The Delivering Ecological Services Index (DESI)

A Proposed Approach for Assessing Changes in Ecological Services from Satellite-based Land Use Mapping

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Proof of Concept - Summary

This project was undertaken as a Proof of Concept to demonstrate an approach for assessment of changes in selected ecological services to accompany the socio-economic assessments conducted by the Rural Territorial Dynamics Program (DTR). The two key research questions of the DTR are: 1) Are there rural territories that in the past 20 years or so have experienced economic growth, social inclusion and environmental sustainability?, and 2) What are the determinants of this type of dynamics at the territorial level? The initial idea of the project was to develop a fourth variable that would be indicative of "environmental sustainability".

To date the DTR has been unable to find a method for assessing environmental indicators that meet the following requirements:

1. indicative of major environmental processes relevant in different types of rural regions in Latin America (e.g., deforestation, soil erosion, pollution due to agricultural intensification, urban expansion);
2. disaggregated at the level of municipality;
3. available for all or most of the 10,000 municipalities in all or most of the 11 countries;
4. available for two periods in time (the 1990s and the 2000s, broadly) so that we can estimate change; and
5. affordable for the program.

This Proof of Concept proposes the development of a Delivering Ecological Services Index (DESI) to assess and report “environmental sustainability” to meet the above criteria. The DESI assigns potential impact rankings to land use practices over an Area of Interest (AOI), relates land cover to land use practice, and then uses changes in the relative areas of land cover/land use groups (LUGs) over the AOI to estimate potential changes in the delivery of ecological services over a time period of interest. In the present Proof of Concept we calculate the DESI for a territory of the O’Higgins region in the Central Valley of Chile over the census years 1992 to 2002 to align with analysis of socioeconomic change conducted for the same area under the DTR program.

The estimated environmental impacts of different LUGs in the AOI are related to the potential loss of targeted ecological services including provisioning (food, freshwater, fuel/fibre), regulating (climate, water quality/quantity), and cultural (recreation, ecotourism, spiritual needs, biodiversity conservation) services, using concepts introduced by the Millennium Ecosystem As-

sessment (MEA, 2005). The linkage between the potential ecological effects of the different LUGs and the MEA ecological services classes is summarized in five Potential Impact Classes (Water Footprint, Chemical Pollution, Soil Erosion, Carbon Footprint, Habitat for Native Biodiversity) that are assigned to each LUG.

The nearest cloud free satellite data to the 1992 target year were taken in 1989, and these were used for the project, together with cloud-free 2001 images. An unsupervised classification approach that identified a starting group of 150 spectrally similar clusters was generated. These clusters were reduced by successive merging steps carried out interactively based on target spectral characteristics and terrain understanding, expert rules derived from analyses of high resolution imagery, and ancillary information.

Land use classifications divide the land cover of the AOI into different classes depending on how the land is used, including protected areas, agricultural areas, forestry areas, urban and suburban areas, and industrial areas. Land Use Groups (LUGs) identified in the O'Higgins AOI and used for the DESI are:

1. Evergreen Sclerophyllous Forest-Shrub
2. Acacia Savanna
3. Grasslands and Pastures
4. Forest Plantations
5. Orchards and Vineyards
6. Tilled Fields
7. Towns and Buildings
8. Others (Water, cloud/shadow)

The resulting classification was evaluated by overlaying the classified image on high resolution imagery available in Google Earth that provided detailed information to check classification success. Because of the broad availability of high resolution imagery it was possible to confirm the classification over the entire AOI, and for all land use classes. Field data collected during December of 2011 were also used for classification and validation.

To provide a consistent approach to assessing the potential for environmental impact of the different types of land use (the LUGs), we developed assessment criteria for each Potential Impact Class. We scaled the values from 0-10 (no land use related potential impact to extremely severe potential for land use related impacts), with values in steps at 0, 2-3, 4-5, 6-7, 8-9, and 10. There are a number of important assumptions in the way the Potential Impact Classes are assessed for each LUG:

- all impact classes are equal;
- the impacts within each class are linear;
- we have sufficient local information to make the assessments, and;
- that land use practices are relatively consistent across the AOI.

We have used these criteria to estimate the potential impacts of the LUGs in the four municipalities, and for the whole AOI based on information available in the AOI in the available literature.

The DESI uses a series of simple calculations to develop an area-weighted and area-corrected assessment of the potential impact of different land use practices on the delivery of ecological services across an area of interest. The index is additive and uses the area of the LUGs and the potential environmental impacts associated with each LUG to make an area based assessment of changes in the potential impacts of land use change. One aspect of the DESI that may be counterintuitive is that higher scores represent higher potential impacts. This is in line with the concept of DESI as an index of potential impacts for a given AOI.

Calculation of the DESI for the four municipalities in the AOI in this Proof of Concept demonstrated the usefulness of the DESI in interpreting land use change and the potential impact of these changes on the delivery of ecological services. The DESI differed among municipalities due to the effects of different land use practice and land use pattern. The lack of protected areas in the O'Higgins AOI was the most significant factor contributing to the DESIs. Overall the DESI increased, i.e., the delivery of ecological services decreased, across the AOI over the 1989 to 2001 period as a result of conversion of natural areas to agriculture, and the increased area of intensive agricultural practices such as viticulture and orchards.

Although the DESI is capable of reflecting relative change in the delivery of ecological services that may result from changes in land use over a given time frame in an AOI, it is also necessary to interpret the DESI scores in the context of overall environmental sustainability. This will make it possible to compare DESI changes across the broad geographic range of potential AOIs encompassed within the DTR program. To begin to understand the broad interpretation of DESI results we conducted some simple scenarios analysis for the AOI by increasing the areal coverage of intensive agricultural practices with high potential for environmental impact to land cover levels that would clearly be unacceptable. The scenarios are intended to envision how the AOI may change as agricultural practices intensify.

For this Proof of Concept we have calculated and carried out assessments of the change in DESI scores for four municipalities in the O'Higgins area of central Chile for the period 1989 to 2001, coinciding with the DTR social analysis for roughly the same period (1991-2001). Our results suggest the DESI reliably reflects the potential ecological impacts of 12 year changes in land use effects, both at the scale of the AOI, and for the municipalities.

We are confident of the accuracy of the land use classification in the present study due to the abundant high resolution imagery available on Google Earth to confirm the classification, the ground validation, and the relatively small area considered. Classification accuracy can be expected to decrease as the area considered becomes larger, high resolution imagery is less available, and the degree of ground checking is reduced.

We predict that the DESI will be applicable to a wide range of landscapes and that the potential impacts and assessments of land use change can be applied broadly as long as there is suitable imagery at a useful scale, and knowledge of the potential impacts of the various land use practices. Although the Proof of Concept has demonstrated the usefulness of the approach, we recommend that the DESI be conducted across a broader range of landscapes and land use practices in order to more reliably establish meaningful thresholds for making the DESI assessments. Other suggestions for further development of the DESI are included in the report.

Background

A.1. The Rural Territorial Dynamics Program

This project was undertaken as a Proof of Concept to demonstrate an approach for an assessment of changes in selected ecological services to accompany the socio-economic assessments conducted by the Rural Territorial Dynamics Program (DTR). The DTR is an initiative of Rimisp - *Centro Latinoamericano para el Desarrollo Rural* that was implemented with over 50 partners in eleven Latin American countries. The DTR program is a research-based policy advice and capacity development program established to design and implement more comprehensive, cross-cutting and effective public policies that will stimulate and support rural territorial dynamics that can lead to economic growth, poverty reduction, greater equality and environmental sustainability.

The two key research questions of the DTR are:

1. Are there rural territories that in the past 20 years or so have experienced economic growth, social inclusion and environmental sustainability?

2. What are the determinants of this type of dynamics at the territorial level?

To answer the first question DTR used the Small Area Estimates method of Elbers et al (2001a, b), widely used in poverty mapping projects. Using the municipality as a proxy for "territory", census and household survey data were used to map out the changes in three variables: per capita income or consumption; poverty rate; and income equality. The analysis was done for each of 10 thousand municipalities, in 11 countries, in two periods of time (the last two population Censes in each country, roughly the early 1990s and 2000s). The change in these three variables was then mapped, and clusters of municipalities with the same types of changes were identified.

The initial idea of the project was to develop a fourth variable that would be indicative of "environmental sustainability". To date the DTR has been unable to find environmental indicators and data that met the following requirements:

1. Indicative of major environmental processes relevant in different types of rural regions in Latin America (e.g., deforestation, soil erosion, pollution due to agricultural intensification, urban expansion);

2. Disaggregated at the level of municipality;

3. Available for all or most of the 10,000 municipalities in all or most of the 11 countries;

4. Available for two periods in time (the 1990s and the 2000s, broadly) so that we can estimate change; and

5. Affordable for the program.

This Proof of Concept proposes an approach to assess "environmental sustainability" that will meet the above criteria. In this report, environmental sustainability is assessed using an ecological services approach based on assessments of land use change developed from satellite imagery over a single territory covering four municipalities in the O'Higgins region of Chile.

Ecology and History of Land Use in the O'Higgins Area

B.1 General Characteristics

For the pilot project, the Area of Interest (AOI) covers the municipalities of Litueche, La Estrella, Marchihue and Pumanque, in the O'Higgins region of central Chile, about 150 km south-west of Santiago (Figure 1). The AOI has a total area of 2,153 km^2 and supported 20,093 inhabitants in 2002 (2002 census). Of them, 67% are rural, which is far more than the country average (13%). The AOI has a primary dependence on extensive agricultural practices and plantation forestry, which employs 39% of the labour force (compared with 10% nationally).

The climate in the AOI is classed as Warm Mediterranean with only 273mm of precipitation falling annually at La Estrella – almost entirely concentrated between April and September, when about 85% of annual precipitation is deposited. The mean maximum daily temperature at La Estrella is 19.2C^{o} for the April to September period, and 28.2C^{o} for October to March. This pattern concentrates dry land agricultural activities to the April to September period to capture annual rainfall, and requires the use of irrigation systems for more intensive agriculture, especially during the dry, hot summer.

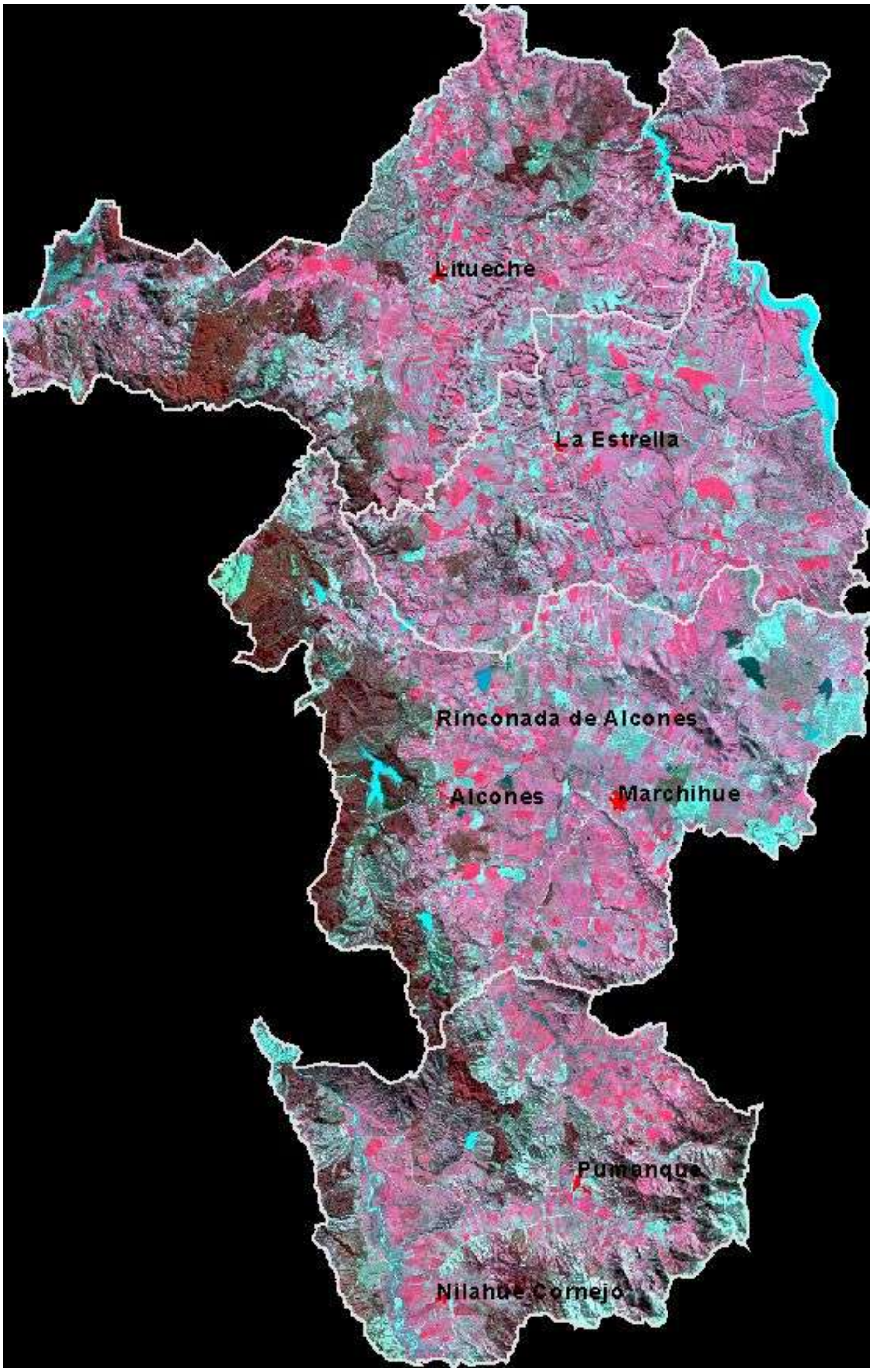


Figure 1: The AOI for the Proof of Concept showing the four municipalities covered by the project. (Landsat ETM+, Nov 2001)

B.2 Ecosystem Change and Land Use

The native ecosystems of the Central Valley of Chile have evolved to reflect one of a few Mediterranean climates globally, with a Dry Sclerophyllous Forest developing in the presence of an extensive native population that impacted the landscape locally with farming and burning (Armesto et al., 2010). Native populations were decimated with the arrival of Europeans, and there is some evidence that forests expanded somewhat at that time as land use pressure was reduced (Armesto et al., 2010). This recovery of native forest was short-lived as mining activities in the early 18^{th} and 19^{th} centuries resulted in broad areas of forest clearing to support mine smelting. More recently, accelerated rates of planting of exotic forest plantation species has reduced native forests to small fragments surrounded by commercial plantations of *Pinus radiata* and *Eucalyptus* sp. (Bustamante and Simonette, 2005). It is estimated that only 3% of the Dry Sclerophyllous Forest remains at this time (Neira et al., 2002).

Native Matoral shrubland ecosystems in the Central Valley have been converted over centuries to Acacia Savanna, and pasture or dryland grain farming, with agricultural products originally serving the expanding mining industry (Armesto et al., 2010). Clearing and burning to support agriculture, beginning in some areas as early as the 16^{th} century, led to the development of persistent Acacia Savannas ('Espinales') that are today the most common land cover type, having now almost completely replaced the native Dry Sclerophyllous Forest and the Matoral, which survive in small patches in gullies and along floodplains unsuitable for agriculture (del Pozo et al., 2005, van de Wouw, 2011). The Acacia Savannas are dominated by the successional shrub *Acacia cavens*, and non-native annuals may account for as much as 95% of the flora (Ovalle et al., 1990). The strong persistence of Acacia savannas is attributed to the ability of *A. cavens* to disperse seed, and to its ability to resprout following fire and cutting (Fuentes et al., 1989). These autecological characteristics of *A. cavens* also facilitate its resistance to damage by exotic herbivores such as livestock, rabbits and hares (Holmgren et al., 2000).

Many global studies have emphasized the uniqueness of Mediterranean ecosystems that are rare on the planet, characterized by high endemism and diversity, and also characterized by a long history of human exploitation (Myers et al., 2000). The combination of a long history of extensive agricultural practices, accelerating intensive agricultural practices, and the replacement of native forests by exotic plantations has resulted in the listing of the Valle Central of Chile as a 'Critical or Endangered Ecoregion' (Olsen and Dinerstein, 2002).

B.3 Recent Land Use Change

Extensive pasturage with dryland grain farming and minimal plantation forestry has characterized the AOI for many years. This situation changed beginning in about 1980 with the expansion of fruit and olive orchards, berries, and vineyards for export (Table 1), and through government incentives for plantation forestry based in *Pinus radiata* and *Euclayptus globulus* (Figure 2). Since the mid-1980s Chile has seen a linear increase in food production, and in fertilizer and pesticide use (Earth Trends, 2003). Sheep farming remains an important land use in the territory (Table 1). The development of the fruit and vineyard sector has resulted in much higher use of irrigation systems (Arumi et al., 2009), so that irrigated farms more than tripled in surface area in 2007, compared to 1997 (Table 1). Also highlighted are large agro-industrial projects in La Estrella and more recently in Litueche in the production of poultry and pigs (Gilles Cliche, 2011, Pers. Communication).

Protected Areas

Protected areas are a category of land use where native ecosystems and the ecological processes and biodiversity that comprise them are protected by statute from other kinds of more extractive land use. The maintenance of native ecosystems in an undisturbed state is considered within the MEA (2005) as an important ecological service that contributes to the sustaining of native plants and animals through habitat protection. Protected areas also provide other important ecological services such as maintenance of water quality and regulation of water flows, protection of shores from erosion, and carbon sequestration, as well as spiritual and recreational enjoyment.

Chile is committed to national conservation targets as outlined in CONOMA (2003) and ratified the Convention on Biological Diversity (CBD) in 1994. The recent CBD AICHI targets (CBD, 2012) set out five Strategic Goals and 20 targets, one of which is to protect at least '...17% of terrestrial and inland water…'. We use this national commitment in the DESI to set a target for ecosystem protection within a given AOI. There are no protected areas within the O'Higgins AOI.

Table 1: Agriculture census data for the AOI for census years 1997 and 2007.

Census Category	1997	2007
No. of Farms	2246	1930
Mean Farm Area (ha)	92.3	107.3
Area in olive orchards (ha)	3.5	909.2
Area in vineyards (ha)	503	3814
Area in blue berries (ha)	0	62.5
Area in cereals (ha)	948.9	257.8
Numbers of sheep	105 826	96776
Area under irrigation (ha)	2222	7513

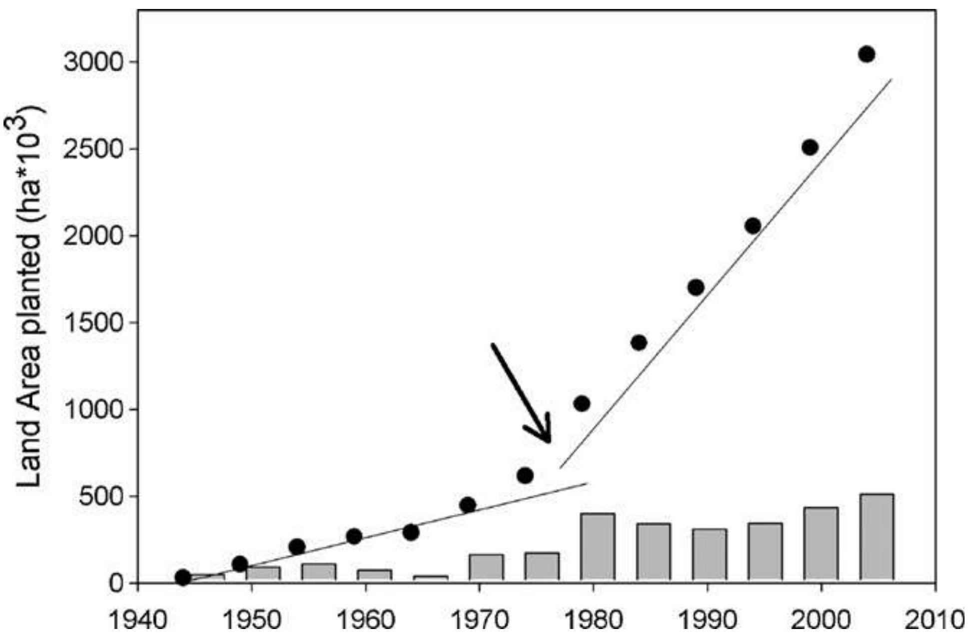


Figure 2: Expansion of commercial forestry plantations (mostly *Pinus radiata* and *Eucalyptus globulus*) in Chile. Points are accumulated area planted; bars are the area planted per year. The arrow indicates the year (1974) when a Government Law (701) began to subsidize the cost of planting (from Armesto et al., 2010)

Remote Sensing and GIS Methods

C.1 Satellite (Landsat) Data

Since 2008-2009, USGS has provided global Landsat archived imagery free of charge to all users (USGS, 2008). The AOI is covered by Landsat Path 233/Row 84. A search for the availability of cloud free scenes at the optimum vegetation phenology stage (i.e., November-December) was made on the USGS global archives. Initially, it was planned to use Landsat imagery for November-December taken in 1992 and 2001, the years of the national population census used for socioeconomic data by Rimisp's DTR program. However, no cloud free satellite data were available in the archives for the desired period in 1990-1994. The nearest cloud free data to the 1992 target year were taken in 1989, and these were used for the project, together with cloud-free 2001 images.

Four Landsat images, Landsat TM, 7 July 1989, Landsat TM, 14 December, 1989, Landsat ETM+, 10 November, 2001, Landsat ETM+, 15 December, 2001, were used to identify the land cover types for 1989 and 2001 years. These images are distributed as an ortho-corrected product generated using the Cubic Convolution (CC) re-sampling method (USGS, 2011).

C.2 Image Preparation

Image ortho-correction was checked through spatially superimposing the GIS layers (streams, road network) received from Rimisp. All four images were checked through image-to-image registration for any mis-registration. Ideally, for a change detection based method, radiometric normalization of all the images to a base image is required (Coppin and Bauer, 1994; Olthof et al., 2005). However, normalizing phenological differences among the scenes is more difficult to address. Some of the potential solutions include enlarging the window during which acceptable data are acquired, usually by adding years from which data may be used; using data from other similar sensors; or attempting a 'phenological correction' based on seasonal trajectories established for similar targets (Cihlar, 2000) . None of these methods could be used due to very limited image availability for the AOI in the GLOVIS archives. Also, phenological differences in July and November were too broad to be corrected through normalization.

C.3 Field Data

A one-day field visit on December 14, 2011 was made by Rimisp personnel. Information on the current land cover (2011) and the expected land cover in 2001 and 1989 were recorded and photographed at 26 sites.

C.4 Image Classification

Two approaches, supervised and unsupervised classification methods, are typically used for classifying satellite imagery (Lillesand and Kiefer, 2000). In the supervised classification *a priori* knowledge of all cover types to be mapped within the classified scene is assumed, and a substantial amount of spatial field data on the classes of interest is required. In the situations where detailed field data are unavailable, adopting an unsupervised classification involving spectral clustering and ancillary data (Vogelmann et al., 1998) is an alternate approach. Unsupervised classification provides more comprehensive information on the spectral characteristics of the area, presents spectrally pure clusters for the labelling step, and gives the opportunity to the analyst to group similar clusters into a smaller number of land cover classes. This approach has been widely used to generate land cover maps of North and Central America (Vogelmann et al., 1998; Latifovic et al., 2004) and vegetation map for South America (Eva et al., 2002).

In the present case, we had very limited field information and data for adopting a supervised classification approach. Therefore, an unsupervised classification approach that identified a starting group of 150 spectrally similar clusters was generated. These clusters were reduced by successive merging steps carried out interactively based on target spectral characteristics and terrain understanding, expert rules derived from analyses of high resolution imagery, and ancillary information

C.4.1 Land Use Groups (LUGs)

Land use classifications divide the AOI into different classes depending on how the land is used, including protected areas, agricultural areas, forestry areas, urban and suburban areas, and industrial areas. Land Use Groups (LUGs) identified in the O'Higgins AOI and used for the DESI are:

1. Evergreen Sclerophyllous Forest-Shrub
2. Acacia Savanna
3. Grasslands and Pastures
4. Forest Plantations
5. Orchards and Vineyards
6. Tilled Fields
7. Towns and Buildings, and;
8. Others (Water, cloud/shadow)

C.4.2 Mapping the LUGs

Six Landsat bands, Band 1 (blue-green, 450-520nm), Band 2 (green, 520-600nm); Band 3 (red, 630-690nm); Band 4 (near infrared (NIR), 760-900nm); Band 5 (short wave infrared (SWIR), 1,550-1,750nm); and Band 7 (SWIR), 2,080-2,350nm) were used in generating 150 spectral clusters for each of the four dates. Not all land cover types have peak phenological stage at the same time. Therefore, more than one image was used to identify various land cover types, both for 1989 and 2001. For example, vineyards had more foliage in December compared to November (Figures 3). Some of the classes were spectrally similar, for example, bare soil in the plantations, bare soil in the semi-natural grasslands, and current agricultural fallow. These classes were separated using decision rules combining the classified image, and a physiographic region layer which consisted of an 'uplands', and a 'plateau' area. Initially it was planned to generate this layer from the Digital Elevation Model (DEM) for the AOI, but the available DEM was too coarse for this purpose. As a result this layer was generated through on-screen digitization using Landsat imagery, and was broadly guided by the available DEM. To separate Sclerophyllous shrubs in the riparian and gullied areas from other shrubs, a riparian buffer zone was created using the updated stream layer. A visual inspection of this layer with the 1989 and 2001 image indicated need for updating. The urban residential area was masked using the urban area layer for both 1989 and 2001.

The resulting classification was evaluated by overlaying the classified image on high resolution imagery available in Google Earth that provided detailed information to check classification success. Because of the broad availability of high resolution imagery it was possible to confirm the classification over the entire AOI and for all land use classes. Field data collected during December of 2011 were also used for classification and validation.

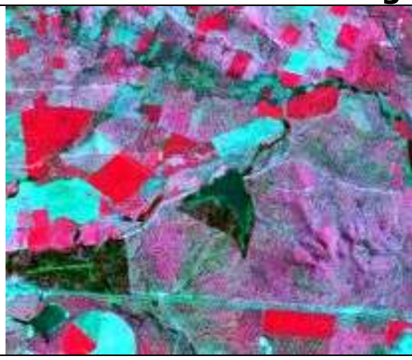
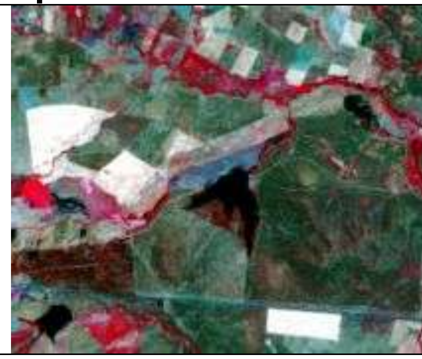
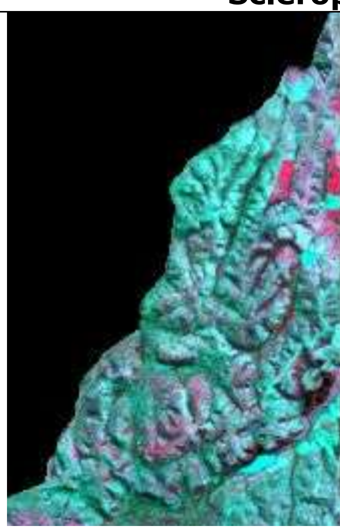
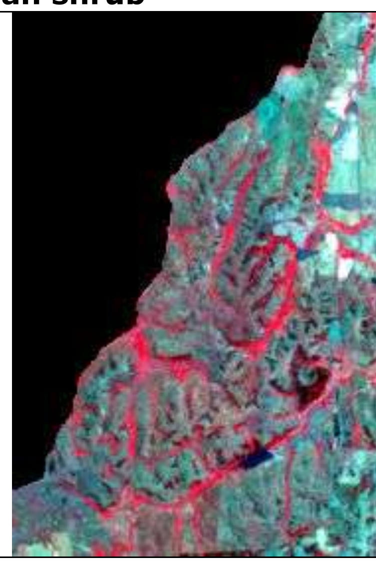
10 November 2001	15 December 2001
Agricultural crops	
	
Vineyards	
	
Sclerophyllous riparian shrub	
	

Figure 3: Phenological differences in various land cover types as seen on Landsat 2001 November and December imagery.

The 1989 and 2001 LUG level land cover maps were spatially compared to assess the areas of change (Figure 4). The grey areas (33%) represent location of the transition/change in the LUG types. White areas (66%) represent areas of no change.

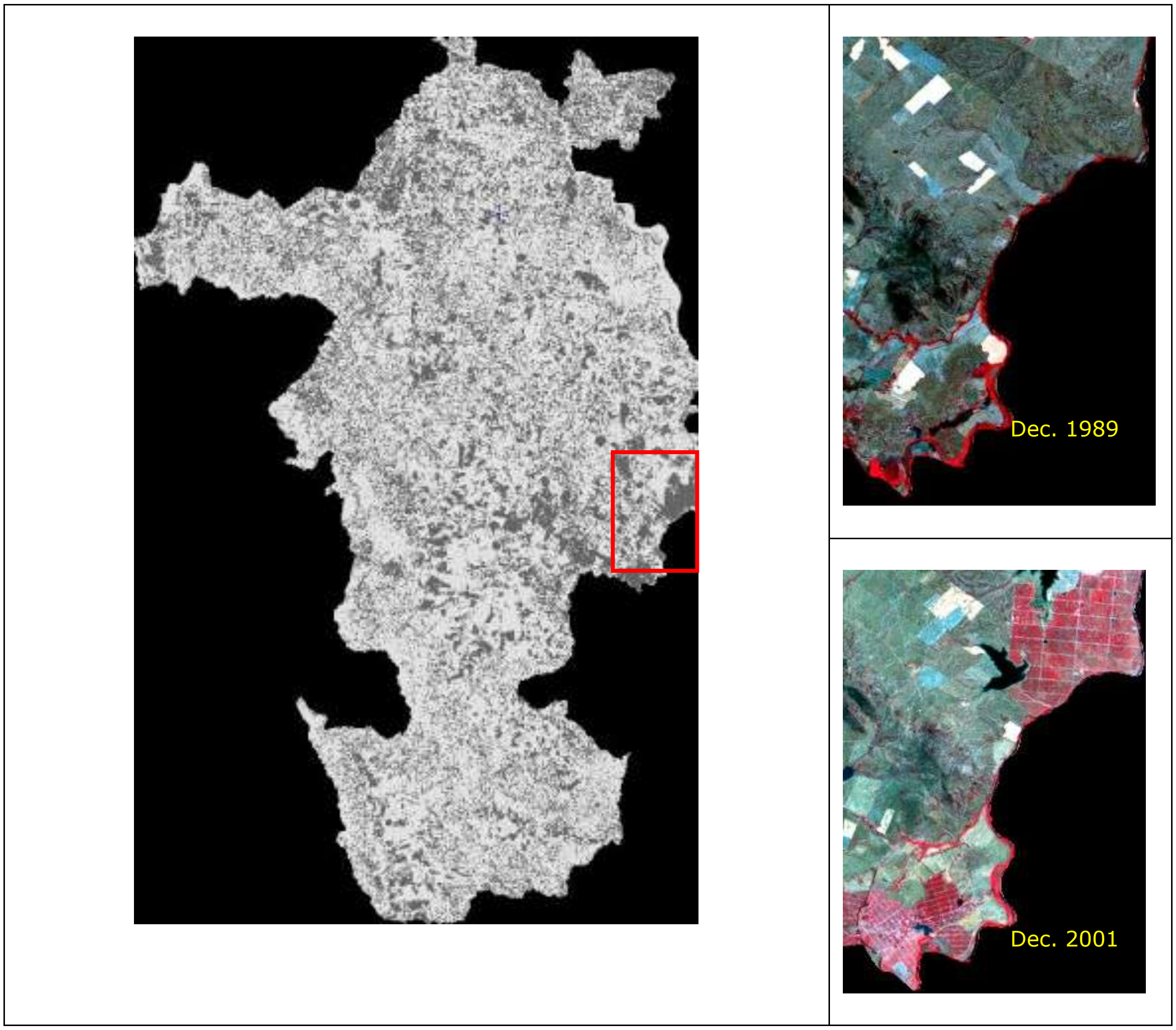


Figure 4: Change-no change mask based on 1989 and 2001 LUG level land cover maps (Grey= areas of change, white= areas of no change). The inset box shows an area converted to a vineyard between 1989 and 2001.

Results

D.1 Land Use Maps and Land Use Groups

The 1989 and 2001 maps of Land Use Groups for the AOI are shown in Figures 5 and 6. The maps are available in GIS compatible formats, or as an overlay in Google Earth (.kmz). The advantage of the Google Earth (.kmz) format is that the classified maps can be overlaid on the Google Earth imagery (much of which is high resolution) to compare the LUG classification and the satellite information. Summary area statistics for the LUGs for each municipality, and for the whole AOI are given in Table 2.

D.1.1 Evergreen Sclerophyllous Forest-Shrub

The Evergreen Sclerophyllous Forest Shrub LUG includes remnant native ecosystems that, over the course of centuries, have been largely overtaken by Acacia Savanna ecosystems, and more recently by exotic forest plantations. This LUG was reduced from 6% to 4% over the AOI between 1989 and 2001. Most of this change occurred in Litueche where coverage was halved from 13 to 6.5% between 1989 and 2001. This LUG is presently relegated to moister, south-facing slopes in gullied terrain, and on active floodplains where land use options are few. This LUG represents the remnant native ecosystems in the AOI and the analysis supports the statement by conservation groups that native flora and fauna are poorly represented and decreasing in the AOI (Myers et al., 2000, Olsen and Dinerstein, 2002). Although not protected, the remaining Evergreen Sclerophyllous Forest Scrub ecosystems that do occur contribute to making up a portion of the protected areas total for AOI in the calculation of the DESI (see Section E).

D.1.2 Acacia Savannas

The Acacia Savanna LUG is the largest in the AOI (35% in 2001) and municipalities showed a 3 to 9% increase between 1989 and 2001, with an overall 5% increase for the AOI. This observation supports the statement that this LUG is spreading in the Central Valley of Chile, mostly at the expense of native ecosystems or grasslands (van de Wouw, 2011). In terms of land use practices, the Acacia Savanna LUG is utilized for extensive livestock pasturage with little tillage, application of fertilizers, water use or carbon emissions. Although it is assumed these ecosystems provide some habitat value, e.g., for songbirds or small mammals, the high reported representation of exotic flora and fauna decreases their value as habitat for native species.

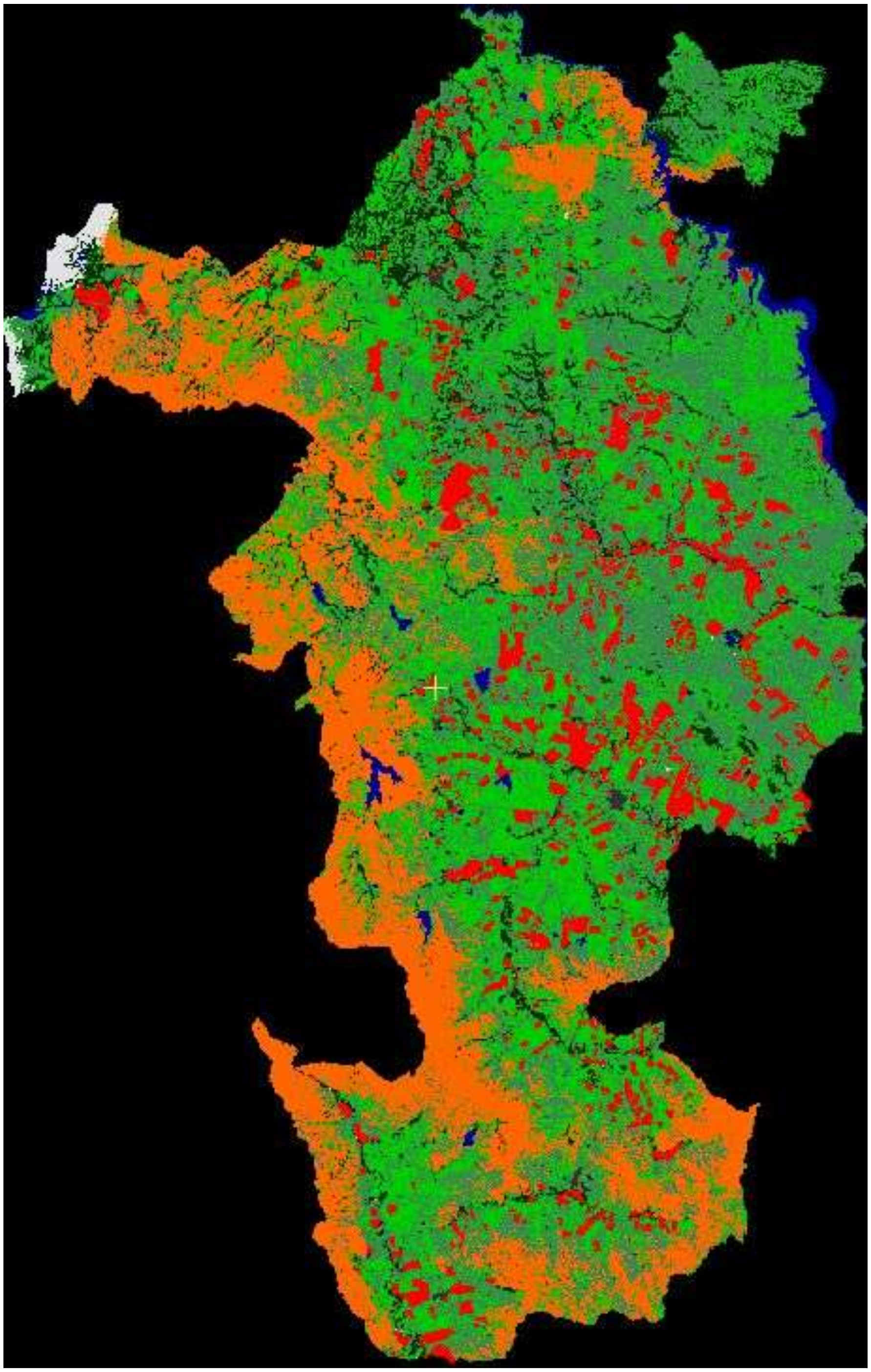


Figure 5: Land use classification for 1989. The LUGs are: Evergreen Sclerophyllous Forest-Shrub, Acacia Savanna, Forest Plantations, Grasslands and Pastures, Tilled fields, Towns and Buildings, and Water.

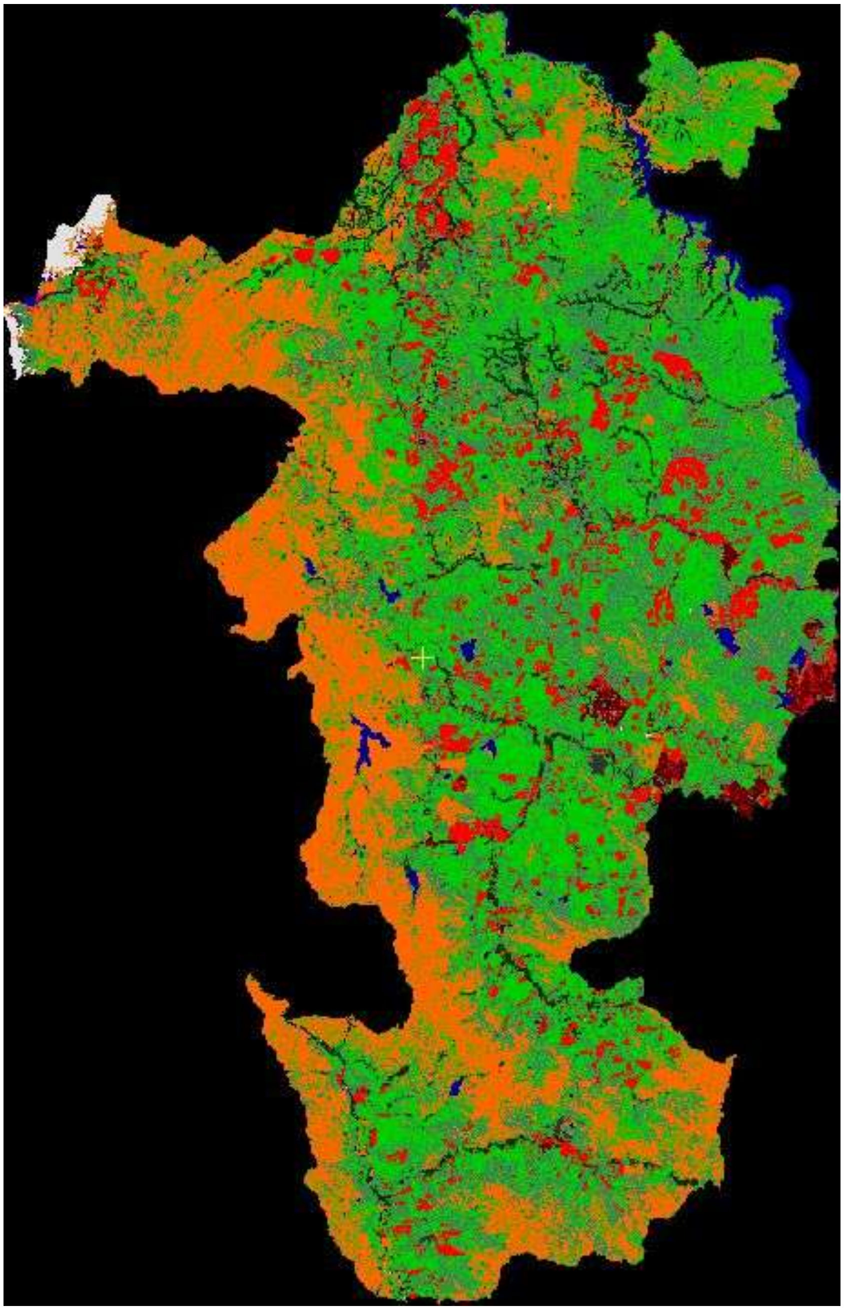


Figure 6: Land use classification for 2001. The LUGs are: Evergreen Sclerophyllous Forest-Shrub, Acacia Savanna, Forest Plantations, Orchards and Vineyards, Grasslands and Pastures, Tilled Fields, Towns and Buildings, and Water.

Table 2: Area (%) of the Land Use Groups (LUGs) for the four Municipalities and the Area of Interest.

Land Use Group (LUG)	Litueche		La Estrella		Marchihue		Pumanque		AOI	
	1989	2001	1989	2001	1989	2001	1989	2001	1989	2001
Evergreen Sclerophyllous Forest-Shrub	13.08	6.53	4.56	4.57	4.20	2.05	3.58	3.11	6.68	4.05
Acacia Savanna	30.93	34.66	31.31	40.18	30.67	33.75	25.02	31.44	29.71	34.82
Grasslands and Pastures	26.41	19.59	45.24	33.86	31.02	24.56	25.75	23.92	31.47	24.87
Forest Plantations	21.43	28.98	4.94	6.11	21.73	26.04	38.79	35.53	21.79	24.84
Orchards and Vineyards	0.00	0.05	0.00	0.01	0.00	2.73	0.00	0.17	0.00	0.89
Tilled Fields	4.57	6.51	10.54	11.80	10.81	8.89	6.29	5.25	8.04	8.04
Towns and Buildings	0.10	0.20	0.06	0.13	0.24	0.26	0.20	0.20	0.15	0.20
Water	1.44	1.44	3.35	3.35	1.33	1.73	0.37	0.37	1.57	1.69
Clouds/shadows	2.04	2.04	0.00	0.00	0.00	0.00	0.00	0.00	0.58	0.58
	100	100	100	100	100	100	100	100	100	100

D.1.4 Grasslands and Pastures

The Grasslands and Pastures LUG occurs primarily in lowland settings and is interspersed on the landscape with the Acacia Savanna and the Tilled Fields LUGs. This LUG showed a 7% decrease in areal coverage across the AOI between 1989 and 2001 (Table 2), this decrease being shared equally across the four municipalities, except for Pumanque, which showed a slight 2% decline. The Grasslands and Pastures LUG declined due to invasion by Acacia Savanna, and because of agricultural development for more intensive land uses.

Land use practices in the Grasslands and Pastures LUG ranges from extensive and moderate grazing of sheep, to tillage and some planting of forage species with phosphorous fertilization (Vera, 2006). For this reason there may be some classification confusion with the Tilled Agricultural Fields LUG, where fields have not been tilled for some time, so are no longer distinguishable as tilled fields. We are assuming that where an area was once tilled, but it has been some time since tilling has occurred, the appropriate impact is more like the Grassland/Pasture that it is classified as, than a Tilled Agricultural Field. As for the Acacia Savanna LUG, it is assumed these ecosystems provide some habitat value, but that high representation of exotic flora and fauna decreases their value as habitat for native species.

D.1.5 Forest Plantations

As shown in Figure 2, a program of government subsidies has resulted in a marked increase in the planting of *Pinus radiata* and *Eucalyptus globulus*, and this is reflected in an increase in the area of mature forest plantations in the AOI between 1989 and 2001 (Bustamente and Simonetti, 2005). Most of this increase was in Litueche, at the expense of native forests (Evergreen Sclerophyllous Forest-Shrub LUG), and possibly the Grassland and Pastures LUG.

Land use practices in the Forest Plantations LUG include clearing of sites, planting of seedlings, possible herbicide and/or fertilizer applications to ensure sapling establishment, and possible stand treatments such as pruning or thinning. Most of the potential impacts occur at the time of plantation establishment, although there are impacts associated with road and landing maintenance to provide access for tree establishment, stand tending, and harvesting activities, with associated risk of surface erosion. Equipment required for plantation establishment, harvesting and log transport will also involve carbon emissions. Although we acknowledge that stands of exotic species are replacing native forests, we assume that plantation forests will have some value as wildlife habitat at all ages of stand development, and will fulfil some of the ecological services of native forest.

D.1.6 Tilled Fields

Dryland grain farming has been practiced in the AOI for many years, and our analysis shows that there has not been a significant increase in this LUG over the 1989-

2001 period (Table 2). We combine current agricultural fallow and with fields carrying crops to make up the Tilled Fields LUG, assuming that fallow fields are tilled, and differ only by the season of the imagery, or are laying fallow according to management rotation.

We are assuming for our analysis that land under the Tilled Fields LUG is ploughed and seeded annually, fertilized (Vera, 2000), and that different kinds of biocides are applied to encourage productivity (Earth Trends, 2003). This will directly influence the impact assessment for potential surface erosion and biocide effects. For the analysis we have also assumed that, for the most part, fields are not irrigated, and that this LUG has a relatively low water footprint. Ploughing and harvesting requires machines so carbon emissions are an issue, and we assume these fields have almost no habitat value.

D.1.7 Vineyards and Orchards

Our comparison of 1989 and 2001 imagery shows that the Vineyards and Orchards LUG was introduced over this period, and this assessment is confirmed by the agricultural census data in Table 1 above. The total of about 4,800 ha in the 2007 census indicates that in 2001 (1,828 ha) this change was just beginning, and that this LUG is continuing to increase as new vineyards and orchards are established. The increase in the Vineyards and Orchards LUG was concentrated primarily in Marchihue – 2.7% of the area in 2001. We are quite confident of our area estimate of this LUG because each orchard or vineyard could be directly confirmed on the high resolution Google Earth imagery.

Land use practices in the Vineyards and Orchards LUG will be characterized by two phases – a relatively short establishment phase, and a long term maintenance phase. Ploughing and biocides are utilized for establishment, and for maintenance, although the soil erosion risk is somewhat lower in the maintenance phase. Drip irrigation is used in both phases, as are mechanized treatments, affecting the assessment of water and carbon footprint respectively. We assume these orchards and vineyards have limited habitat values.

D.1.8 Towns and Buildings

The Towns and Buildings LUG, as the name implies, described developed areas in and around towns, as well as buildings. Although the analysis showed little change in the areas of towns (La Estrella had the largest increase), there was an interesting increase in Rural Buildings (111 ha) over the 1989 to 2001 period. From our observations of the high resolution Google Earth imagery these buildings are for the most part greenhouses, with some industrial pig and chicken barns. It is worth noting that pig and chicken barns have the potential to provide an impact far in excess of their aerial coverage, because of issues around manure and potential detrimental effects to surface water and aquifers, high amounts of area and energy required to provide feed, and other maintenance issues such as electrical and transportation costs. Some of the same assumptions could be made for towns as well. This potential impact is not reflected in the present analysis. A multiplier could be used in the calculation of the DESI to reflect these potential risks.

D.1.9 Other Classes

The Other Classes LUG includes surface water and clouds and is not included in the DESI assessments. In that there are few natural lakes or ponds in the AOI, the surface water class may act as an indicator of reservoir ponds for irrigation purposes. There was a small increase in surface water over the 1989 to 2001 period, but this small amount may be a significant indicator of increased irrigation as ponds for irrigation are small (say 1-2 ha), and a 0.10% increase means an increase in area of about 200 hectares, so that could represent as many as 100 new irrigation ponds .

The very low cloud class shows the essentially cloud-free nature of the imagery in 1989 and 2001.

The Delivering Ecological Services Index (DESI)

The DESI approach we are proposing follows an ecological services model linked to classes developed by the Millennium Ecosystem Assessment (MEA, 2005) and shown in Figure 7. The MEA (2005) acknowledges that land must be developed and used to support human communities, and the recent increase in more intensive agriculture and forestry practices in the O'Higgins AOI has generated new income, improved lifestyles and reduced rural poverty (Modrego et al., 2011). However, the development of land at the expense of natural ecosystems involves a trade off between improving human economies and degrading natural and semi-natural ecosystems –degradation that often reduces ecological services provided by healthy ecosystems. The DESI is designed to be sensitive to reduced impacts of more sustainable land use practices within land use categories, e.g., sustainable viticulture, careful use of water, buffering of aquatic ecosystems, or zero tillage agriculture.

E.1 DESI Potential Impact Classes

As discussed above, extractive land use inevitably involves a certain level of environmental impact, and we have identified five Potential Impact Classes that summarize the possible negative effects of land use on the delivery of ecological services over the AOI (Figure 7) for each LUG. It is an important caveat that these are potential impacts associated with the land use classes, and not measurements of actual impacts on ecological services. Measuring actual impacts is impossible given the scale of the analysis, lack of data, and the broad areas to be covered. It follows then that the accuracy of the assessments of impact for each LUG will rely on knowledge of land use practice within the AOI, and must be informed by defensible local information.

For each Potential Impact Class we rate the scale of the potential impact from 1 to 10 depending on the land use and the nature of the impacts. Table 3 shows the -criteria for we are proposing to making the assessments for each of the five classes. The discussion below describes the impact classes and the assessment scales for each.

E.1.1 Impact Class 1: Habitat Quality

This impact class estimates the potential negative effects on the conservation of native biodiversity by assessing the potential impacts to habitat that result from the different land use practices being used. The MEA (2005) identifies biodiversity conservation as an important Cultural Service, where declining biodiversity and the quality of native habitats also impacts Recreational, Spiritual, and Ecotourism Services (Figure 7).

The assessment process assumes that healthy native ecosystems, both inside and outside protected areas, will provide unimpacted habitat quality (impact score = 0) for the conservation of native biodiversity. We acknowledge that this may not be the case where protected or unprotected native ecosystems are small, highly fragmented, or are utilized in ways that are not evident at the scale of the analysis, e.g., unregulated hunting or gathering.

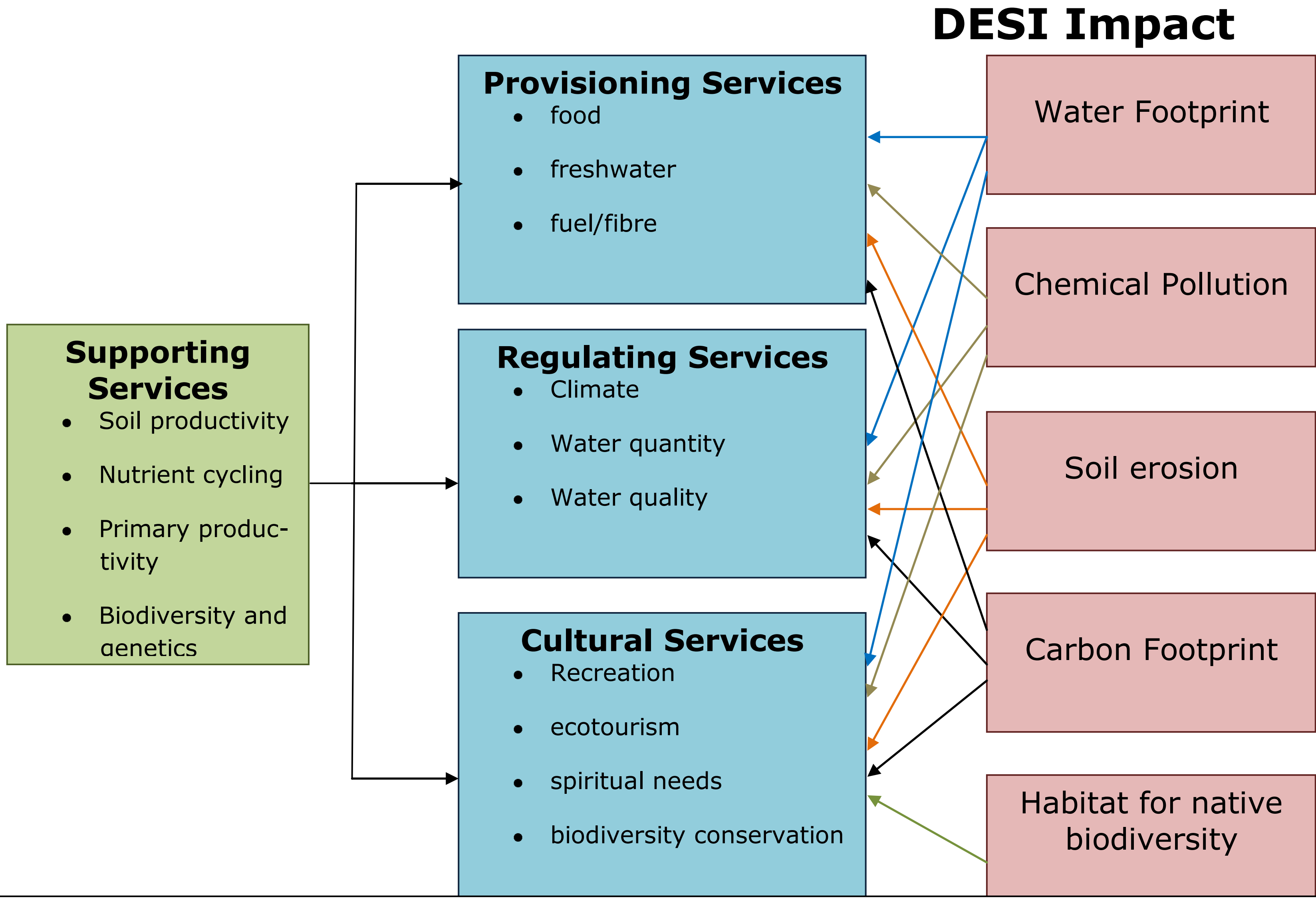


Figure 7: Linkage of Potential Impact Classes to Millennium Ecosystem Assessment ecological services

In the DESI we compare other land uses to those provided by relatively unimpacted native ecosystems, so that all impacts for native ecosystems are 0, and the potential impacts for other land uses range from 1 to 10 depending on the nature of the land use. In the O'Higgins AOI, the scale of impact rises from native ecosystems, through semi-natural systems such as Acacia Savanna and Grasslands/Pastures, to extensive and intensive agriculture, and finally to developed lands in urban and semi-rural areas.

E.1.2 Impact Class 2: Potential for Chemical Pollution

The use of biocides (insecticides, herbicides, fungicides and pesticides) and fertilizers for agriculture and forest plantations has the potential to contaminate water, soils, and biota. The application of biocides has the potential to directly impact all three categories of ecological services (Figure 3) through its toxic effects on biota, water quality and human food. Nitrogen fertilizers are regularly applied with grain and fruit crops in the Central Valley at rates between 175 and 200 kg/ha annually to encourage higher production (Arumi et al., 2005). The main potential impact of agricultural fertilizers is the enrichment and possible eutrophication of aquatic ecosystems that can result in major impacts to aquatic biota and nitrate pollution of regional aquifers.

For assessments of potential chemical pollution we identify those land uses that utilize biocides and fertilizers, and rank the potential impacts according to the intensity and frequency of use. These range from no impact in native and semi-natural ecosystems, through limited use for the establishment of forest plantations, to intensive use in tilled fields, orchards and vineyards.

E.1.3 Impact Class 3: Potential for Soil Erosion

Land use practices that expose mineral soil, such as ploughing for crop agriculture or herbicide applications for intensive viticulture, provide an opportunity for rainfall to cause surface erosion that washes soil into nearby rivers and lakes. This erosion and deposition reduces water quality, can change the sediment dynamics of riparian floodplains, harm aquatic habitats, especially fish spawning, and can introduce biocides and fertilizer that may be in the eroded soil. Biocides in soil can directly impact aquatic biota and nutrients in fertilizer can cause aquatic eutrophication. Persistent soil erosion can also decrease soil quality and long term agricultural productivity.

For assessments of soil erosion potential we identify those land uses that expose mineral soils, and rank the potential impacts according to the frequency of exposure. Assessments range from no impact in native and semi-natural ecosystems, through intermittent and patchy soil exposure in forest plantations (including access roads) and infrequent mineral soil exposure in orchards and vineyards, to frequent mineral soil exposure in tilled fields.

E.1.4 Impact Class 4: Potential to Increase the Water Footprint

The utilization of water by different land use practices has a direct effect on all three categories of Provisioning Services (Figure 3), impacting food production, water quality and quantity, and biodiversity conservation, especially aquatic ecosystems. Water footprint has been defined as the volume of water used to produce a given amount of a crop or other ecosystem service, e.g., kg of grain/litre of water (Ridoutt and Poulton, 2009). As crops diversify and specialize, irrigation becomes more common, replacing primarily dryland management systems. Whereas dryland systems have little potential to impact water budgets, a change to irrigated systems can create a 100 fold increase in water use (Ridoutt and Poulton, 2009). This increase in water use can impact other water-based ecological services such as water supplies for other agricultural users, drinking water, and the health of riparian and aquatic ecosystems.

For assessments of potential increase in water budget we compare land uses in terms of their water footprints, and rank the potential impacts according to the potential scale of the footprint, relative to water availability. That is, for a given practice, the potential impacts of a high water footprint will be ranked much higher in arid and semi-arid areas, compared to areas of high annual precipitation. Assessments range from no impact in native and semi-natural ecosystems, through intermediate impacts in dry land agricultural to high impacts in irrigated land uses, especially in arid and semi-arid climates.

E.1.5 Impact Class 5: Potential to Increase the Carbon Footprint

As it becomes more and more evident that human-produced carbon is dramatically altering regional climates and ecosystems, the need to reduce the carbon emissions of different land use systems is becoming an urgent requirement (IPCC, 2007). As for many of the impact classes, climate driven ecosystem changes effect on all three categories and all subcategories of Provisioning Services (Figure 3). The carbon footprint of a particular land use can be defined as the amount of carbon or other greenhouse gas produced for a given amount of a crop or other ecosystem service. As agricultural systems become more intensive, they require more mechanized approaches and thus the carbon footprint increases significantly over extensive agricultural or forestry practices (MEA, 2005).

For assessments of carbon footprint we compare land uses in terms of their emissions of carbon or other greenhouse gases. Assessments range from no emissions in native and semi-natural ecosystems, through intermediate emissions in forestry and extensive agriculture, to relatively high emissions in intensive mechanized agriculture and developed areas. Transportation fuel usage to deliver products to foreign markets is another important component of the carbon footprint for a LUG and is assumed to increase with the level of mechanization for a given LUG.

E.2 Draft Criteria for Assessing the Potential Environmental impacts of Different Land Use Practices

To provide a consistent approach to assessing the potential for environmental impact of the different types of land use (the LUGs), we have developed draft assessment criteria for each Potential Impact Class (Table 3). We have scaled the values from 0-10 (no land use related potential impact to extremely severe potential for land use related impacts), with values in steps at 0, 2-3, 4-5, 6-7, 8-9, and 10. It could be argued that a smaller scale could be proposed that combines the two value steps, but our position is that having two steps provides flexibility within classes to account for a broader range of land use practices. The stepped classes are also combined (Table 3) to provide some generic descriptions of the level of potential impact – No Potential Impact (0), Low Potential Impact (2-5), High Potential Impact (6-9), and Severe Potential Impact (10). There are a number of important assumptions in the way the Potential Impact Classes are assessed for each LUG within the DESI:

- all impact classes are equal
- the impacts within each class are linear; the shape of the impact curve is similar between all classes.
- we have sufficient local information to make the assessments, and that land use practices are relatively consistent across the AOI

Concerning the first assumption we take the approach in the DESI that, although we acknowledge that there may be differences in the effects of the different impact classes in different AOIs, all impacts contribute to a potential loss of ecological services, and, at the scale we are conducting the analysis, we generally do not have the information to weight the factors in any knowledgeable way. In the absence of this information, it is best to consider all potential impacts to be equal. Similarly, we assume a linear relationship for the potential impact within classes, although the actual impact probably has a curvi-linear shape – as for the weighting we simply do not know what that shape is and so assume a linear increase to be consistent across classes and between AOIs.

The third assumption, that we have sufficient knowledge to make the assessments, and that these assessments are accurate, is critical to the success of the DESI for a given AOI. We recommend a workshop comprised of various subject experts who have knowledge of local land use practice for a given AOI. The assessments made in this version of the DESI are based on the best guesses of the authors, using information from the literature, and are used to demonstrate the DESI approach.

We have used these criteria to estimate the potential impacts of the LUGs in the four municipalities, and for the whole AOI (Table 4) based on information available in the AOI in the available literature. As for the criteria, the scores in Table 4 could be refined, e.g., by municipality, through local knowledge of land use practices. For example, the use of surface or ground water for crop irrigation may vary among municipalities, and this would alter the impact scores for that municipality, and change the DESI accordingly, depending on the area under the LUG. As discussed above, the potential land use impact for native ecosystems is assumed to be 0, and is a baseline for all other land use practices. Semi-natural systems, such as the Acacia Savanna in the AOI will have low potential impacts, Grasslands/ Pastures will be somewhat higher, and intensive agricultural land uses (Tilled Fields, Vineyards/Orchards, Towns and Buildings) will be relatively high, and this logic is reflected in the preliminary scores we have developed (Table 4).

Table 3: Draft criteria for assigning potential impact scores to Land Use Groups (LUGs) for 5 DESI impact classes.

	Weight	Habitat Value	Chemical Pollution	Erosion Effects	Water Footprint	Carbon Footprint
None	**0**	native ecosystems with high habitat value for native species	no fertilizers or biocides	no significant land use caused surface erosion into aquatic ecosystems	baseline land use based water utilization	baseline land use related C emissions
Low	**1-3**	semi-natural ecosystems with good habitat value for native species	land use utilizes very infrequent (> 10 yrs) application of fertilizers and/or biocides	land use results in a very low risk of surface erosion into aquatic ecosystems	very low land use related water utilization in relation to supply	occasional land use related C utilization with very low C emissions
	4-5	semi-natural to managed ecosystems with fair habitat value for native species	Land use utilizes occasional application (4-9 yrs) of fertilizers and/or biocides	land use results in a low risk of surface erosion into aquatic ecosystems	low land used related water utilization in relation to supply	frequent land use related C utilization with low C emissions
High	**6-7**	managed ecosystems with some habitat values for native species	land use utilizes application of fertilizers and/or biocides every 2-3 yrs	land use results in a moderate risk of surface erosion into aquatic ecosystems	moderate land used related water utilization in relation to supply	frequent land use related C utilization with moderate C emissions
	8-9	managed ecosystems and developed land with poor habitat values for native species	land use utilizes annual application of fertilizers and/or biocides, or both	land use includes bi-annual to tri-annual exposure of mineral soil in high risk landscape positions that often threatens aquatic ecosystems	heavy land use related water utilization in relation to supply	continuous land use related C utilization with high C emissions

High	**10**	developed land with minimal habitat value for native species	Land use utilizes annual or multi-annual applications of both fertilizer and biocides	land use includes annual exposure of mineral soil in high risk landscape positions that persistently threatens aquatic ecosystems	very heavy land use related water utilization in relation to supply	intense and continuous land use related utilization of C based fuels with very high C emissions

Table 4: Preliminary assessments of LUG Impact Scores for the AOI.

Land Use Group (LUG)	Habitat Impact	Chemical Effects	Erosion Effects	Water Footprint	Carbon Footprint	LUG Impact In-
Evergreen Sclerophyllous Forest-Shrub	0	0	0	0	0	**0**
Acacia Savannas	4	0	3	0	0	**7**
Forest Plantations	6	2	4	1	4	**17**
Vineyards and Orchards	9	10	8	10	10	**47**
Grasslands and Pastures	5	0	4	0	0	**9**
Tilled Fields	9	8	8	8	8	**41**
Towns and Buildings	9	2	6	10	10	**37**

E.2.1 Calculating the DESI

The DESI uses a series of simple calculations to develop an area-weighted and area-corrected assessment of the potential impact of different land use practices on the delivery of ecological services across an area of interest. The steps are shown below.

a. Sum the scores (each out of 10) for the 5 Potential Impact Classes to get a LUG Potential Impact Index (also shown in Table 4).

$$PII\ (LUG) = \sum_{J=1}^{5} PII\ (i,j,k)$$

where i=Area Of Interest (AOI), j=LUG, k=year

b. Multiply the LUG Potential Impact Index by the total area in hectares for the LUG in the area of interest, to get an Area Weighted LUG Total Potential Impact.

$$PII\ (LUG\ total\ (i,k)) = Area\ (LUG\ (I,J,K)) * \sum_{j=1}^{5} PII(i,j,k)$$

c. To create an Area Corrected LUG Potential Impact Score so that AOIs of different area can be compared, multiply the Weighted LUG Total Potential Impact by the relative area of the LUG for the AOI being assessed.

$$PII(acAOI(i,k)) = \sum_{j=1}^{\#LUG(i)} \frac{Area\ (LUG(i,j,k))}{Area\ (AOI(i,k))} * \sum_{j=1}^{5} PII(i,j,k)$$

d. To assess a Potential Protected Areas Impact subtract the total % area of protected areas and native ecosystems from 17%, and multiply the difference by 100. (If this area is greater than 17% then the number will be negative and will decrease the overall impact score.)

$$PPAI(acAOI(i,k)) = \left(\frac{17}{100} - \frac{(Protected + NativeEcosystem\ Area)}{\sum_{j=1}^{\#LUG(i)} Area(AOI(i,k))}\right) * 100$$

e. To calculate the DESI, sum the Potential Protected Areas Impact and the Area Corrected LUG Potential Impact Scores.

$$DESI(AOI(i,k)) = PII(acAOI(i,k)) + PPAI(acAOI(i,k))$$

f. Finally, divide the DESI by the number of LUGs to develop an index that is not dependent on the number of LUGs in the calculation for the AOI

$$nDESI(AOI(i,k)) = \frac{DESI(AOI(i,k))}{j}$$

One aspect of the DESI that may be counterintuitive is that higher scores represent higher potential impacts. This is in line with the concept of DESI as an index of potential impacts for a given AOI.

E.2.2 The DESI for the AOI and for the four municipalities

Calculation of the DESI for the four municipalities in the AOI demonstrates the usefulness of the DESI in interpreting land use change and the potential impact of these changes on the delivery of ecological services. The DESI differed among municipalities due to the effects of different land use practice and land use pattern.

Overall the DESI increased across the AOI over the 1989 to 2001 period, reflecting a decrease in ecological services.

Litueche showed the largest potential increase in land use impact (decrease in ecological services) over the 1989 to 2001 period, with the DESI increasing from 200 to 319 (Figure 8). This change was due almost entirely to the decrease in the area of native ecosystems from 13% to 6.5% - a decrease that was driven by increases in the area of the Forest Plantations, Acacia Savanna, and Tilled Field LUGs. The Grasslands/Pastures LUG showed a 6% decrease and the Agricultural Fields LUG increased by 2% over this period in Litueche.

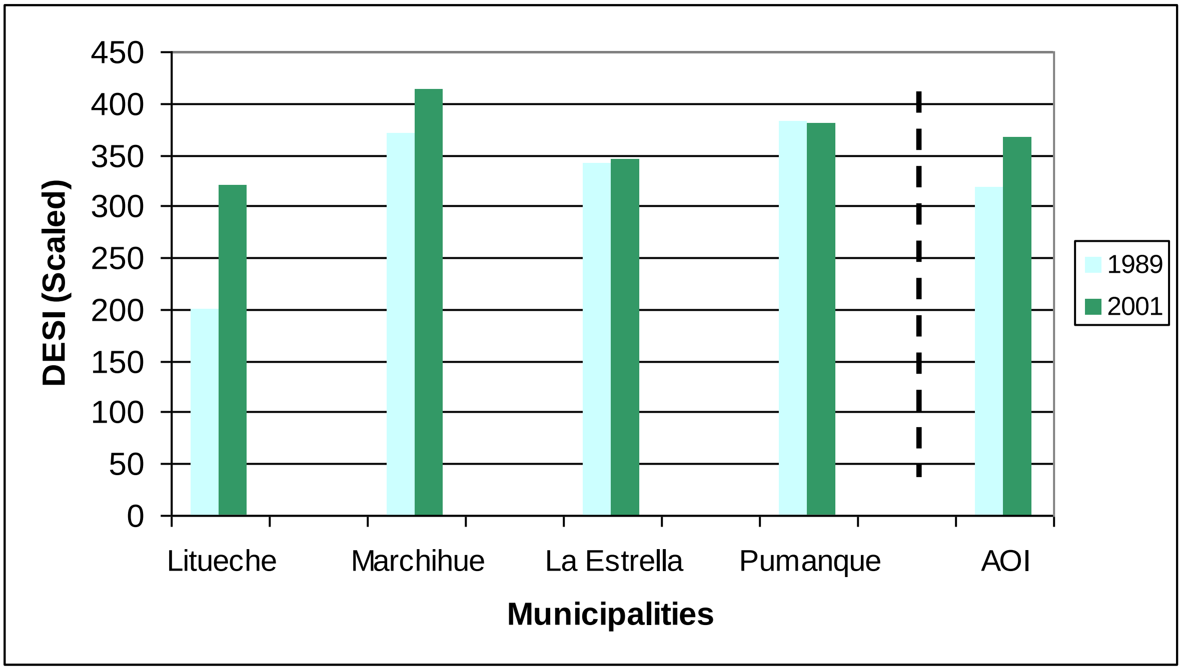


Figure 8: Changes in DESI (1989 and 2001) for four municipalities, and for the AOI.

La Estrella and Pumanque had very slight changes in the DESI over the 1989 to 2001 period, although changes did occur in the LUGs. In La Estrella the Acacia Savanna LUG increased by about 9% at the expense of Grasslands and Pastures. The lack of change in the DESI reflects similar and low Potential LUG Impact scores for these 2 LUGs (see Table 4). In Pumanque the Acacia Savanna LUG increased slightly and reflected decreases in a number of other LUGs.

Marchihue showed a moderate increase in potential impact over the 1989 to 2001 period (DESI increasing from 371 to 414) due mostly to a loss of native forest and an increase in Forest Plantations.

The overall DESI for the AOI averages these changes, reflecting the overall increase in potential impact and consequent decrease in the delivery of ecological services. The interpretation of these land use changes using the DESI appears to provide a defensible and logical assessment of the potential impacts of land use change on the delivery of ecological services.

The largest impact creating changes to the DESI in the AOI was due to the conversion of native ecosystems (Evergreen Sclerophyllous Forest Shrub LUG) to other land uses. This effect is the result of the x100 multiplier we use for the difference in area between a protection target of 17% and the level of protection in any area under consideration. There is a concern that this level of effect on the DESI will mask important changes in other land uses. To look at this we subtracted the Protected Areas component of the DESI for the four municipalities and the AOI (Figure 9).

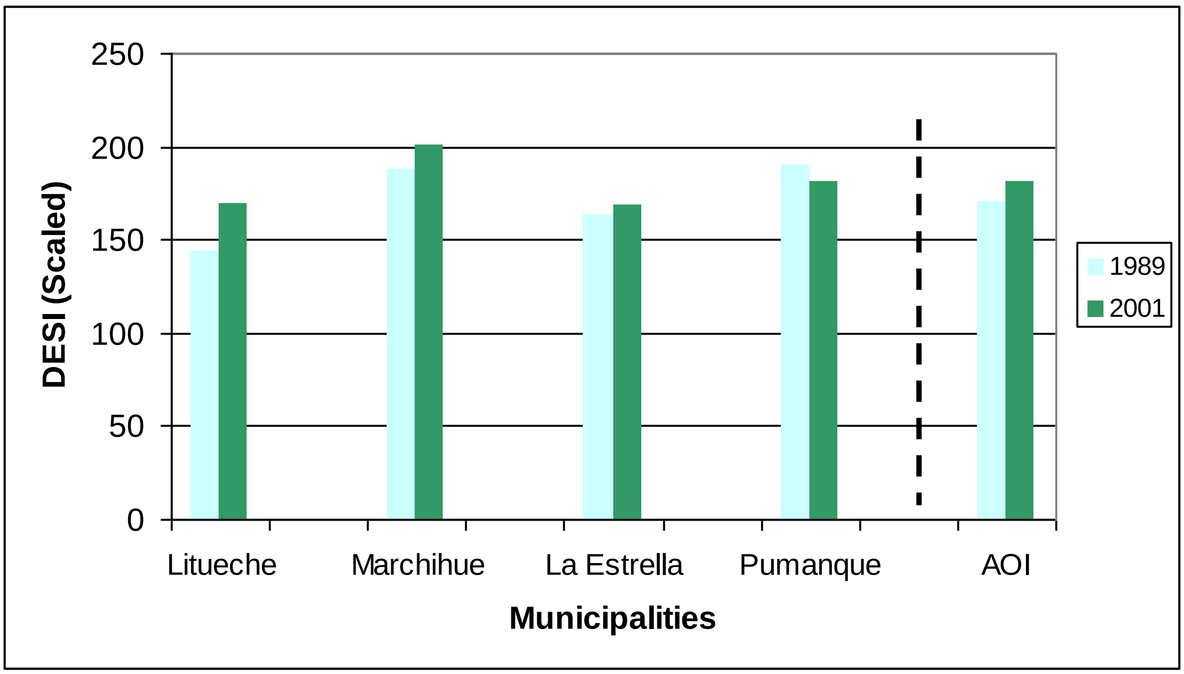


Figure 9: The effect on DESI of removing the Protected Areas factor (1989 and 2001) for four municipalities, and for the AOI.

The pattern of land use change stays more or less that same as for Figure 8, but the magnitude is less. Give the importance of protection of native biodiversity in the MEA ecological services model, the complete lack of protection on the AOI, and the similar pattern in the DESI with and without the Protected Areas factor, we would recommend maintaining our present approach until we can look at how the DESI behaves in a wider range of landscapes.

E.2.3 Developing DESI Thresholds – Scenarios Analysis

Although the DESI seems capable of reflecting relative change in the delivery of ecological services that may result from changes in land use over a given time frame in an AOI, it is also necessary to interpret the DESI scores in the context of overall environmental sustainability. This will make it possible to compare DESI changes across the broad geographic range of potential AOIs encompassed within the DTR program. To begin to understand the broad interpretation of DESI results we conducted some simple scenarios analysis for the AOI by increasing the areal coverage of intensive agricultural practices with high potential for environmental impact to land cover levels that would clearly be unacceptable (Table 5). The scenarios are intended to envision how the AOI may change as agricultural practices intensify. We make the assumption in the scenarios that, for the AOI, the land in Forest Plantations stays more or less that same, and that expansion is at the expense of the Grasslands/Pasture and Acacia Savanna LUGs.

1. In Scenario 1 – Current Conditions - we use the condition of the AOI in 2001. The relative areas of all LUGs are the same as in Table 2.

2. In Scenario 2 – slight increase in intensive agriculture - we increase the area in the Orchards/Vineyards and the Tilled Fields LUGs to 5% and 20%, respectively, a small increase in these land uses reflecting an estimate of land use in 2012.

3. In Scenario 3 – moderate increase in intensive agriculture - we further increase the area the Orchards/Vineyards and the Tilled Fields LUGs to 15% and 45%, respectively, a larger increase in these intensive land use practices, possibly foretelling the direction of land use in the AOI.

4. In Scenario 4 – significant increase in intensive agriculture - we further increase the area in Orchards/Vineyards and the Tilled Fields LUGs to 25% and 61%, respectively, a very large increase in intensive land use practice.

5. In Scenario 5 - small increase in intensive agriculture with establishment of 17% protected areas - we slightly increase the area in the Orchards/Vineyards and Tilled Fields LUGs to 3% and 15% respectively, and we assume 17% Protected Areas.

Table 5: Scenarios to develop interpretation thresholds for the DESI. Numbers indicate the relative percent coverage of the different LUGs in the AOI.

Land Use Group	Relative Area of LUGs (%)				
Scenarios	**1**	**2**	**3**	**4**	**5**
Evergreen Sclerophyllous Forest-Shrub	4	4	4	4	15
Acacia Savanna	35	25	10	0	25
Plantations	25	25	21	25	25
Vineyards and Orchards	0.9	5	15	10	3
Grasslands	25	20	5	0	15
Agricultural Fields	8	20	45	61	15
Towns and Buildings	0.2	0.2	0.2	0.2	0.2
DESI	**428**	**452**	**676**	**729**	**214**

Given the logic used in Scenarios 1 to 5 above, the change in land use between Scenarios 3 and 4 are assumed to cross a threshold where the land use intensity in Scenario 4 would have a clear and likely undesirable potential impact on the delivery of ecological services, given present land use practices. To begin developing a meaningful threshold we set this upper threshold at a DESI of 700 (Figure 10), and so would interpret the DESIs for Scenarios 3 and 4 as almost Inadequate and Inadequate. This analysis is preliminary and intended to demonstrate how we can develop the DESI approach to interpret changes in land use in the context of overall environmental sustainability. The final designation of these thresholds can only be ascertained after applying the DESI to a larger number of AOIs that encompass a range of land uses that demonstrate Adequate to Inadequate delivery of ecological services.

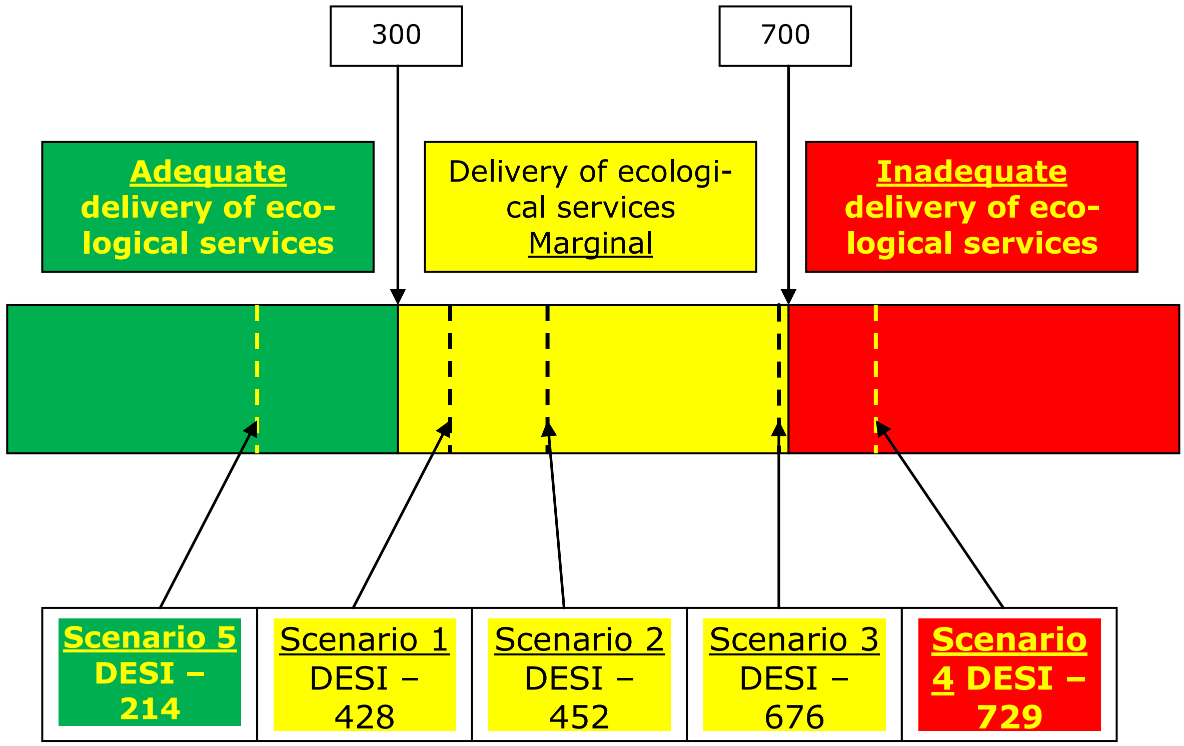


Figure 10: Development of potential thresholds differentiating three condition categories for the DESI.

For the lower threshold between Adequate and Marginal delivery of ecological services categories, a threshold of 300 would place the AOI in 2001 just above our preliminary assessment of 'Adequate'. The main reason for this DESI score is the complete lack of protected areas in the AOI. In Scenario 5 we can envision a state for the AOI where there are modest increases in intensive land use (perhaps close to the 2011 values) but where 17% of the AOI has been protected. The result (Scenario 5) is a DESI well into the Adequate category. This conclusion seems logical in that only about 6% of the AOI was utilized for intensive agriculture in 2002. Also, even after regular and long term fertilizer use, the aquifer of the Central Valley has acceptable nitrate levels (Arumi et al., 2005), indicating an unpolluted condition.

Many other assumptions need to be tested to further explore the potential impacts of different combinations of changes in land use practice, e.g., for the individual municipalities, and to assess these results in terms of the preliminary thresholds presented here.

E.2.4 Communicating Results

The DTR program aims to develop assessments of environmental sustainability for large number of territories across Central and South America, with the basic unit being municipalities. Using the three DESI categories defined above, potential changes in the delivery of ecological services can be communicated for a large number of assessments using summary tables that could report the change in DESI scores to correlate with social-economic changes (Table 6). By colour coding the boxes associated with each municipality, a clear and simple communication of the change in ecosystem condition that accompanies the social-economic change can be presented. These colours can also be projected on regional maps to show trends in municipal environmental sustainability across broad areas.

Table 6: Summary table showing the change in DESI, and the change in environmental condition for the four municipalities in the AOI.

Municipalities	1989	2001
Litueche	**200**	**319**
La Estrella	**371**	**414**
Marchihue	**341**	**346**
Pumanque	**382**	**380**

Discussion and Conclusions

We have developed the DESI in an attempt to provide a rapid and repeatable assessment of potential changes in the delivery of key ecological services that may result from changes in land use, to be associated with changes in the socio-economic status of the DTR municipalities study. The DESI assessment procedure relies on the interpretation of archived Landsat imagery, and so is applicable at the scale of the regional landscape, i.e., in the present study, municipalities within a country. It does not replace an analysis based on local scale data (e.g., farm by farm data – see Viglizzo et al., 2003, 2006), nor is it appropriate for international or global applications (e.g., MEA, 2005).

For this Proof of Concept we have calculated and carried out assessments of the change in DESI scores for four municipalities in the O'Higgins region of central Chile for the period 1989 to 2001, coinciding with the DTR social analysis for roughly the same period (1991-2001). Our results suggest the DESI reliably reflects the potential ecological impacts of 12 year changes in land use effects, both at the scale of the AOI, and for the municipalities.

We are confident of the accuracy of the land use classification in the present study due to the abundant high resolution imagery available on Google Earth to confirm the classification, the ground validation, and the relatively small area considered. No quantitative accuracy assessment has been made for the present project. Classification accuracy can be expected to decrease as the area considered becomes larger, high resolution imagery is less available, and the degree of ground checking is reduced.

Impact Scores for the LUGs in this report have not been assessed by local experts knowledgeable about land use practices in the O'Higgins AOI. We recommend this kind of workshop with local experts as a critical component of the DESI process in any AOI. The proposed thresholds for the DESI scores need to be tested and assessed through further scenarios analysis, and by repeating the DESI process in a broader range of ecological settings (e.g., in areas where the natural vegetation is Tropical, Sub-tropical and Temperate Forest), and where land uses differ. Such an analysis would refine the broad usefulness and applicability of the DESI process, and in particular, refine the breakpoints for the assessment thresholds.

Carrying out the DESI may be more difficult in some areas of the DTR project if suitable Landsat imagery for the classification, and high resolution imagery for the development and validation of the classification, is not available. For the present study it was necessary to compromise on the imagery dates to find cloud free imagery that was phenologically acceptable. Also, characteristics of the AOI can confuse classifications, especially steep topography that creates shade effects, a common factor in many of the DTR regions. These issues are typical of satellite-based classifications and can be largely overcome using well-developed approaches.

At this time the DESI is designed to develop assessments of potential impacts on ecological services of area-based land use change in rural settings, as required by the DTR project. There are other important land uses, e.g., industrial-scale pig and chicken barns, greenhouses, industrial plants, that are not area-based, and that can have important effects on the delivery of ecological services. During the analysis we were able to assess for example, small increases in greenhouses and in urban area change, but we did not include these changes in the DESI. This kind of analysis of point sources of potential impacts on the delivery of ecological services can be included in the DESI as it evolves.

Finally, the DESI is a semi-intensive process that relies on a focussed effort and relevant expertise to ensure accurate land use classification and mapping, and the calculation of reliable Impact Scores. The processing of the Landsat imagery to ensure reliable mapping, and the required checking to ensure sufficient accuracy to have confidence in the results, is labour intensive and would not be practical across the entire area of the DTR study. For example, to cover the municipalities in Chile alone would require the acquisition, pre-processing and classification of about 140 Landsat images (compared to two images for this Proof of Concept study). We propose that the DESI could be applied to a stratified random sample of the DTR municipalities, and conclusions in terms of environmental impacts about the DTR municipalities as a whole could be made from this sample.

References

Aalders, I. 2008. Modeling land-use decision behaviour with Bayesian belief networks. *Ecology and Society* 13(1): 16. [online] URL: http://www.ecologyandsociety.org/vol13/iss1/art16/

Adelle, C., and M. Pallemaerts. 2009. Sustainable Development Indicators. An Overview of relevant Framework Programme funded research and identification of further needs in view of EU and international activities. European Commission. European Research Area. IIEC.

Armesto, J.J., D. Manuschevich, A. Mora, C. Smith-Ramirez, R. Rozzi, A.M. Abarzua, and P.A. Marquet. 2010. From the Holocene to the Anthropocene: A historical framework for land cover change in southwestern South America in the last 15,000 years. Land Use Policy 27: 148-160.

Arumi, J.L., R. Oyarzun, and M. Sandoval. 2005. Natural protection against groundwater pollution by nitrates in the Central Valley of Chile. Hydrologic Sciences 50(2):331-340.

Arumi, J.L., D. Rivera, E. Holzapfel, P. Boochs, M. Bollib, and A. Fernald. 2009. Effect of the irrigation canal network on surface and groundwater interactions in the lower valley of the Cachapoal River, Chile. Chil. J. Ag. Res. 69(1):12-20.

Aspinall, R. 1992. An inductive modelling procedure based on Bayes' theorem for analysis of pattern in spatial data. *International Journal of Geographical Information Systems* 6(2):105–121.

Bustamente, R.O., and J.A. Simonetti. 2005. Is *Pinus radiata* invading the native vegetation in Central Chile? Demographic responses in a fragmented forest. Biological Invasions 7:243-249.

CBD. 2012. Convention on Biological Diversity. Aichi Targets. http://www.cbd.int/sp/targets/

Cihlar, J. 2000. Land cover mapping of large areas from satellites: Status and research priorities, International Journal of Remote Sensing, 21: 6, 1093 - 1114

Cihlar, J., and Jansen, L. 2001. From land cover to land use: A methodology for efficient land use mapping over large areas. The Professional Geographer 53(2): 275-289

Coffee Research. 2011. http://www.coffeeresearch.org/politics/birdsafe.htm

Collen, B., McRae, L., Kothari, G., Mellor, R., Daniel, O., Greenwood, A., Amin, R., Holbrook, S. and Baillie, J. 2008. Living Planet Index. 2010 and beyond: rising to the biodiversity challenge (ed. By J. Loh), WWF, Gland, Switzerland.

CONOMA. 2003. National Biodiversity Strategy of the Republic of Chile. Gobierno de Chile. Comicion National de Medio Ambiente. Programa de las Naciones Unidas para el Desarrollo. http://www.cbd.int/doc/world/cl/cl-nbsap-01-en.pdf

Coppin, P. R. and Marvin E. Bauer. 1994. Processing of Multitemporal Landsat TM Imagery to Optimize Extraction of Forest Cover Change Features. IEEE Transactions On Geoscience and Remote Sensing, VOL. 32, NO. 4, 918-927

Del Pozo, A., C. Ovalle, M.A. Casado, B. Acosta, and J.M. de Miguel. 2005. Grassland diversity in the Mediterranean zone of Chile is greatly affected by land use system and grazing intensity. Options mediterraneennes, Series A, No. 79.

Earth Trends 2003. Country Profiles. Agriculture and Food – Chile. (earthtrends.wri.org)

Elbers, C., Lanjouw, J. & Lanjouw, P. 2001a. Welfare in villages and towns: *micro-level estimation of poverty and inequality*. Vrije Universiteit, Yale University and the World Bank (mimeo).

Elbers, C., Lanjouw J., Lanjouw, P. & Leite, P. 2001b*. Poverty and inequality in Brazil: new estimates from combined PPV-PNAD data*. Vrije Universiteit, Yale University, the World Bank and Pontificia Universidade Catolica do Rio de Janeiro (mimeo).

Enterprise Vineyards. 2011. http://www.enterprisevineyards.com/

EPI. 2012. The Environmental Performance Index. http://epi.yale.edu/

Eva, H.D., Miranda, E.E., Di Bella, C.M., Gond, V., *Huber*, O., Sgrenzaroli, M., Jones, S., Coutinho, A., Dorado, A., uimarães, M., Elvidge, C., Achard, F., Belward, A.S., Bartholomé, E., Baraldi, A., De Grandi, G., Vogt, P., Fritz, S., and A. Hartley. 2002. A vegetation Map of South America. EUR 20159 EN, European Commission, Joint Research Centre.

Fuentes, E.R., R. Aviles, and A. Segura. 1989. Landscape change under indirect effects of human use: the Savanna of Central Chile. Landscape Ecology 2(2):73-80.

IPCC. 2007. Climate Change 2007 – The Physical Science Basis. Contribution of Working Group 1 to the Fourth Assessment Report of the Intergovernmental

Panel on Climate Change. ed. S. Solomon, D. Qin, M. Manning, M. Marquis, K. Avery, M. Tignor, H.L. Miller Jr., Z. Chen. Cambridge University Press.

Modrego, F., Ramírez, E., Yánez, R., Acuña, D., Ramírez, M., Jara, E. 2011. "Dinámicas territoriales del Secano Interior de la Región de O'Higgins: Las fronteras de la transformación agroindustrial". Documento de Trabajo N° 80. Programa Dinámicas Territoriales Rurales. Rimisp, Santiago, Chile.

Neira, E., H. Verscheure, and C. Revenga. 2002. Chile's Frontier Forests: Conserving a global treasure. Global Forest Watch. (www.globalforestwatch.org)

Hill, M. J., R. J. Aspinall, and W. D. Willms. 1997. Knowledge-based and inductive modeling of rough fescue (*Festuca altaic, F. campestris*, and *F. halli*) distribution in Alberta. *Canadian Ecolological Modeling* 103:135–150.

Holmgren, M., R. Aviles, L. Sierralta, A.M. Segura, and E.R. Fuentes. 2000. Why have European herbs so successfully invaded the Chilean matorral? Effects of herbivory, soil nutrients, and fire. J. Arid Envs. 44:197-211.

Latifovic, R., Zhu, Z.L., Cihlar, J., Giri, C., and I. Olthof. 2004. Land cover mapping of North and Central America—Global Land Cover 2000. Remote Sensing of Environment 89 (2004) 116–127.Lillesand, T.M. and R.W. Kieffer. 2000. Remote sensing and image interpretation. John Wiley & Sons, Inc, New York p724.

Malczewski, J. 2006. Ordered weighted averaging with fuzzy quantifiers: GIS-based multicriteria evaluation for land-use suitability analysis. International Journal of Applied Earth Observation and Geoinformation 8 (4), 270-277.

MEA. 2005. The Millennium Ecosystem Assessment. http://www.maweb.org/en/index.aspx

Myers, N., A. Russell, C.G. Mittermeier, G.A.B. da Fonseca, and J. Kent. 2000. Biodiversity hotspots for conservation priorities. Nature 403:853-858.

Olsen, D.M., and E. Dinerstein. 2002. The Global 200: Priority ecoregions for global conservation. Ann. Missouri Bot. Gard. 89:199-244.

Olthof, I., Butson, C., and R. Fraser, 2005. Signature extension through space for northern landcover classification: A comparison of radiometric correction methods. Remote Sensing of Environment, Volume 95, Issue 3, 15 April 2005, Pages 290–302

Ovalle, C., A. Aronson, A. del Pozo, and J. Avendano. 1990. The Espinal: Agroforestry systems of the Mediterranean-type climate regional of Chile. Agrof. Sys. 10:213-239.

Ridoutt, B., and P. Poulton. 2009. SAI Platform Australia water footprint pilot project: wheat, barley and oats grown in the Australian state of New South Wales. Summary Report. National Research Flagships, Sustainable Agriculture. CSIRO.

Tucker, K., S. P. Rushton, R. A. Sanderson, E. B. Martin, and J. Blaiklock. 1997. Modelling bird distributions—a combined GIS and Bayesian rule-based approach. *Landscape Ecology*12:77–93.

USGS, 2008. Imagery for Everyone, *Timeline Set to Release Entire USGS Landsat Archive at No Charge.* http://landsat.usgs.gov/documents/USGS_Landsat_Imagery_Release.pdf

USGS, 2011. Thematic Mapper (TM). http://eros.usgs.gov/#/Find_Data/Products_and_Data_Available/TM

Van de Wouw, P., C. Echeverria, J.M. Rey-Benayas, and M. Holmgren. 2011. Persistent *Acacia* savannas replace sclerophyllous forests in South America. 2011. Forest Ecology and Management 262: 1100-1108.

Vera, R. 2002. Country pasture / Forage Resource Profiles. www.fao.org/ag/AGP/AGPC/doc/Counprof/**Chile**/cile.htm

Viglizzo, E.F., A.J. Pordomingo, M.G. Castro, and F.A. Lertora. 2003. Environmental assessment of agriculture at a regional scale in the Pampas of Argentina. Env. Monitoring and Assess. 87(2):169-195.

Viglizzo, E.F., F. Frank, J. Bernardos, D.E. Buschiazzo, and S. Cabo. 2006. A rapid method for the assessment of environmental performance of commercial farms in the Pampas of Argentina. Env. Monitoring and Assess. 117(1-3):109-134.

Vogelmann, J.E., Sohl, T.L., Campbell, P.V., and D.M. Shaw. 1998. Regional land cover characterization using Landsat Thematic Mapper data and ancillary data sources. Environmental Monitoring and Assessment 51: 415–428.