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MONITORING OF CHRONOLOGICAL STAGES OF DEFORESTATION – AFFORESTATION: THE CASE OF SOUTHERN CHILE

Suivi spatio-temporel des phases de déboisement – reboisement dans le sud-chilien

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Abstract

Industrial forest plantation expansion is dramatically impacting the environment (biodiversity, soil, water, etc.) and social sphere. Since the enactment of Decree Law 701 (DL 701) in 1974 under the military government of Augusto Pinochet, forestry practices have become more intensive (genetic manipulation, high yield clearcutting and short rotation). The law (and its successive updates) cover up to 75% of plantation costs and is the keystone of pine and eucalyptus forest expansion. This paper presents a pluriannual detection model for monitoring and characterizing the high cutting frequency of these timber plantations. Thirteen Landsat and Spot images taken between 1976 and 2008 are used and combined with ground data (oblique aerial photography, GPS field surveys and field sheets). A trichromatic composition is built from spectral information taken from a Red and Mid-Infrared (MIR) wavelength along a temporal gradient of 32 years. This multi-temporal on-screen visual interpretation has led to a dynamic interpretation grid which reflects forest management stages in direct relation with pine and eucalyptus crop cycles. The method was tested on various time-steps covering the entire time period on two spatial scales – local and regional. All the spatio-temporal results are conclusive and the model established by remote sensing is of operational value.

Keywords

Spatio-temporal modeling, change detection, forest management, environment, southern Chile, Landsat and Spot

Mots-clés

Modélisation spatio-temporelle, détection des changements, gestion forestière, environnement, sud chilien, Landsat et Spot

1. INTRODUCTION

One of the great advantages of remote spatial sensing is its capacity to repeatedly observe the same environment over time. Thus, environmental spatio-temporal dynamics can be taken into account via regularly taken satellite images (HEALEY *et al.*, 2005; HEALEY *et al.*, 2008; HUANG *et al.* 2010).

Use of satellite images appears to be particularly well suited to southern Chile, given the forest metamorphosis that has reigned there since 1974. Indeed, “Decree Law 701” (D.L.701), enacted by General Pinochet shortly after his coup d’état, was the triggering act of a vast transformation in the countryside. The native Valdivian forest type was methodically destroyed to make room for plantations of the profitable and quick growing species pine and eucalyptus. This widespread phenomenon developed unequally in both time and space. Begun south of the capital, Santiago de Chile, in the country’s *del Bio-Bio* Region, also known as the 8th Region, surrounding the town of Concepcion, it spread inexorably southwards, reaching the 9th Region of *Araucania* near the town of Temuco, the 10th Region of *Los Lagos* surrounding Osorno, and the 14th Region of *Los Rios* surrounding Valdivia.

A periodical inventory can be taken of plantations and their respective states, to observe the correlative degradation of the environment via satellite images, as long as each deforested and then reforested plot of land extends over large surfaces. But what synergy is established between forest rotations and spectral signatures?

Our objective was to arrive at a multi-dated spectral characterization of exotic plantations (as related to their plot of land), and to develop a model to be applied to such plantations and that can be used again in both time and space (a pluri-annual detection model). It was also our goal to be able to

automatically detect forest rotation and monitoring, thus allowing us to distinguish a section of native forest from a plot given over to exotic plantation.

Via this process, one automatically sees how Chilean forestry functions. The diachronic processing applied to the images furnished cartographic results (for both the past and the present) and a regular quantitative estimation of the number of hectares planted or under transformation. They ensured continuous surveillance of implantation and the management of pine and eucalyptus plantings.

To develop this methodology and make it operational, we obtained 13 Landsat and Spot images that covered a period of 32 years, from 1976 to 2008. We also undertook several missions in the field (in 2001, 2007, 2008, 2009 and 2010) with the objective of establishing the closest link possible between the biophysical content of the plots and their radiometric variations. Oblique photos taken from a plane at low altitude were also of help in observing and describing the plots.

To take into account the regional variety of plantations and the geomorphological conditions of their locations, 333 field plots were identified on pre-established transects along the coastal foothills. Located by GPS, each plot furnished physiognomic readings classed according to the following criteria: species and tree structure, phenology, rate of land cover, state of health, slope, relief, orientation and access. We insisted particularly on the impact of human works, perceptible either directly in the field or indirectly in the forest management plans of companies or managerial organizations in the wood industry.

2. STUDY AREAS AND FOREST PLANTING ROTATIONS

2.1. Selection of satellite images

The inventory of available Landsat and Spot scenes is as follows (**Table 1**):

Chile - OSORNO		Coordonnées		Longitude:	Latitude:				
				73°30	40°06				
Inventory	Geometric Correction			WGS 1984	UTM18S	Spot : NAD27			
K-J ou Path-Row						Interv. Time/ Year	Resol. metre	Number :	
	MSS-Ldt1	SPOT	TM-Ldt 4-5	ETM-dt.7	Channels			Image	Channels
250-88	09-Feb-76				MSS 4.5.6.7		57	1	4
233-88 671-431/5		24-Oct-86	25-Sept-86		TM- 2.3.4.5.7	10	20	1	5
					XS 1-2-3	0	28,5	1	3
233-88 671-431/5		31- Oct-98	22-Sept-88		TM- 2.3.4.5.7	2	30	1	5
					XS 1-2-3	10	20	1	3
233-88 671-431/6		23- Mar -01	23-Oct-99		TM- 2.3.4.5.7.8	1	15	1	6
					XS 1-2-3-4	2	20	1	4
233-88			29-Nov-01		TM- 2.3.4.5.7.8	0	14,25	1	6
233-88 233-88			20-Feb-03		TM- 2.3.4.5.7.8	2	15	1	6
			15-Feb-04			1	25	1	5
233-88 233-88 233-88			09-Feb-05		TM- 2.3.4.5.7.8	1	15	1	6
			18-Aug-07			2	15	1	5
			10-Dec-08			1	25	1	5
Totaux :								13	63

Table 1: Inventory of Landsat and Spot imageries used.

The preferred periods, annual and phenological, for satellite image acquisition, is from August to March, the spring and summer seasons in the southern hemisphere. The total time cover is of interest in that it begins just two years after enactment of D.L. 701. The choice is justified by the influence of meteorological conditions (weak precipitation, rising temperatures), especially by the minimization of cloud cover, light intensity and increasing photosynthetic activity. The wave lengths of the Landsat and Spot satellites being nearly identical, they cover the electromagnetic spectrum from Green to Mid-Infrared (optical domain).

The 13 images and their 63 channels were created using the software *Er-Mapper* which automatically manages the different spatial resolutions of the initial images.

For diachronic analysis, all the scenes were geo-referenced according to the cartographical norms in force in southern Chile: WGS84 with projection in UTM18 South. An average of 15 GPCs, spread over the entire extent of the image, suffice (weak RMS) to correct the geometry and render the

images superimposable. Brought together and geometrically superimposed, the images form a single and unique multi-spectral image with 63 channels which is thus capable of an average spatial resolution of 14.25 meters.

2.2. Nested areas of study

The regional study zone (**Plate 1**) is located between longitudes $-73^{\circ}9'11$ to $-73^{\circ}7'11$ and latitudes $-39^{\circ}32'1$ to $-41^{\circ}5'48$, between the towns of San José de la Mariquina and Fresia. Found within the regional zone, the local study zone is located in the 10th Region of *Los Lagos*, west of the town of Osorno (longitude $-73^{\circ}30$ and latitude $-40^{\circ}06$).

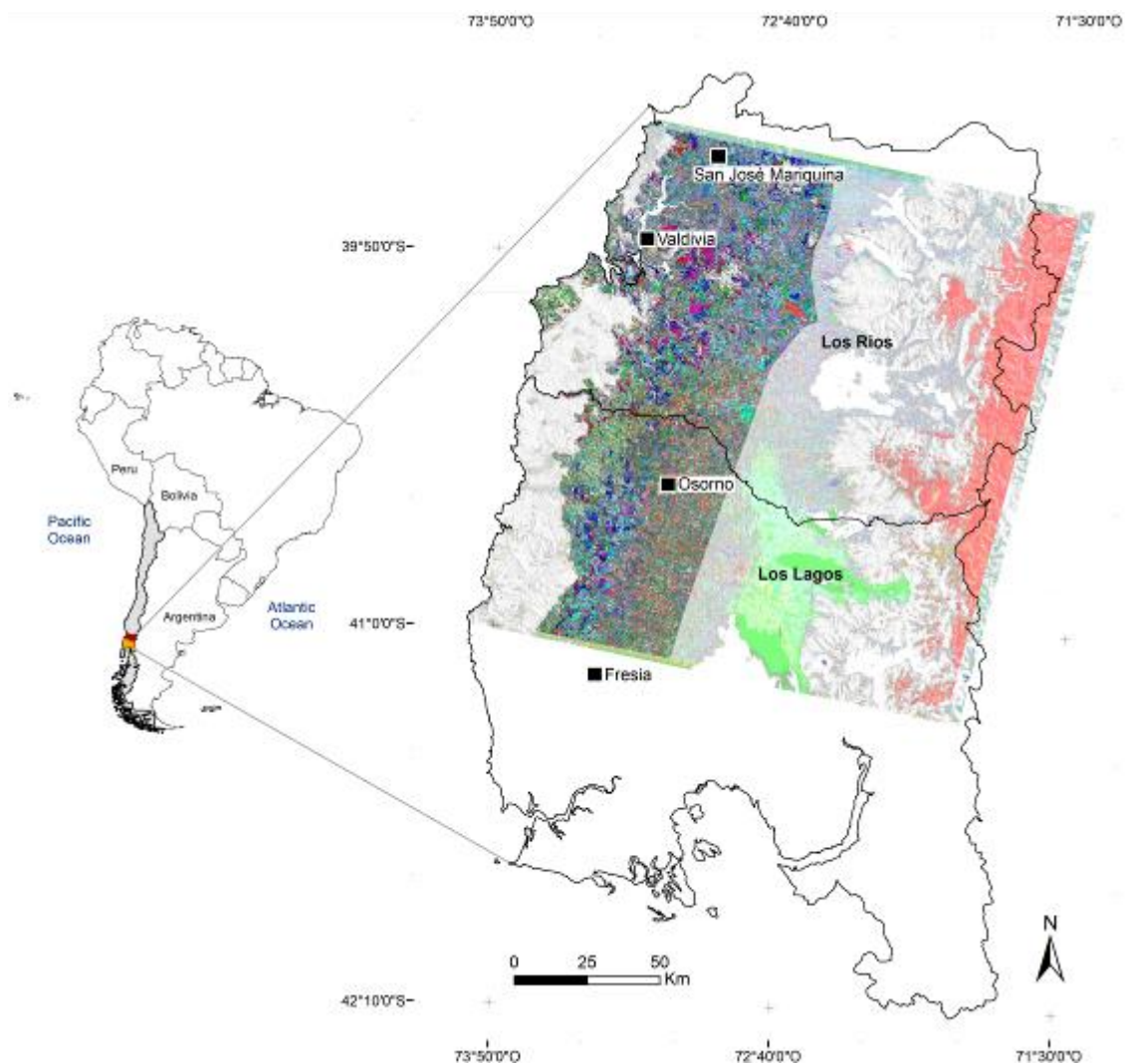


Plate 1: Landsat: Complete scene imagery with Coast Range and Central Valley. In grey: area excluded from study.

A geometric mask was applied to the resulting image (**Plate 2**) so as to exclude the Coast Range to the west, the eastern part of the Intermediate Depression and the Andes Range where plantations of exotic woods are nearly non-existent. The study is therefore focused on the piedmont, the foothills of the Coast Range.

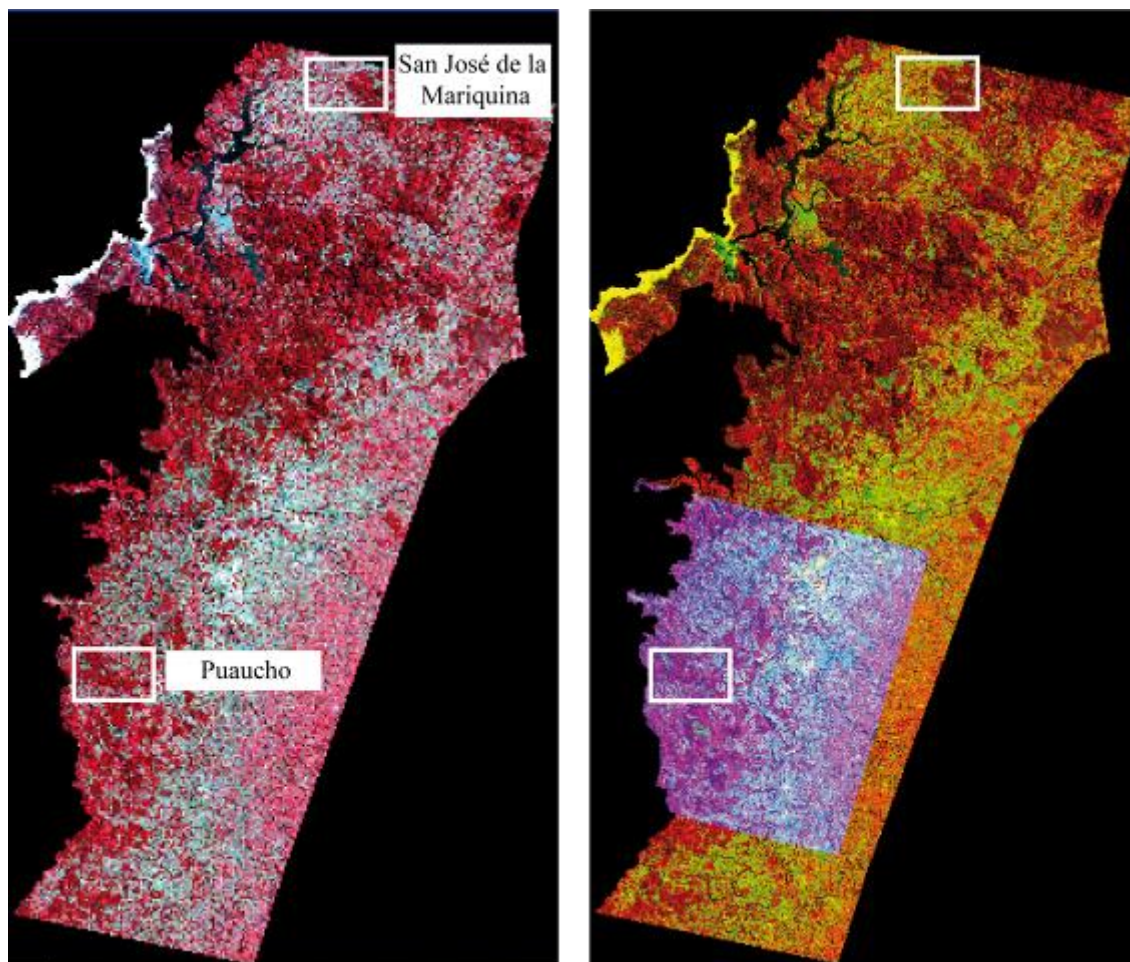


Plate 2: Landsat masked scene of February 2004 and Spot scene of March 2001 (blue)

Two samples, two zones, one generalization

Within the geographic boundaries of the study area (**Plate 2-left**), two sampling spaces were selected: Mariquina in the north and Puaicho in the south. At these two sites large-scale local analyses were undertaken. Puaicho nevertheless benefited from a greater number of images since the Spot

images were included, as can be seen in the colored composition in **Plate 2-right**. The method and results from the Puaucho site are not presented in this paper.

Taking advantage of advances made in image processing at the local level, a mid-scale generalization was attempted. This regional analysis could not be undertaken for the entire piedmont - from the 14th Region to the 10th- due to the obvious disparity and unequal spatial coverage between the Landsat and Spot scenes.

2.3. Industrial plantations and forest rotation

Beginning with D.L. 701, southern Chile experienced a considerable extension in exotic forest plantation of pine and eucalyptus to the detriment of native forests. Between 1975 and 2007 the average annual planted forest area (both planting and re-planting) on the national level was 95,141 hectares, to attain a total area of 2.2 million hectares in 2007 (INFOR, 2008).

The Chilean forest industry is, in fact, highly competitive on the international market. Exports of wood chips of *Eucalyptus globulus* went from 990,000 tons in 1998 to 1.5 million in 2003, to then surpass the level of 2.5 million tons in 2006 (INFOR, 2007). Exports of forest products were worth 4.9 billion dollars in 2007, 7.3% of Chile's exports. The impressive growth in forest product exports has shown the strength of the forestry sector and its economic potential for the future. In 1964 exports reached a level of around \$27 million, \$127 million in 1974, \$577 million in 1987 and \$2.3 billion in 2000. Forest exports grew by 27.3% during the period 2006-2007 and by 41.7% for the period 2005-2007 (INFOR, 2008).

Increased production thus becomes a major objective as it allows businesses to be more competitive and to offer products at a lower cost through an economy of scale. Genetic manipulation and clearcutting are two of the main practices contributing to these objectives.

The improvement of vegetal species via genetics “*has as its goal the development of varieties which increase the quantity and quality of harvested products*” (WHITE *et al.*, 2007). It is by maximizing productivity—and thus calling directly upon the resiliency of plantations and their accelerated growth—that intensive forestry reveals its potential with respect to time.

Manuel TORRAL IBÁÑEZ (2007) observes that forest species (pines and eucalyptus) present great capacities of resistance to certain external disturbances such as insects and lichens, bacteria and certain chemical products.

For pines, forest rotations are of about 22 years (CUBBAGE *et al.*, 2005), with 30 m³/ha/year growth in volume; for eucalyptus the rotation cycle is about 8 years (GELDRES and SCHLATTER, 2004), with an annual growth of 45 m³/ha, or 60 m³/ha/year at an experimental site.



Plate 3: Young timber plantation of *Pinus radiata* and *Eucalyptus globulus* (Lake Region) - December 2008
© N. Maestriperi

3. IMAGE PROCESSING METHOD

Multi-spectral analysis performed on several dates is a permanent advantage when describing with precision the dynamics of land occupation changes. With their time intervals spread over periods of from one to ten years, the thirteen satellite images enhance the monitoring of transition processes and can distinguish stationary periods from the highly volatile processes that may take place within very short intervals. Analysis practiced frequently has the advantage of furnishing a better vision of the

ruptures that may take place following extreme events (fires, climatic disturbances) or forestry operations (thinning, clearcutting) (HUANG *et al.*, 2010).

3.1. Surveillance by transects

Spatio-temporal analysis of the images required a prior reconnaissance of the forest test plots along the entire Coast Range. Two mutually complementary methods prevailed in establishing this inventory: the first by tracing transects from an airplane and the second by geolocalization on the ground (**Plates 4, 5 & 6**).

Oblique photos were taken from an airplane flying towards Valdivia over the northern part of the foothills of the San Pablo Coast Range (near the River Bueno). Comparing the shapes and colors (both natural and IRC), similar terrains can be recognized on documents of different terrains but from similar periods: oblique photographs, Google Earth and Landsat images from 2008. The Google Earth image makes clear at the outset the latitude-longitude coordinates of the location. This georeferencing was then applied to the resulting image using Er-Mapper. Once each site was recognized on the 2008 image, it was then quite easy to “go back in time” against the same georeferenced backdrop and to draw conclusions as to the intrinsic dynamic of the site as presented in **Plate 4** below.

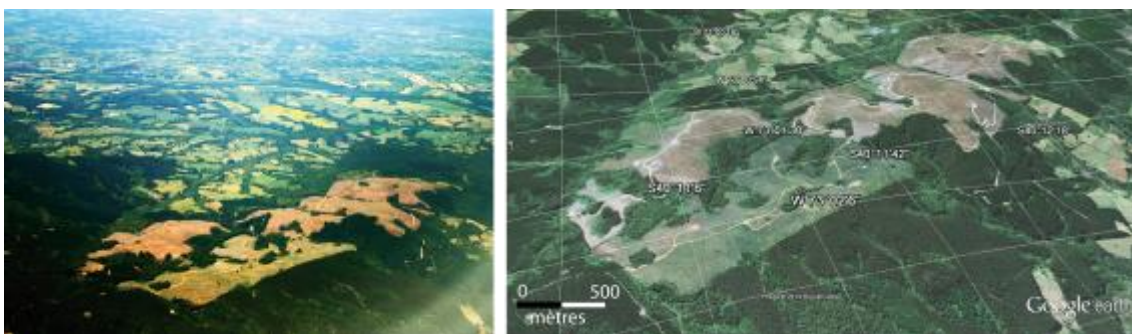


Plate 4: *Oblique aerial photograph – plane – December 2008 © G. Selleron and screenshot from Google Earth*

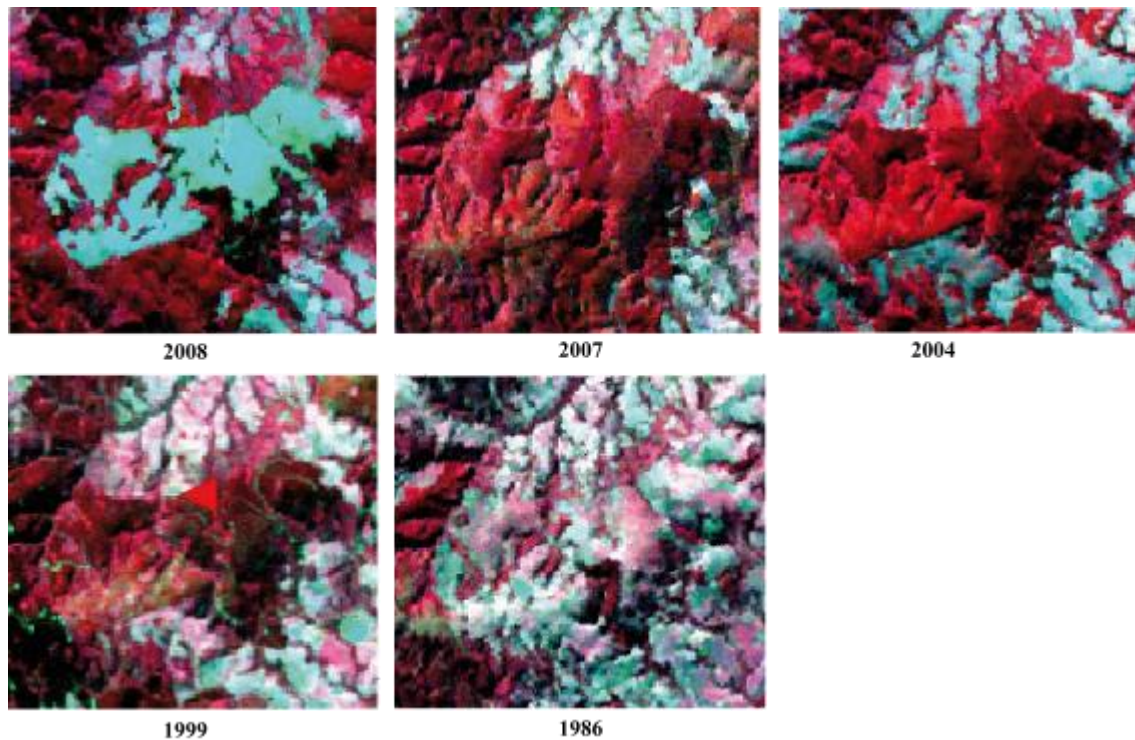


Plate 5: *IRC Landsat imagery (same area)*

By using the second method, sample plots can be determined from previously traced transects, themselves produced through a visual approach to the most recent Landsat images. Also, the terrain can then be surveyed while integrating a certain local biogeographical variation on the piedmont. Along these different itineraries in the field, panoramic slides (**Plate 6**) and ground readings are taken along either side of the transect according to the variety of land use, of forest types and of industrial plantations. These readings are reported on pre-established sheets integrating an entire set of thematic data (description of vegetal entities, phenological, geomorphological and sanitary variables, etc.) and geocoded by means of a GPS. In addition, the data is completed from information collected through qualitative interviews with the population and institutional representatives registered in 2001 and 2008.

Plate 6 below gives a synthesis of this approach: global vision and thematic breakdown.

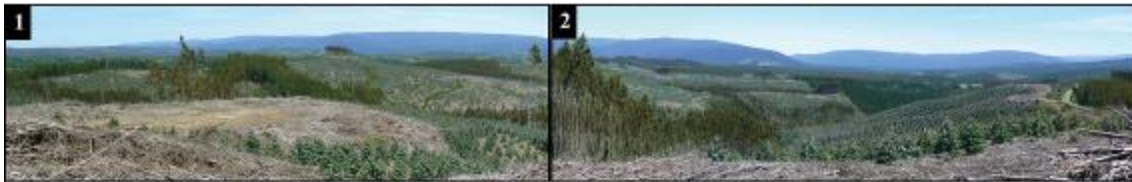


Plate 6: Pre-coastal range landscape: transect n°8, field survey n°12-13 in the sector of Puaicho (S 40°37'0 – W 73°27'1) – December 2008 © N. Maestriperi

3.2. Multi-spectre: Choice of Red and Mid-Infrared channels

The proposed method consists of creating an original colored combination by selecting three identical spectral channels on three successive dates and displaying them, respectively, on three RGB image planes in an increasing temporal order.

Two types of complementary and pertinent wave lengths are selected:

- on the one hand, those between 0.6 – 0.7 μm (Landsat Red channel 1.2.3.), 0.63 – 0.69 μm (Landsat 4.5.7), 0.61 – 0.68 μm (Spot Red channel 1.2.3.4.5.) ;
- on the other hand, a wavelength of 1.55 – 1.75 μm (MIR channel for Landsat and Spot5).

The Red and MIR 5 bands effectively condense and concentrate the specific radiometric information desired in relation to the objective.

The Red channels reveal a sufficiently narrow relation, of the nature and the physiognomic state of plantations caught up in their own dynamic, which schematically extends from native forest to plantation, including clearcutting. In addition, human infrastructure is more clearly indicated than in MIR 5, which is a help to the spatio-temporal reconnaissance of changes that have taken place on the three successive analyzed dates.

This dynamic, along with the components of the relationship between “*plant to ground formations*”, is also perceptible in the Mid-Infrared wavelength (MIR 5). MIR also has the advantage of furnishing a clearer and more detailed reading of the plot on which stable types of vegetation appear with greater nuance, in both their structure and in the physiognomy of their populations, due to the visual isolation of the degree of plant humidity.

By using MIR, plants can be individualized through simplifying the range of colors (primary and secondary). This observation, updated by KONÉ *et al.* (2002, p. 191), shows that this wavelength “*can refine discrimination between wooded savannahs and forests [...] as opposed to the classic colored composition obtained via the Green, Red and Near-Infrared channels*”.

This band is highly sensitive to the water content in plants, to biomass and to changes in vegetation (LIBONATI *et al.*, 2010). This also enables it to solve “*current ambiguities when distinguishing between nonphotosynthetic vegetation (NPV) and the types of ground commonly accepted by using data from other sections of the electro-magnetic spectrum*” (MUSHKIN *et al.* 2005, p.142).

Thus, according to the time period covered by the experiment (1976-2008) and the satellites under consideration, one or the other of these wavelengths can be used, but with a time restriction since the MIR wavelength appears only on Spot5.

3.3. Diachronic method of selection of MIR 5 Red channels

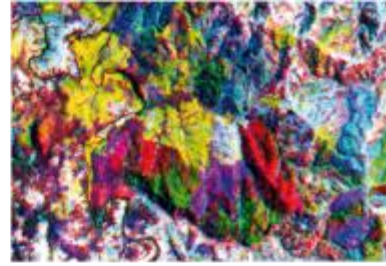
By means of the formula below, the selection of three images with consecutive dates, between 1976 and 2008, can be schematized:

$P1 (t1, t2, t3) P2 (t2, t3, t4)$, etc.

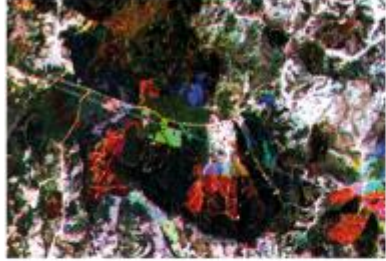
where P represents the time period of the colored composition and t the different successive dates. At each step, the two dates from the previous period are incremented by one new date to constitute the following period.



R/76-86-99



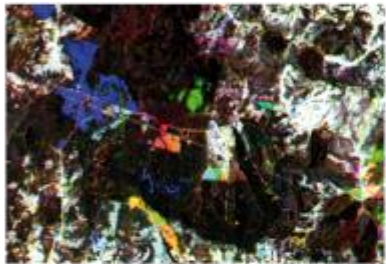
R/76- MIR 86-99



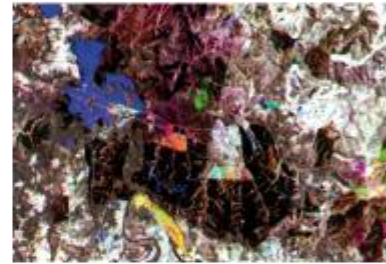
R/99-01-03



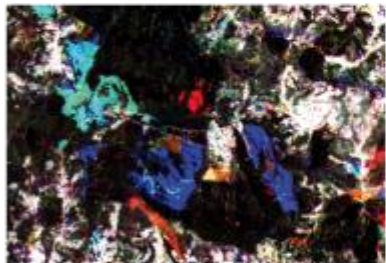
MIR5 99-01-03



R/01-03-04



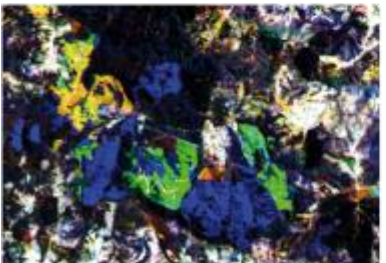
MIR/ 01-03-04



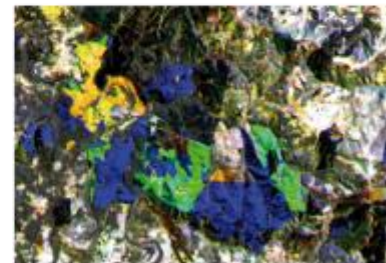
R/03-04-05



MIR/03-04-05



R/04-05-07



MIR/04-05-07



R/05-07-08



MIR/05-07-08

Plate 7: Colored multi-date compositions in R and MIR from 1976 to 2008

Each of the colored compositions thus established reveals a variation in colors which surpasses the usual false-color mono-date vision. This new method gives rise to an immediate spatial perception of an entire set of radiometric -and thus thematic- changes which have taken place over the course of the period under study, as much by assemblages of the Red as by the Mid-Infrared wavelength. The question thus becomes: why such colors? What meaning and interpretation must we give to their themes?

3.4. Regressive method: construction of a dynamic method from 1976 to 2008

From the six series of tri-dimensional colored compositions seen above, the signatures or spectral transects of each one of the chronological combinations help to measure the amplitude of the radiometric variations for each one of the temporal periods under consideration. Thus, **Plate 7** clearly demonstrates the changes having taken place in the Puaucho sector (transect no. 8) along with their detailed spatial localizations.

In the example below (**Plate 8**), which uses the MIR channels from the years 2003-2004-2005, the spectral-spatial correspondence is, in fact, highly perceptible all along the A-B line between the colored band and (in the enlarged image) the breakdown/superimposition of the radiometric values of the three MIR channels.

The three peaks revealed by the MIR channel of 2005 (in pink: spectral values included between 100 and 125) are thus especially discernable, adjusting themselves to the blue spaces along the path of the image's transect, but also to the multiple small spectral peaks (blue and black; values below 50) corresponding to the yellow-green nuances of the band of the MIR channels of 2003-2004, emphasizing relatively linear elements, a spatial structuring that came about between 2003 and 2004. Note that below the spectral curves all of the radiometric curves thus produced are georeferenced.

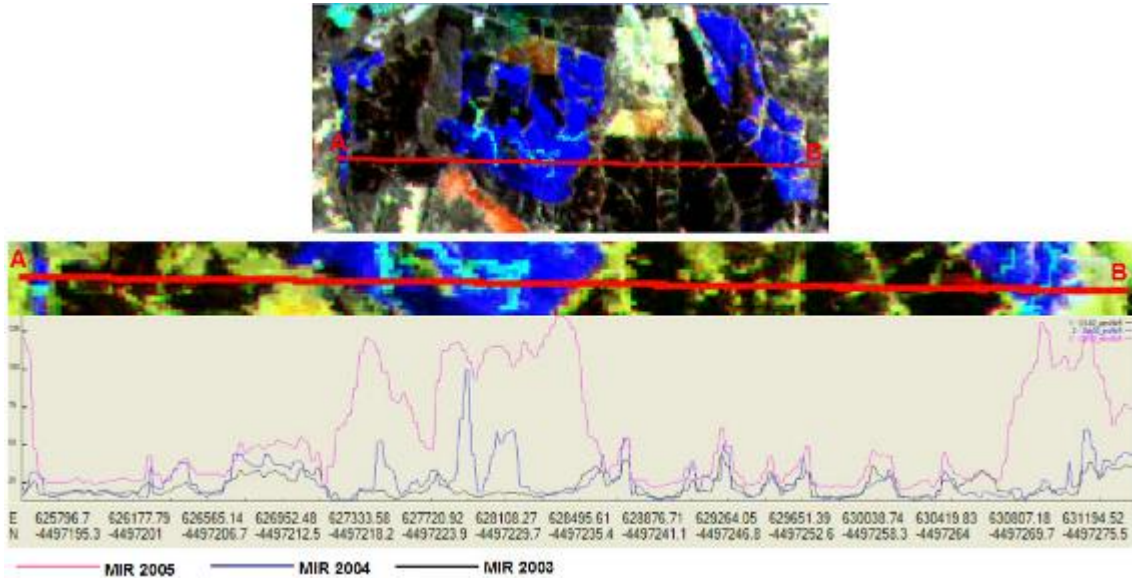


Plate 8: Radiometric transect 2003-04-05 in MIR on the transect n°8 (nb: the colors of the transect do not match the colors of dynamic legend)

Towards a spectro-spatial generalization

The dynamic interpretation grid encourages the reading of the diachronic colored compositions in **Plate 7 (Table 2)**. The method, the choice of wavelength and the color rendering are thus closely related to environmental dynamics.

Each color reflects the alternation between the forested/deforested zones and vice versa. Black and grey/white correspond to stable states. Wooded surfaces thus correspond to exotic plantations as well as to native forest. Deforested surfaces are clustered around grasslands, barren soil and clearcut zones.

Color on screen	Date 1 (R)	Date 2 (G)	Date 3 (B)	Interpretation
Red				Deforested at Date 1, forested at Date 2
Green				Deforested Date 2, forested Date 3
Blue				Deforested Date 3
Yellow				Deforested Date 1 and 2, forested Date 3
Magenta				Deforested between Date 2 and Date 3
Cyan				Forested Date 1, deforested Date 2 et 3
Black				Forested, stable
Gris/White				Deforested, stable

Table 2: Dynamic interpretation grid

Thus, the individualized and noticeable solid colors in each colored composition in **Plate 7** are vectored and specify the alternation of forested/date and deforested/date. With this method each of

these dynamics can be grouped together (**Plate 9**) and quantified (**Table 3**) along an extended temporal gradient.

4. RESULTS AND DISCUSSION

4.1. Multi-date and multi-spectral analysis

This type of diagram concentrates spectral information over the entire period of 1976-2008 and can thus give a global vision of temporal dynamics. It furnishes a complementary element to the reading of dates.

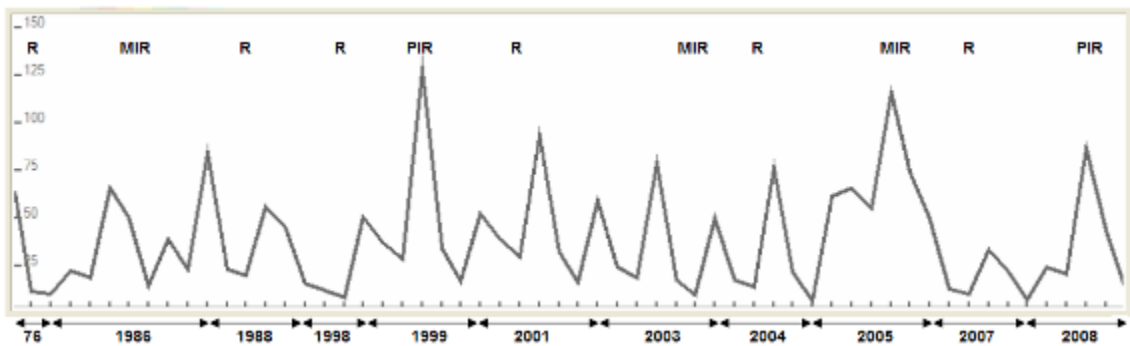


Figure 1: Diagram of the 58 radiometric values. Chronological indication Red, PIR and MIR. Transect n°8

4.2. Rotation monitoring and distinction of species

Though the colored compositions (**Plate 7**) clearly emphasize landscape transformations that can be used in the description of forest types (native, matorral, plantation) and their evolution (cutting, reforestation), they show no distinction between plantations of pine and eucalyptus.

In each of the colored compositions, the solid colors corresponding to the dynamic grid are manually vectorized. All of these colored temporal vectors are thus compiled and superimposed on a chosen colored composition, as can be seen in **Plate 9** below. Distinction between exotic species thus becomes possible.

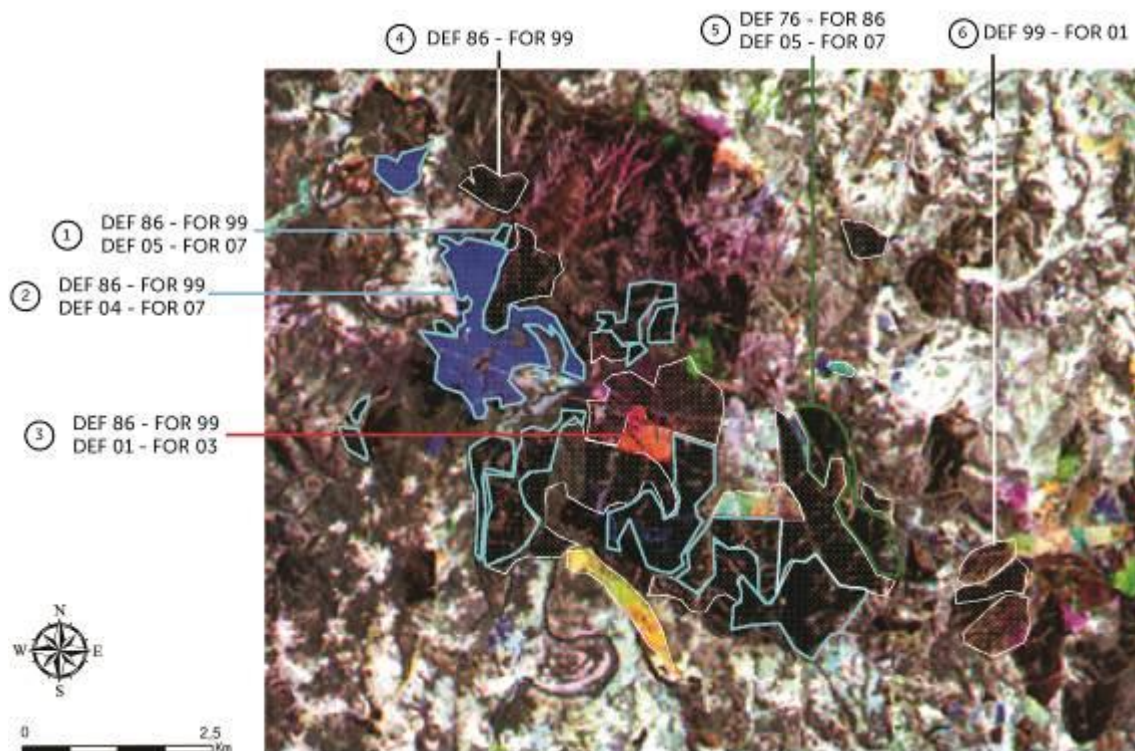


Plate 9: Landsat TM – MIR/ 01-03-04 – transect n°8; summary of results. DEF: deforested / FOR: forested

The forest rotations on plots 1, 2, 3 and 5 (cyan contours) are perceptible via their frequency and the alternation “forested/deforested” on four dates, whereas they cannot be identified on plots 4 and 6 (white contours) due to an alternation too reduced in time.

Plots 1 and 2, reforested in 2007, correspond to eucalyptus as the rotation is of 6 years for the first plantation (1999-2005) and 5 years for the second (1999-2005), in conformity with the forestry schema presented by GELDRES *et al.* (2004, p.58) that takes into account the 18-month fallow period left between two plantings “so that stump shoots and new growth during this period will indicate which coppices are the healthiest”.

Plot 5 (green contour) corresponds to a pine plantation, though there may be some confusion with eucalyptus. Its rotation is in fact of 19 years (86-05), in accordance with the average rotation of pine. Yet, if the period is subdivided with the rotation duration of eucalyptus (8 years + 18 months) the results are also in agreement (forested in 1986, cut in 1994, reforested in 1996 and cut again in 2004).

Finally, the plantation on plot 3 (red contour) presents an extremely weak rotation duration (2 years). It may have undergone sanitary damage, with the development of parasites (caterpillars, lichens) between 1999 and 2001. The plot was totally clearcut to avoid propagation and then reforested.

The entire set of spatio-temporal dynamics for a given period can also be determined quantitatively (**Table 3**).

Rotation	1	2	3	4	5	6
	d86a99d05a07	d86a99d04a07	d86a99d01a03	d86a99	d76a86d05a07	d99a01
Area (ha)	151.6	219.6	27.7	158.9	82.7	87.7

Tableau 3: Area of forest crop rotation in hectares. Note: d = deforested and a = afforested

4.3. Generalization on a regional scale

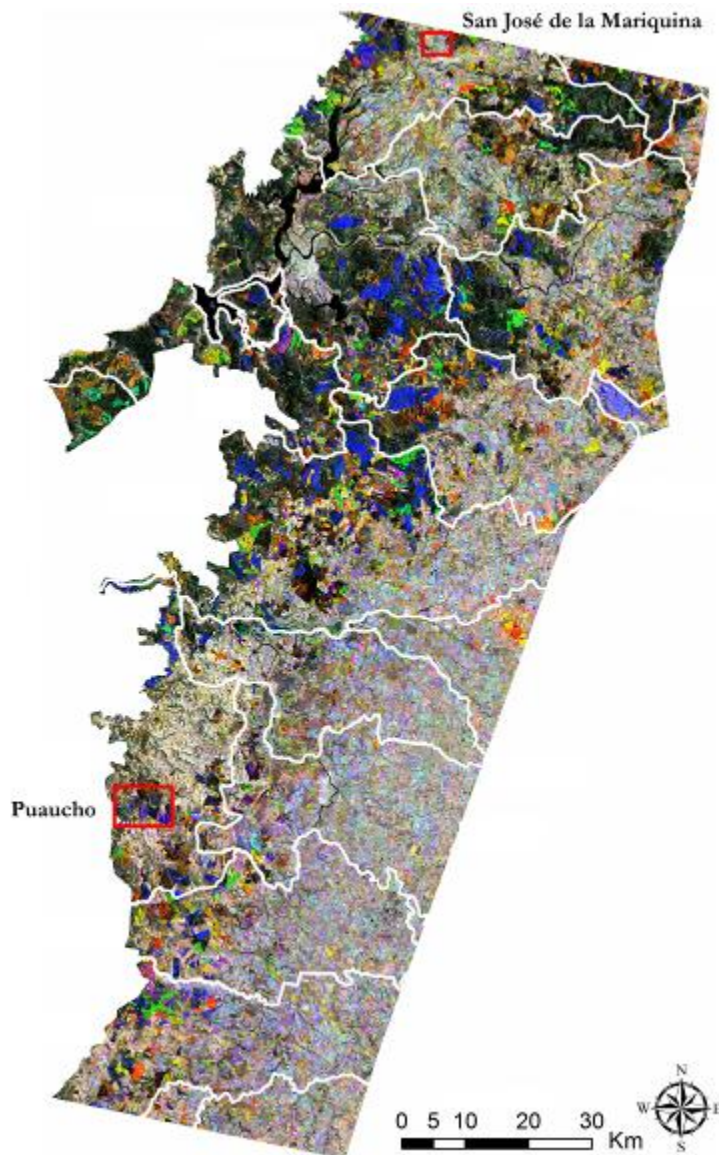


Plate 10: Multi-temporal color composition (MIR 5 channels: R-99/V-01/B-08)

Using the results obtained at Puaucho, **Plate 10** gives us a spatio-temporal reading which can be compared to interpretations on the regional scale, with plantations clearly concentrated in the west (coastal foothills) facing a little noticed Intermediate Depression, with the exception of the communities of *Los Lagos* and *Paillaco* (14th Region).

Though plantations affect the entire foothill area, they are concentrated essentially to the south and east of Valdivia, to the east of Paillaco, to the north of La Unión and in the township of Corral, which is to say the townships of the 14th Region. The plantations in the townships of the 10th Region, however, are diffuse but less extensive.

This method tends to prove the existence of a north-south gradient of methodical implantation of new exotic forests.

5. CONCLUSION

Our objective, both methodologically and operationally, has been to spectrally describe the entire process of extension of exotic tree plantations in southern Chile by means of a radiometric model that can be reiterated in both time and space. Operationally, this consisted of cross referencing a body of environmental and biogeographic information that integrates the impact of human works on 333 sets of field data acquired over a period of several years (collected on the ground as well as via aerial transects), and of interpreting their spectral reflections on 13 Landsat and Spot images covering a period of 32 years, from 1976 to 2008.

This cross referencing and interpretation gave insight into and enabled automatic detection of plantations of pine and eucalyptus, the crop rotation of these species and their management. Let us note that this phenomenon developed extensively to the south of Santiago de Chili and dates from Decree-Law 701, enacted by the president and dictator Pinochet as of 1974.

The originality of the method is found in the fact that it is based on the creation of specific and multi-dated colored compositions, focusing on spectral information relative to Red and Mid-Infrarouge wavelengths. Some of the colors resulting from these choices of wavelength appear recurrently. They are decoded by means of a dynamic interpretation grid resulting from the fusion of field data and specific spectral compositions and reveal the very close relations they have with the growth cycle or the crop rotations of exotic plantations.

This experimentation is being tested on several spatial scales, from the local to the regional, and on several temporal scales, with identical results. The method also enables perception, geolocalization, quantification and the cartography of environmental forest dynamics.

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