figure 14).

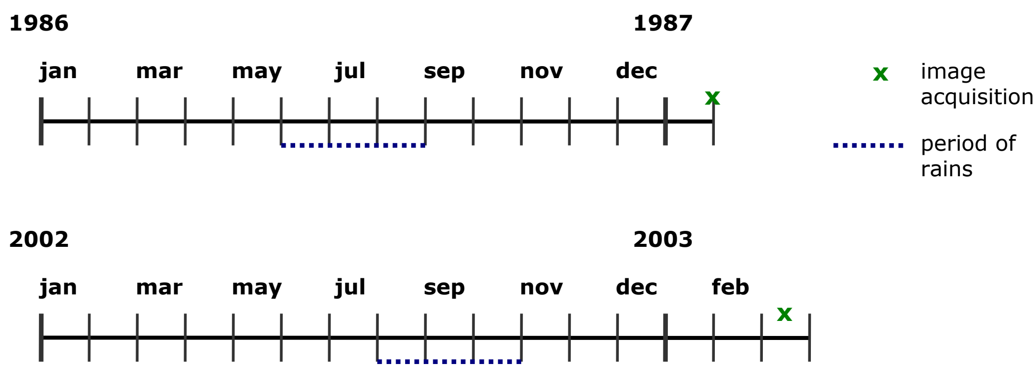


Figure 14. Comparative time scales, indicating the rainy season for the previous years to image acquisition, and the image acquisition approximate dates. The time lag between rainy seasons might have been compensated by the time lag between image acquisition dates.

For the above described, attribution of changes in vegetation between scenes due to precipitation patterns is discarded.

Correspondingly, some remarks regarding phenology should be made. Scene 1, acquired in late January is characterized for mid-summer season; whereas scene 2, acquired in March, corresponds to late summer. Therefore, there might be a difference in the physiological activity of vegetation, which might explain some of the detected changes. However, no studies approaching the yearly physiological behaviour of vegetation, and the correspondent response in vegetation indices are yet available in the region. Nevertheless, a possible minor difference in phenology could not describe an increase in the photosynthetic activity in late summer (when *image 2* was acquired). On the contrary, major photosynthetic activity takes place during plain summer season (the moment of *image 1* acquisition), and not when autumn is about to come. Therefore, if existing a detectable phenology effect on the comparison of both images, it should have resulted in a general decrease in vegetation photosynthetic activity, and not in an increase, as it actually happened. Hence the reason that does not allow a description of the detected general increase in photosynthetic activity through phenological states in this study.

5.2.2 Livestock composition change

Pickup and Chewings (1994) define degradation in rangelands as *"a grazing-induced long term reduction in the capacity of the land to produce forage for grazing animals in response to rainfall."* They distinguish therefore two components to degradation. One of them involves a reduction in the capacity of producing vegetation as a whole, and indicates a loss of total productivity. The other component entails changes in the ratio of palatable to unpalatable plant cover, and reflects a change in forage quality. This study deals exclusively with capacity to produce vegetation cover as a whole, as it is more likely to be described by changes in the vegetation index values.

The change in the composition of livestock occurred in the area could actually explain, at least partly, the increase in the amount of vegetation experienced in the area. The share of sheep within the livestock reduced sharply, whereas the contribution of cattle augmented.

As explained elsewhere, grazing of cattle is less damaging for the vegetation cover than sheep grazing, especially at overstocking rates. Therefore, a shift from a sheep-oriented towards a mixed livestock industry, in addition to an overall diminution in the number of sheep in the area, could have lead to an improvement in the state of vegetation in the grazing areas, that is, the lowlands, including *mallines*. Furthermore, ranches in the area seem to have lower number of livestock heads in comparison to their potential capacity (Fertig, personal communication), which would contribute to an improvement of the lands in respect to earlier reported overgrazing.

A hypothetical land restoration occurrence is supported by the fact that rangelands and *mallines* were actually subjected to further grazing at the moment of *image 2* acquisition, than at the moment of *image 1* acquisition, since the grazing season extends from mid November until late April. The proportion of green vegetation in *mallines* is around 60% in the beginning of the grazing season, the rest corresponding to dry material, whereas it decreases to around 15% of the total vegetal material by the end of the season (Lloyd, 2002). That would imply the presence of less green vegetation in the *mallines* and other grazing areas in *image 2*, acquired in March. Nevertheless, that potential negative change has been barely detected in some areas, mainly in image with thresholds at $\pm 1\sigma$. Conversely, an overall positive change has been found in the referred lowlands and *mallines*.

5.2.3 Occurrence of fires

The occurrence of fires in the area during the period of the study was confirmed, but information about their geographic position was not available, thus making impossible to determine the land cover change they are assumed to provoke. Between 1987 and 2003, 109 fires were reported in the area, accounting for 524.5 affected hectares (DGByP, unpublished data). Difficulties to locate the changes produced by wildfires when trying to make a visual assessment might have been the result of other factors as well, related to the nature of the vegetation affected by the fire. The majority of the reported fire events took place in shrubs and grasses lands, only 160 hectares corresponded to native forests. Shrubs and grasses have a great potential of regenerating immediately after the fire, not taking long before the vegetation of the area is recovered. Fires occurred in grass and shrublands long before *image 2* was acquired are not likely to have produced detectable changes then. In addition, 158 hectares from the forest-affected areas correspond to a single fire occurred in early 1988, and 15 years later, the affected area might have been re-covered with vegetation, witnesses of a new succession event, impeding the detection of any land cover change produced by that fire.

According to the scarce information regarding geographic position of fires in the area (only from 1998 on, and very vague), there is a high concentration of fires nearby the main town in the area. Operations applied to the geographic information system demonstrated that 25% of the fires in the study area occurred since 1998 took place within 1 km from Cholila, the main town; whereas 70% of the fire events took place within a radius of 5 km. That would support the argument favoring their mainly anthropogenic nature, in view of the likely high human activity taking place in the town, and the vehicular movement that concentrates in it and surroundings.

5.2.4 Afforestation

The evaluation of changes due to afforestation is difficult as well, once again due to the lack of proper "ground truth" data, that is, information obtained in the field, as well as from official records.

Records with geographic reference of the location and area of plantations were obtained only since year 1995. Information about 24 afforestation sites was provided, accounting for 1995 hectares (DGByP database). These plantations could not be visually identified in *image 2*, or the changes they might have occasioned. The reason for this could be that plantations grow slowly in Patagonia during the first few years, since they have to face some adverse climatic conditions, plus the harassing of animal species that feed themselves from the seedlings. Especially the European hare produces severe damages to seedlings of the genus *Pinus* until the third or fourth year after plantation (Rodriguez, 1997).

Data prior to 1995 lacked any geographic reference in digital format. Some mature plantations were identified in scene 2 and digitized on the screen, in order to search for any connection with the observed land cover changes. This generated information must be considered with caution, since it might be incomplete; and should be regarded mainly as an example. Digitized plantations summed 23, comprising an area of 373 hectares.

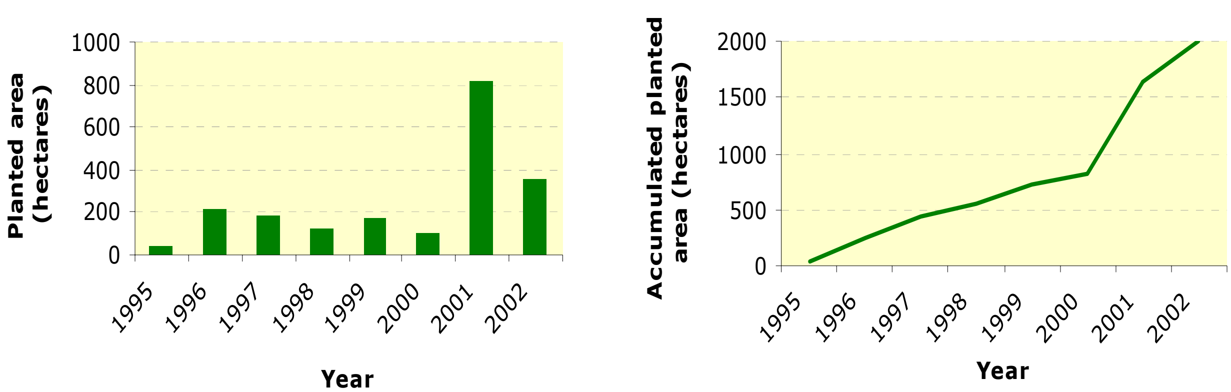
Even if less dramatic when considering the unexpectedness with which it happens, afforestation might be regarded as the opposite condition to fire occurrence, in terms of land cover change. It provides a sharp increase in the amount of vegetation present in the area, especially after some years since the actual plantation of trees took place.

Table 9. Proportion of the total positive change caused by mature Pinus sp. plantations, for the three change images.

	±1σ	±2σ	±3σ
share of total (+) change	1.54%	3.76%	7.8%

Plantations represent increasing percentages of total positive change in the different change images (±1σ; ±2σ; ±3σ). Quantities are shown in table 9. This indicates a decreasing sensitivity to other "lighter" positive changes, whereas the increasing presence of plantations within the positive change context might point out afforestation as an important type of land cover change occurring in the area.

This must be taken in careful consideration, in view of the amount of the recently afforested area. The area that is planted each year has remained rather stable until year 2001, when a larger contribution to the total planted area in the last years was made. Area afforested in 2002, if not as large as 2001's, was significantly larger than that of previous years (see figure 15). Therefore, this type of land cover change is likely to continue.



a) b)

Figure 15. Area planted each year since year 1995 until 2002 in a); and accumulated planted area for the same period in b) (note that the contributions for each year have been accounted since 1995 exclusively, leaving out the existent planted area from previous years, due to a lack of proper information).

5.2.5 Intrusion of exotic species: sweetbriar rose

Data about sweetbriar rose coverage was available for a portion of the study area. The area covered by the spiny shrub was reported to be approximately 2,126 hectares (Martinez, unpublished data), which represents 1.7% of the total study area. Contributions to positive, negative and no change in the different change images are shown in table 10.

Even though the area covered by sweetbriar rose in 1987 is unknown, it is a fact that it has increased sharply (Lencinas, personal communication; Guitart, personal communication).

Presence of sweetbriar rose mostly resulted in positive vegetation changes, indicating an increase in the vegetation amount in the areas affected by the invader shrub. This could be due to the fact that it generally takes over areas previously covered with grasses and shrubs, thus augmenting the amount of vegetation in the affected area. Values and variations of the percentage of contribution to the other categories of change along the three different change images are minor.

Table 10. Proportion of the neutral condition, positive and negative change, caused by sweetbriar rose, for the three change images.

	±1σ	±2σ	±3σ
share of total (+) change	4.6%	7.9%	4.0%
share of total (0) change	1.3%	1.6%	1.7%
share of total (-) change	1.0%	1.0%	0.6%

The change image with the threshold set at ±2σ has resulted to be the most sensitive to the positive changes originated by the exotic shrub, since it shows the highest value of the share of sweetbriar rose to the positive changes.

5.2.6 Action of defoliating insects

In the southern portion of the study site a relatively large area resulted to be affected by a negative change, which had a rather uniform appearance, and was consistent throughout the three change images. The area corresponds to a portion of *Nothofagus pumilio* native forest (Martinez, unpublished data). After visual assessment of *image 2*, the possibility of a wildfire that might have occasioned that severe diminution in the amount of vegetation, establishing such a particular contrast with the surroundings, was considered. An inspection of a Landsat 7 scene from December 15th 2002[21] did not show the same patch of affected vegetation; therefore the event causing the phenomenon should be very recent then (see figure 16). The idea of a wildfire event was discarded after consultation of the fire records for the region, where no such a fire was documented. The hypothesis of forest defoliation due to the massive attack of insects was then supported by consultation with researchers at CIEFAP and DGByP[22]. There is an antecedent of this kind of phenomenon for the Andean Patagonian *N. pumilio* forest, occurred in February 1999, and detected and reported by Lencinas (2001) in a study based on the use of remotely sensed data. The insect species responsible for foliage damage in that opportunity, and likely to be the responsible for defoliation in this opportunity as well, is *Ormiscodes cinnamomea*, a coleopteran with an ample distribution within Patagonian native *Nothofagus* forests (Dapoto *et al*.,

[21] Subset of an image Landsat 7ETM, from December 15th, 2002, provided by CIEFAP.
[22] PhD. José Lencinas; MSc. Norberto Rodriguez and Eng. Vivian Postler. All personal communications are duly referenced in the last section ("References") of this thesis.

2003). The insects' attack only produces defoliation, not the death of the trees, which are expected to develop new foliage the following spring. The harmful action of this insect is exacerbated by dry hot summers (Lanfranco *et al.*, 2001). It is therefore worth mentioning that the wildfires risk indices (which are based on temperature and humidity among other factors) for the region for the summer season 2002-2003, were the highest in ten years (PNMF). That means that the summer when the event took place was especially hot and dry. As to year 2001, unusual defoliations were observed in the southern Andean forest in Chile in the last five years (Lanfranco *et al.*, 2001), and climate change causing dry summers is considered as a driving force that enhanced population irruptions of defoliators.

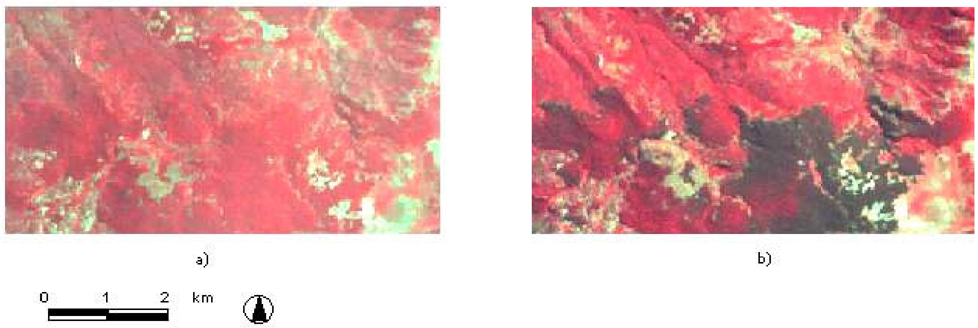


Figure 16. Comparison of the area affected by insects. Part a) corresponds to December 2002, before the defoliation; b) represents the area in March 2003, after the defoliation. A false color composite, combination of bands 4-3-2, was used in both images to discriminate the affected area, which is seen in green tones of in part b) of the figure.

It is noteworthy that this attack of *N. pumilio* forests by defoliating insects in the area was not registered before, and it is documented by this study for the first time.

The area affected by a defoliating insect was digitized on the screen. A large part of the overall negative changes identified in the change images account for this single event, which affected 1,810 hectares of native forests. In the different change images the areal magnitude of this phenomenon represented increasing percentages of the total negative changes (see table 11). That indicates more sensitiveness to negative changes of other nature in images with thresholds at levels 1σ and 2σ, than 3σ. In the latter one, which accounts only for changes corresponding to extreme values that are far away from the average values, this defoliating event represents as much as 62.7% of the total negative change. Consequently, defoliation by insects could be considered as the driver of a "drastic" change in the vegetation cover of the area.

Table 11. Proportion of the total negative change accounted for a defoliating insects attack occurred during the summer season 2002-2003, for the three change images.

	±1σ	±2σ	±3σ
share of total (-) change	12.9%	38.2%	62.7%

5.2.7 Proximity to urban centers

Anthropogenic activities are concentrated in urban centers and surroundings, possibly causing intense land cover change. In this study, that hypothesis was investigated through the areal quantification of land cover change in the proximities to the mean town in the study area, Cholila. Buffer zones were generated in the GIS as concentric circles at distances of 250; 500; 1,000 and 2,000 meters from the town's external borders. Distances larger than those were not considered, given the small size and population of the settlement (0.19 km^2 and 1767 inhabitants respectively, as to year 2000). Over longer distances direct human influence on land cover change was assumed to be equivalent as that for any other portion of the study area. As parts of the concentric areas where affected by the presence of sweetbriar rose, the positive change attributable to it was identified and quantified.

Calculations of land cover change were carried out over the change image product of a threshold set at ±2σ, for it being considered to be an intermediate representative of change. Results are given in table 12. Positive changes presumably caused by sweetbriar rose are also shown in a separate column[23].

Table 12. Percentages of negative, positive and no change in concentric areas, considered as circular rings placed at the indicated distances from the town external borders. The percentage of positive change attributable to sweetbriar rose is also shown for areas 0-1000 meters and 1000-2000 meters.

Distances from town borders (meters)	(0) 2σ	(-) 2σ	(+) 2σ	% of (+) change attributable to sweetbriar rose
0 – 250	93.2%	2.7%	4.1%	
250 – 500	89.1%	4.7%	6.3%	19.8%
500 – 1,000	87.9%	2.9%	9.2%	
1,000 – 2,000	84.6%	2.2%	13.2%	15%

In all concentric areas the large majority of the land cover remained stable. Slight negative changes were surpassed by positive changes in vegetation cover. This indicates that human activities nearby Cholila have not caused a diminution in the amount of vegetation, but on the contrary, the amount of vegetation has increased. This could point out that human behavior in the area does not tend to degrade the environment, at least in the form of decreasing the amount of vegetation, which is the focus of this study. Nevertheless, this result must be taken with only due optimism, as in the overall, 17.4% of positive changes could be attributed to the presence of sweetbriar rose in the area, and for the elsewhere exposed reasons it is not considered to be a desirable positive change.

5.3 Brief review and final remarks

This chapter has reviewed the results of the study, in terms of the areal extent of land cover change in the study site; and the nature of change, considering the categories *positive*, *negative* and *no change*, which describe an increase, decrease or no variation in vegetation amount. Each type of change was accounted for the thresholds utilized for the creation of the different change images. Also, changes were related to possible drivers, as well as actual features on the ground when applicable.

Firstly, the necessity of proper raw data and the generation of DEMs, in order to achieve better registration of images have been highlighted. It must be also emphasized the importance that should be given to the possibility of counting on accurate an reliable ancillary information for successful studies of this nature.

Contrary to what have been repeatedly reported regarding Patagonian environmental status, no advancing land degradation was detected in the area. Furthermore, an overall increase in the amount of vegetation was found.

[23] Note that the positive changes possibly attributable to sweetbriar rose are still included in the results. The discrimination of the percentage caused by sweetbriar rose only intends to put the resultant positive changes under perspective.

Precipitation patterns were so similar for the moment that the images were acquired, as well as for previous months, that is does not seem feasible that vegetation changes can be explained by a response of vegetation cover to differences in rainfall.

Conversely, positive changes due to afforestation and negative changes from the action of defoliating insects were certainly identified.

Positive vegetation changes in lowlands and *mallines* are likely to be described by a change in the composition of livestock, which increased the share of cattle and diminish the overall number of sheep.

Gradual invasion of sweetbriar rose in parts of the area has caused positive changes in the vegetation cover.

There are some detected areas of change whose nature could not be clearly identified. Positive changes could be attributed to other factors than the aforementioned. Visual interpretation of *image 1* could not confirm the occurrence of fires or any other mass destruction event that could have occasioned a decrease in vegetation in the referred areas before the acquisition of the image, and no records as old as early 1980's were available. On the other hand, Veblen and Lorenz (1988) have indicated vigorous tree regeneration at the Patagonian forest-steppe ecotone, which would signify an eastwards steppe retreat. They considered that the encroachment of *A. chilensis* and other tree species into the steppe has started some 100 years ago, and it might be feasible that this study has detected the last 16-year effect of this positive change.

Overgrazing, as a possible land cover change driver in the region, could not be specifically identified; moreover a change in the composition of livestock has been assumed as a most probable positive change producer. However, it cannot be discarded the possibility of a contribution by overgrazing to detected areas of negative change in the lowlands and *mallines*. On the other hand, a decrease in photosynthetic activity in certain parts of *mallines* could be simply due to the advanced of the grazing season in *image 2*, and the normal diminution in the proportion of green vegetation as a result.

Location of timber activities sites could not been identified within the study area. Even though they are known to cause detectable land cover change (Coppin and Bauer, 1996), there was not available information about their geographic location, thus impeding the evaluation of potential changes caused by them in the study area. Nevertheless, a cautious visual inspection of the difference image was made, and no obvious negative changes in the forest cover were found.

Even though no particular change could be attributed to climate change, the massive attack of defoliators could be noticed as a response to a change in climate towards drier and hotter summers, which could be the result of climate change. From the precipitation records it was observed that in the last 30 years drier periods have become more intense in the area, which could have further responses on land cover in the future.

The identification of fire effects in land cover change was impeded by the lack of reliable ancillary data to contrast the suggestion of it being a land cover change driver. The ability of this methodology to detect wildfire events' effects is therefore not discarded.

A threshold set at ±2 mean standard deviations would seem to be reasonable to be used in studies of similar characteristics as this. The same threshold was used by Washington-Allen *et al* (1998) successfully in a change detection study in agro-pastoral communities of the Bolivian Altiplano. In the present research, it showed to be susceptible enough to the different categories of change, and for changes caused by different factors. Thresholds set at $\pm 1\sigma$ consider what might be only slight differences in vegetation as definite changes, whereas limits conservatively set at $\pm 3\sigma$ detect only extreme alterations of the vegetation cover. However, a combination of the three threshold levels would be recommended for the evaluation of the degree of change in the amount of vegetation in a certain area of change. In relative terms, change would be indicated only in the $\pm 1\sigma$ thresholds image if weak, in the $\pm 2\sigma$ image if intermediate, or in the $\pm 3\sigma$ image if severe.

5.4 *Concern about sustainability in the region*

In an attempt to infer about sustainability in the region from the results obtained in this study, some observations are to be made.

An increase in the amount of vegetation in the region would indicate an improvement in the state of the vegetation cover, and therefore, in the state of environment as a whole. However, if such an increase in the amount of vegetation is the result of the introduction of exotic species, as the case of pine plantations and the invader shrub sweetbriar rose, the issue of sustainability is questionable. Consequently, and to get to a stance regarding sustainability in the region, consequences for the detected positive changes in vegetation cover must be addressed, and even the drivers that underlie the causes reviewed in Chapter III, which have led to vegetation change.

As argued by Lambin and colleagues (2001), causes that lead to land cover change should not be simplified since, in turn, they might trigger decisions over economy and development policies. It was found that important changes occurred in the region have been the response to economic opportunities, which were in turn facilitated by institutional factors. Opportunities for new land uses were created as a result of market constraints on the one hand; market demands on the other hand and newly established policies. The shift occurred in the range activities, facilitated by the declaration of the area as FMD-clear, and impelled by the declining wool market is deemed to have brought beneficial environmental consequences, such as land restoration, deduced from the increase in vegetation in the grazing areas. However, future research with a closer interaction to ranchers is recommendable, in order to get closer knowledge on the ranching management techniques, and be able to draw definite conclusions about the existence of relationships between the found increased vegetation and the action of livestock on the environment.

Afforestation in the area constitutes a delicate issue. International organizations, programs and non-governmental organizations such as the Food and Agriculture Organization (FAO), the United Nations Development Programme (UNDP), the United Nations Convention to Combat Desertification (UNCCD) and the German Agency for Technical Cooperation (GTZ), among others, strive to promote the afforestation of semi-arid lands as a primary measure to prevent and combat land degradation. The fundaments to set up implanted forests in degraded areas are that an increasing vegetation cover would help to fix the soil and would promote and stabilize the hydrological balance, avoiding the excessive run-off and erosion, while maintaining land quality and productivity (UN Agenda21, Chapter 12). Considering that NW Chubut has been affected by land degradation, to advocate for afforestation activities seems reasonable. Cultivation of forests has been promoted by provincial and national laws, which set the legal framework and ensure economic support for its development. The potential of the region to sustain implanted forests offer different commercial opportunities, which would increase and diversify the current economic activities, so that rural people would become less dependant on livestock breeding as the only source of income. These opportunities could imply the setting up and development of a forest industry, where wood could be extracted and used in different ways, from firewood, to high quality wood to be used in the construction of houses and furniture. Non-timber forest products could also be collected from the implanted forests, such as gum, essential oils, mushrooms, fruits, etc. In addition, functions of protection of soils and slopes, restoration of degraded lands and improving the quality of water should be taken into account as environmental services. The broadening of recreation opportunities in direct contact with nature, and the improving of visual effects in the landscape, must be added as valuable functions of the implanted forests as well. Activities needed in the initial process of afforestation, later management interventions to the implanted forests (thinning and pruning), extraction of wood, wood commercialisation, the construction of houses and furniture, and the commercialisation and trade of non-timber products, would increase the current employment market in the region, as the economic system would be broadened and labor would be needed. Therefore, the economic sustainability would be increased. Furthermore, as claimed by Sedjo (1999), with the advent of the Kyoto Protocol, carbon sequestration values create financial incentives for creating planted forests. On the other hand, counterarguments for the plantation of exotic species, such as competition for ecological niches and the spread of monocultures, could be tackled through encouraging the implementation of appropriate techniques. Leaving patches of the original vegetation cover within the plantations, agro-forestry practices and the diversification and mixture of the tree species planted should be encouraged. Nevertheless, the original ecosystem would be changed, which would bring about a decrease in the environmental sustainability in that sense However, a study has shown that the content of carbon of the first 30 cm of soil under pine plantations is not significantly different from that outside plantations (Buduba *et al*, 2002), which would be a good sign for the stability of soil conditions before and after plantations take place. Nonetheless, the economic situation in the area would improve, and so would the social conditions. At the time of an overall assessment, sustainability as a whole would be increased, especially if taking care of the measures that must be taken in order to minimize the negative environmental effects that afforestation could cause.

The issue of the sweetbriar rose is not as "defendable", as a causal of positive land cover change, as it certainly does not promote sustainability. As previously reviewed, even though the fruit has some uses among the people, it impedes the growth of other plants; subtracts considerable areas of land, which loses the potential for grazing; it is very difficult to combat; and the worse characteristic still given by the provision of an habitat for the rodents that spread the deadly dangerous *hantavirus*. Besides the health risk for humans, it could also negatively affect the development of tourism in the area. Serious measures for its eradication, or at least controlled spread, must be taken as soon as possible, in view of the negative effects to the environmental, social and economic magnitudes of sustainability.

Fire events frequency in the region can be busted by the phenomenon of climate change, through the existence of drier and hotter summers can influence on the occurrence of fires. Also, the increasing number of tourists that visit the area each year raise the risk of fire. Fire is detrimental, not only for the environment, which degrades; but also for the economy, causing losses of large magnitude, whereas poses high risk for the society. Thus it is necessary to take appropriate cautious measures when promoting tourism and eco-tourism in the area.

From all the above exposed, results of change detection cannot be interpreted in terms of sustainability in a decisive manner if not contrasting them with features on the ground, and with ancillary data describing the real situation of the area for the dates compared. Nevertheless, they can be used as probable estimations or valuable hints about the occurrence of directional changes, either towards sustainability, or in the opposite direction. For the particular case of this study, and in consideration of all the above exposed, an overall increase in the amount of vegetation within the studied period of time is deemed to be related to an increase in environmental sustainability on the one hand, supported by a possible land restoration; a parallel decrease in the same realm of sustainability, brought about by the sweetbriar rose; and an arguably increase/decrease of ecological sustainability produced by the afforestation of the area. As opportunely pointed out, the area has shown an improvement in the economic and social indicators over the last two decades, and this must be born in mind when evaluating the effects of the detected land cover changes. Even if a phenomenon of rural migration was not observed, tendencies might have changed in the last few years, which should also be considered when accounting for new economic opportunities in the area, which in turn would retain the rural population.

Conflicts in the evaluation of regional sustainability commonly arise when focus is placed in either of its components and not in their interaction. A call for attention to local conditions and reality is made now. In the case of NW Chubut, a region that experiences the harshness of necessity and the lack of proper opportunities, which are concealed by general poverty, the issue of sustainable development must be addressed carefully. It should be understood that sustainability in the long term will sometimes require a trade off among its components, and the institution of proper education and health systems among the population should be a priority, which will in turn lead to the rural community's well being. By no means intends this to encourage the development of economic activities that may harm the environment (which would eventually decrease sustainability), but only to avoid defending extremist postures that, far from protecting the environment and a "potential" development yet to come, only contribute to its prevention.

The necessity of encouraging joint actions leading to the increase of sustainability has been envisioned in the region, and national and regional research institutions have been established in the past two or three decades, such as the National University of Patagonia, with a branch in the city of Esquel; the National Institute of Agricultural Technologies (INTA); and the Andean Patagonian Forest Research and Extension Center (CIEFAP). Projects undertaken by these institutions have involved most segments of people in the region, and included areas of research, education, extension and experimentation. Consequently, people have become gradually aware of environmental problems and have gained consciousness about sustainability and the multiple functions of the ecotone, from the environmental services to the potential economic possibilities it provides.

Not the wool industry, nor the beef or the pine plantations will lead the way to economic development and social welfare in the area by themselves. The immense possibilities that the area present for an integrated and multiple use of its resources constitute the foundation for an unequivocal path towards sustainability. Further diversification of economic activities that reflected the true potential of the area, in addition to proper education and an open-mind attitude of political and social leaders will permit to keep a balance among the three components of sustainability.

5.5 Limitations and recommendations for further studies

Means for solving the problems and drawbacks that emerged during the different stages of this study are now suggested as recommendations to be paid heed to in further studies.

The need of generating ortho-images for a proper correction of topographic effects, and the necessity of original raw data will not be further elaborated. Or even more, as asserted by Collins and Woodcock (1996) efforts should be placed in developing change detection methods that do not require of exact image registration.

Even though the methodology applied in the present study is regarded as satisfactory for the convenience of its application, as duly explained before, other methodologies should be tried as well, aiming at comparing and finding the most appropriate one for this specific kind of environment.

As expressed by Coppin and Bauer (1996) *"the proper understanding of the nature of the change and the principles that enable its detection and categorization usually encompass more sophistication than the simple detection of the change event itself"*. Even though all efforts were made to gather as much information as possible about the factors that could have promoted land cover change in the region, the impossibility of carrying out a field survey to account for the accuracy of the change detection procedure constitutes a limitation for the validity of the study. That is something that should be considered in future research, and even as a continuation of this study. At the same time, scarcity of information for rural regions in Argentina is a factor that will condition every study, which must be realized and by no means should represent a barrier to continue with this kind of research. On the contrary, research of this nature should be encouraged, in view of the relevance of the results, in addition to the stress that would be placed on the necessity of generating reliable ancillary information, and with the hope that it will be gradually created.

A closer interaction with farmers and community people is recommended for further studies, as well as a deeper regard for the occurrence of sweetbriar rose, as it seems to be a raising problem in the area.

Chapter VI "Conclusions"

In such a mountainous region as part of the study area, the application of change detection methods based on very precise image registration turns into a very difficult task, unless the existence of digital elevation models and proper raw data facilitates the generation of ortho-images.

It is feasible the detection of changes with the proposed methodology, although some restrictions were observed in the mountain ridges.

The amount of vegetation increased in the region in the 16-year period, indicated by greater values of vegetation index in 2003 respect to 1987.

Economic opportunities have been identified as major drivers of significant land cover change in the area.

The occurrence of defoliating insect attacks in native forests and the existence of mature plantations constitute drivers of "extreme" land cover changes, negative and positive respectively. Other known drivers of change, such as the alteration of the livestock composition, the introduction of the foreign shrub sweetbriar rose" generate intermediate changes.

The change in the composition of livestock from mostly sheep to greater shares of cattle seems to have resulted in an increase of the vegetation cover, which is deemed as a land restoration process.

A detected increase in the vegetation cover cannot be translated immediately into an environmental improve and an increase in sustainability before considering the nature of the land cover change and the potential consequences. In the case of this study, an overall increase in the vegetation cover does appear to indicate an increase in the sustainability of the area.

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