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Remote Sensing to Detect and Monitor Trees in Various Environments: Case Studies in Chile

Guido Staub

Abstract

Today, the presence of green areas in cities plays an important role for the well-being of its inhabitants and its sustainable development. Modern cities need green spaces for environmental, psychological, esthetic, economic, and social reasons. In this meaning, Chilean cities, although Chile is still considered by the United Nations[1] as a developing economy, are no exception. Given the importance of this common good, it is necessary to optimize its permanent care. An incident factor in the deterioration of vegetation in urban and rural areas is stress, which can be of biotic or abiotic origin. One way to systematize care of trees is by the application of multispectral sensors and modern digital image processing. Once plantations or trees are spectrally characterized, one can proceed to develop plant health mitigation programs. This article shows the potential of remote sensing for tree stress detection, in the central south of Chile. Focus is given on rural areas as forestry for the Chilean economy is of great importance. These approaches can easily be adapted to urban scenarios.

Keywords: trees, stress, remote sensing, image processing, rural, Chile

1. Introduction

Public open green spaces, urban and national parks, playgrounds, plazas, and even trees, grass, and shrubs on sidewalks or elsewhere, are important elements meant for recreation or to enhance the esthetic appeal of a neighborhood. So does vegetation planted or loosely installed on rooftops. A couple of particular benefits can be identified in this context. Not only green infrastructure helps to mitigate the urban heat island effect by filtering air and reducing runoff but also contribute to a couple of economical and environmental benefits. A study of low-income

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[1] http://www.un.org/en/development/desa/policy/wesp/wesp_current/2014wesp_country_classification.pdf

Philadelphia neighborhoods published in [1] shows that newly planted trees boosted sale prices of nearby houses by 2%. Parks and green spaces, accessible by public, which include protected natural lands, ecological reserves, wetlands, and other green areas are critical to provide healthy habitats for humans, wildlife, and plants. The preservation of regional ecosystems is crucial for natural landscapes in a time cities tend to grow faster and faster.

Furthermore, some important health benefits such as better perceived general health, reduced stress levels, reduced depression, associated with access to public open space and parks, such as the Central Park in New York, USA (**Figure 1**), have been discovered. The World Health Organization (WHO) stated out that major public health risk is caused by physical inactivity during a prolonged period of time. In general, citizens or visitors of public green spaces prefer spaces that are highly attractive (e.g. due to high level of diversity), widely open, and in their nearby vicinity, see [2].

To grant access to green spaces and parks, for example, trail networks can be generated to link cities with parks or individual parks between each other. City parks can be made accessible through bikeways or even old rail tracks that can be transformed into greenways.

On the one hand and according to [3], in Chile, there are about 1.5 million hectares of plantations of *Pinus radiata* D. Don whose main use is commercial. Especially, the Chilean central south is considered as the most important region for the commercial forestry sector nationwide as climate conditions favor tree growth. The national forest institute INFOR indicates that only between the region Maule and Aysén, there are approximately 1.4 million hectares of *P. radiata*, both ponderosa as radiata, equivalent to 95% of the *P. radiata* trees planted across the country.

On the other hand, Chilean national parks and nature reserves play a fundamental role. In Chile, there are 36 national parks, 49 nature reserves, and 16 nature monuments. Fifty-eight (over 50%) of them are located in the central south. Flora and fauna are protected by law and its sustainable conservation is of public interest.

Figure 1. Urban public green space Central Park, New York, United States of America (https://de.wikipedia.org/wiki/Central_Park#/media/File:New_York_City-Manhattan-Central_Park_(gentry).Jpg).

In Chile, current pest and damage monitoring is mainly realized outdoors by specially trained personnel in order to detect symptoms and damages. The method used is based on polls or surveys that involve the visual inspection of trees in areas under threat and already affected areas, as described in [4]. It is necessary to have a tool or develop a methodology, that allows the detection of any disease in time and to take appropriate measures.

Our natural environment is changing constantly. It may be that these changes are natural (season of year, climate and weather, etc.), caused by human beings (construction, agriculture, etc.), or a combination of both. Today more than ever exists the necessity to understand natural processes and manage carefully the human activities. However, to carry out and establish a complex monitoring and analysis system of nature-human interaction, geospatial information is required. This information is generated based on observations that have been transformed into data, which finally is processed, thus achieving to extract what is particularly required, as for example, the physical state of nature. The observations can be acquired in different ways either through direct measurements, where the instrument must be in the same place where the object is located, or through remote measurements, the instrument is located at a considerable distance from the object and does not have physical contact with it.

According to [5], stress in nature can be defined as an external factor coming from any source that has a negative influence on a plant. It differs between biotic factors by the intervention of other living beings and abiotic, which are of a physical and/or chemical nature. The extent to which stress affects a plant is determined through measuring the survival of the plant, the crop yield, growth, or primary assimilation processes.

Detecting stress in plants is not a straightforward task. While on-site inspection by experienced professionals in the area can identify high-damaged trees or plants very accurately, the time required for inspecting larger areas is the most limiting factor for such a task. Through methods such as remote sensing, it is possible to study large surfaces in a much shorter time and with a high degree of reliability. Particularly, it is necessary to study certain plant characteristics such as visible symptoms of damage in the cup of trees and branches structure or properties associated with the reflection of electromagnetic energy coming from solar lighting.

2. Remote sensing

Remote sensing as defined by [6–8] and others, which includes a huge variety of procedures that allows to derive information about our environment, is based on the observation realized by a sensor located at a large distance (without having physical contact with the objects) of the reflected and/or emitted electromagnetic radiation. So, the goal is to capture the degree of interaction between electromagnetic energy and the objects with which it comes into contact. This way, it is possible to determine the degree of reflection and absorption of electromagnetic energy by any kind of object, whether it is natural or artificial.

One has to distinguish between two types of observing systems: active and passive sensor systems (**Figure 2**). The main difference between these systems is the source of the electromagnetic radiation emitted, which finally enters in contact with the objects.
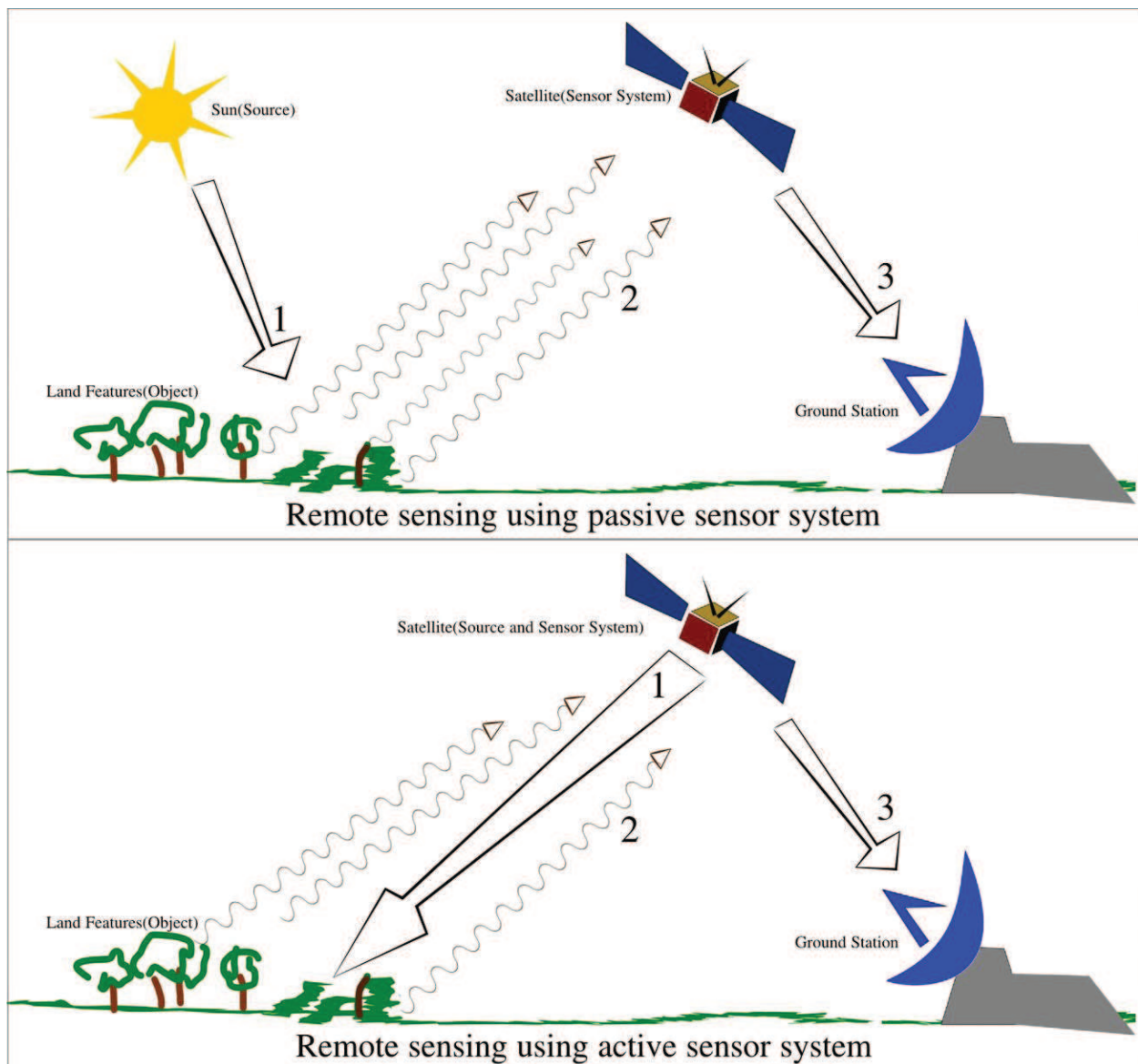
Figure 2. Principle of active and passive remote sensing sensors (adapted from https://en.wikipedia.org/wiki/Remote_sensing#/media/File:Remote_Sensing_Illustration.jpg).

The electromagnetic spectrum is formed by the energy distribution of the radiant energy according to its wave length λ and extends from gamma rays (shorter wavelength) until radio frequency (longer wavelength). However, remote sensing systems tend to make use of specific intervals within the electromagnetic spectrum, basically the visible, infrared, and microwave spectra **Figure 3**. This relies on the fact that within these spectra, atmospheric windows can be observed in which the transmission of the electromagnetic radiation is not altered by absorption and distortion.

The most relevant in the field of remote sensing are:

• Visible spectrum ($\lambda = 0.38$–0.78 μm).
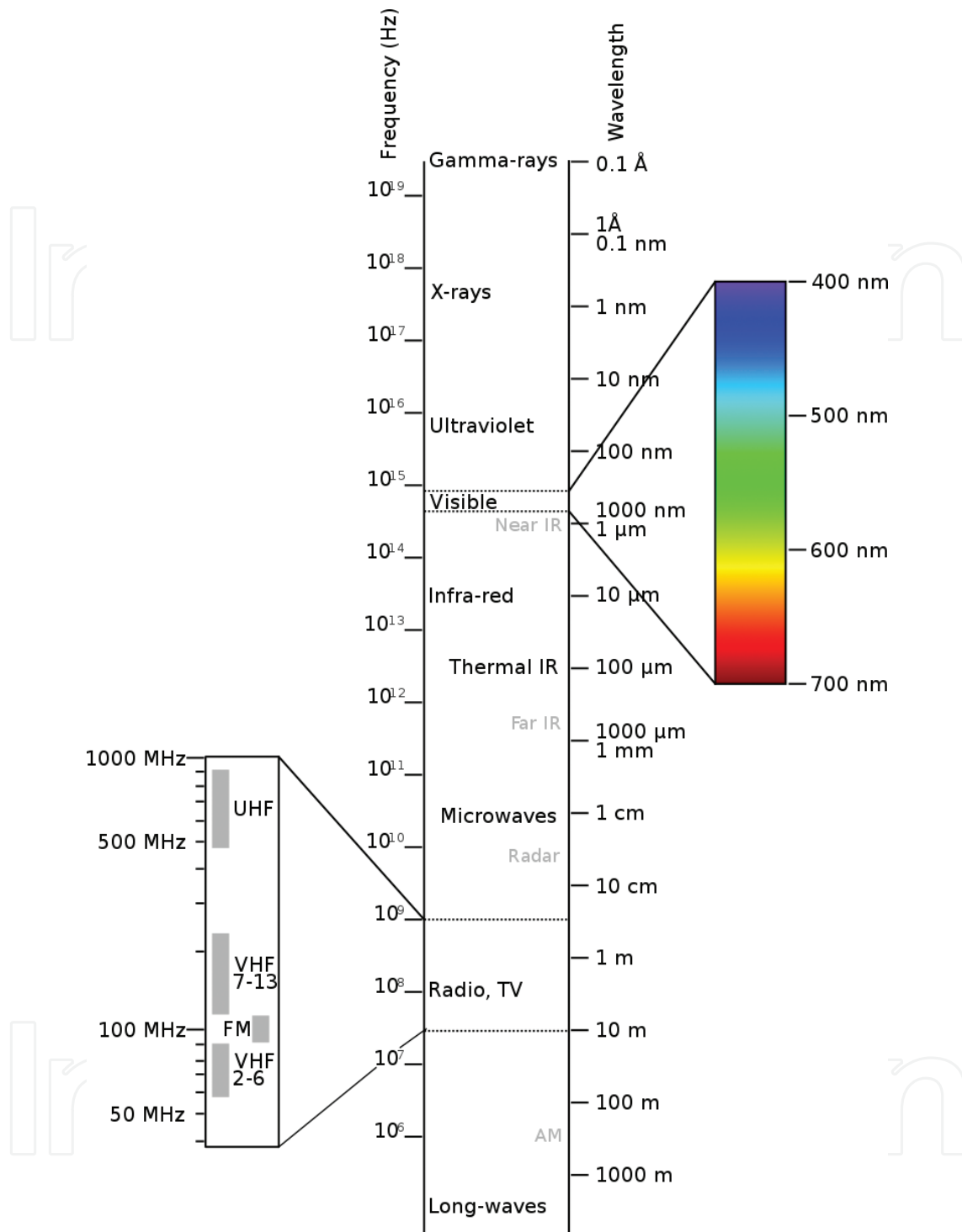
• Near infrared ($\lambda = 0.78$–3.0 μm).

Figure 3. Electromagnetic spectrum (adapted from: https://en.wikipedia.org/wiki/Electromagnetic_spectrum#/media/File:Electromagnetic-Spectrum.svg).

- Short-wave infrared (λ = 3.0–50 μm).

- Thermal infrared (λ = 50–1 mm).

- Microwaves (λ = 1 mm–1 m).

2.1. Vegetation study based on remote sensing techniques

One of the most outstanding features of the majority of all remote sensing sensors is that they allow carrying out scientific studies on vegetation due to observations made not only in the visible but also in the infrared spectrum. This is where the magnitude of reflection is highly correlated with the amount of biomass, which is intact in the plants. In simple words, this phenomenon can be explained as the greater the degree of energy absorption in the near infrared, the lower the amount of active biomass and vice versa. More healthy vegetation shows less reflection in the visible spectrum.

The spectral plant characteristics relate to the photosynthetic activity of the pigments and the water stored in the leaves. The low degree of reflection in the visible spectrum is due to the absorbing effect of leaf pigments, mainly chlorophyll b, phycoerythrin, and phycocyanin, see **Figure 4**. However, there is a specific range in the spectrum in which absorption of electromagnetic energy is almost zero. Around 525 nm, which is located at the green band, the leaves have a high degree of reflection, which causes the human eyes to see the vegetation in this color.

Having knowledge of this theoretical background, it is possible to realize scientific studies on vegetation and their health. For example, through the normalized difference vegetation index (NDVI), it is possible to calculate the degree of active biomass in vegetation, considering the intensity of the reflection and emission of radiation in certain bands of the electromagnetic spectrum. This can be correlated to health and growth of a plant. The NDVI is calculated as follow:

$$NDVI = (NIR - R)/(NIR + R)$$

where NIR is the near infrared and R is the red band of a specific sensor.

An example is shown in **Figure 3**, which shows the result of calculating the NDVI for the Biobío region during second half of December 2014. Possible values for the NDVI range between −1.0 and +1.0. In this context, it was standardized so that a zero value indicates the absence of vegetation while values higher than 0.5 indicate little or sick vegetation. Values superior to 0.7 represent areas where vegetation is vigorous and healthy.

2.2. Systems for tree stress detection based on imagery

In countries like the USA, Canada, Australia, Germany, and Brazil described in [9–13], various techniques for forest monitoring were successfully implemented in the past. The possibility to derive the health of forest plantation through observations acquired by remote sensors has been demonstrated repeatedly, as in [14]. There are also examples of the proof of both the use of aerial photographs and satellite images. In Australia, aerial photographs were used for the detection of forest decline in native eucalyptus trees. Some of the most important aspects described by [15] considered during the planning and implementation of monitoring were that photographs should be acquired during a cloudy day to ensure a better view of the undergrowth and to avoid very likely pronounced reflectance, which could jeopardize the interpretation of the data. In addition, it requires a monitoring system available anytime that takes advantage of weather conditions, favorable for imaging. In China, since 1992, a
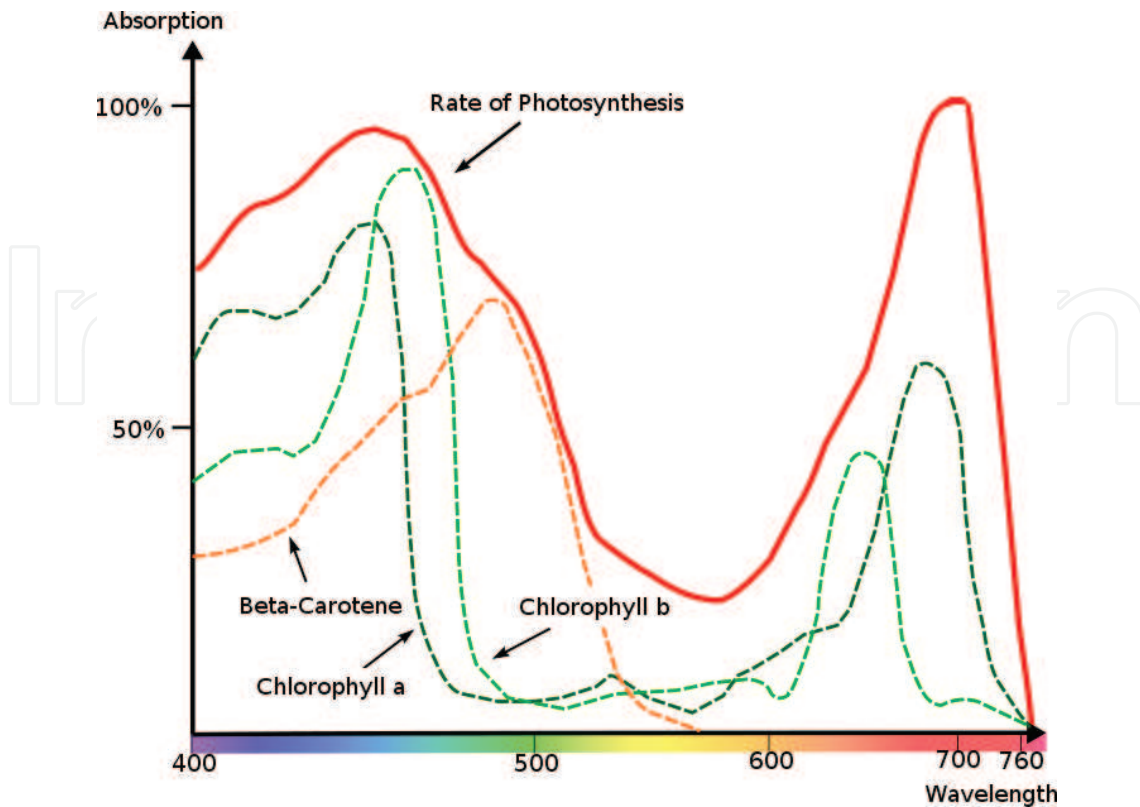
Figure 4. Leaves absorbing light at different wavelengths (adapted from https://de.wikipedia.org/wiki/Photosynthese#/media/File:Engelmannscher_Bakterienversuch.svg).

project funded by United Nations Development Program (UNDP) has been developed with the objective to establish a monitoring system consisting of an airborne video camera for sketchmapping, color infrared (CIR) digital camera, and a geographic information system, according to [14]. In Germany, and according to [12], it established a permanent monitoring program with archived observations since 1983 through satellite imagery (Landsat TM), CIR aerial images, and an airborne multispectral scanner. The image scale that was used in most cases was between 1:5000 and 1:6000, according to [16]. However, the tree classification and ground truthing was carried out in-situ.

For urban areas, it is possible to think of similar systems and solutions. Remote sensing systems, which in the past have already been successfully used in monitoring and detection of rural forest damage, can be adopted to monitor vegetation, and in particular trees, in cities although there is no coverage of large areas with a single species. For ornamental species, a higher ground sampling distance (GSD) needs to be considered beside a hyperspectral system. Therefore, a satellite-based approach should not be chosen, but rather opt for a different platform such as a drone equipped with an appropriate hyperspectral sensor. This way, it will be possible to study and detect individual trees and take appropriate measures that already have been checked and approved by the governmental authorities such as the Chilean Agricultural and Livestock Service Servicio Agricultura y Ganadero (SAG). Ref. [17] presented a review of latest advances made in recent years in both the technological part and with respect to the processing of hyperspectral observations in the field of urban forests. Typical applications

include mapping of surfaces covered with trees, transport network planning, studying urban heat islands, and measurement of vegetation stress, etc. However, since [18] published the need for continuous monitoring of the urban forest, few solutions were proposed. For example, [19] discuss different geospatial solutions and techniques, including GIS, remote sensing, and global positioning system (GPS). The combination of these tools allows collection of reliable forest information at different scales. [20] presented an approach based on hyperspectral imagery to classify urban tree species. In order to improve the reliability of the classification results, it is also proposed to use various techniques such as principal component analysis, indexes, and statistics. This way they managed to identify 91.4% of the species present in a sample consisting of a total of 500 urban trees. To date, there are very few operational systems. One of the most advanced systems is the one proposed by [21]. This work not only presents a discussion with respect to the platform but also with respect to the sensor. The conclusion indicates that the ideal system to detect and monitor stress in plants consists of a combination of an unmanned aerial platform, a hyperspectral sensor, and a couple of simulation tools.

The following five case studies, all related to tree stress, show the actual situation in the Chilean central south, see **Figure 5**. Stress caused by climate, insects, weeds, and even volcanic eruptions often affect trees in the Chilean central south. Satellite images help to detect them at almost real time and by the calculation of geospatial statistics and indices, which furthermore make it possible to quantify tree health.
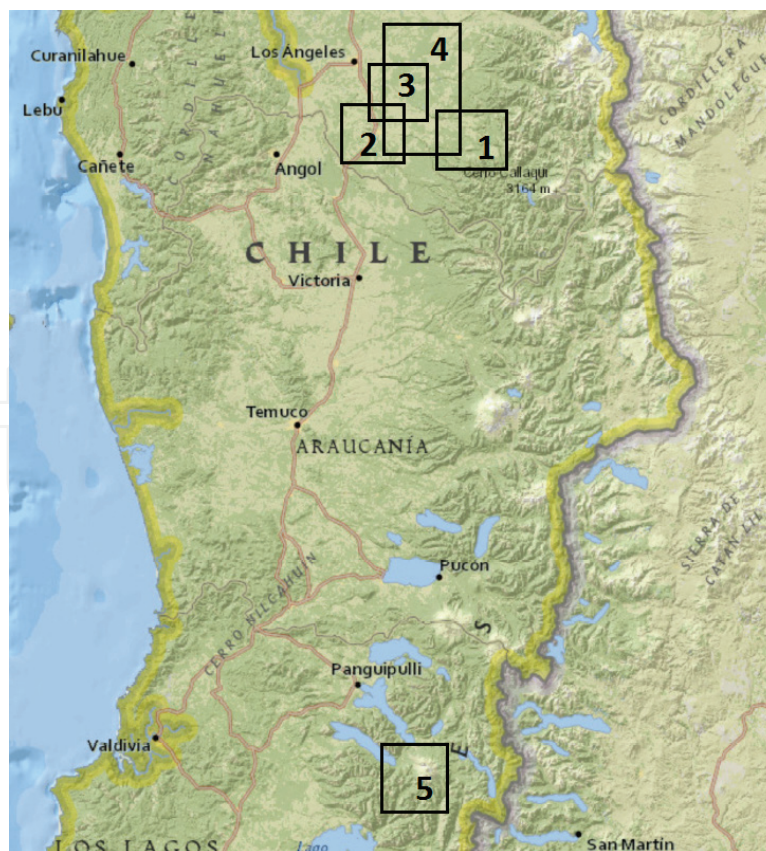

Figure 5. Case study locations in the central south of Chile (adapted from: http://www.geoportal.cl/Visor/).

3. Pine plantations affected by Sirex woodwasp

3.1. Background

During the last decades *Sirex noctilio* Fabricius, 1773, a Hymenoptera of the Siricidae family, which is composed of more than 40 species of wasps, has produced extensive damage worldwide in forest plantations of *Pinus radiata* D. Don and its different subfamilies. This damage can lead to death of the infected tree, in almost 80% of the cases observed worldwide. Although, its origin is in Europe, Siberia, and Mongolia, due to exportation of wood, dispersion of the wood wasp was uncontrollable and today it is present in Australia, New Zealand, South Africa, and South America. In Chile, it is present since 2001. Several municipalities in the Maule, Biobío, La Araucanía, Los Ríos, Los Lagos, and Aysen region are under quarantine and the Agriculture and Livestock Service is forced permanently to establish new quarantine areas. Furthermore, in the Biobío and Maule region, the Agriculture and Livestock Service has established phytosanitary measures to get control over the plague. First, a biological control program against *S. Noctilio* was established. A complex of specific natural enemies is created in laboratory and released in the affected plantations. The second action consists in the control of wood transport from quarantined areas to other areas that might be endangered.

The main objective of this case study was to identify a suitable and reproducible methodology to timely detect *S. Noctilio* infections. Such a methodology can be very helpful when it comes to monitor large pine plantations, which are difficult to access.

3.2. Methodology

The study area is located in the commune of Quilaco, Biobío region (**Figure 6**) and comprises approximately 1800 km², and almost 70% is currently affected by *S. noctilio*. Therefore, it has been declared that quarantine area with a radius of 20 km for locations might be affected by *S. noctilio*.
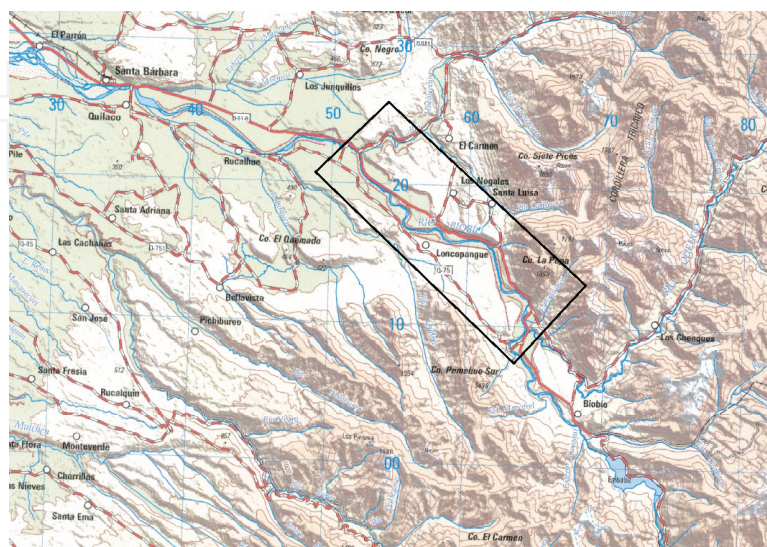

Figure 6. Study area where *S. Noctilio* has been detected (adapted from: http://www.geoportal.cl/Visor/).
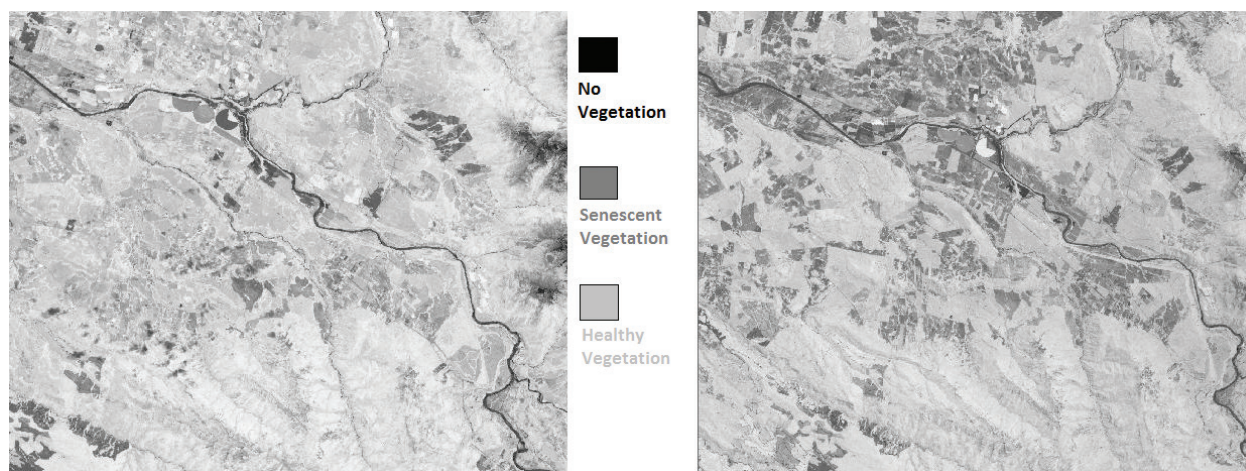
Figure 7. NDVI comparison 2010–2011.

Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) satellite images taken on November 2010 and February 2011 were used in this study. NDVI calculations were carried out to detect variations in time in photosynthetic activities of pine trees.

3.3. Results and conclusions

The results indicate that in the study area, certain sectors show a significant decline in photosynthetic activity during summer period of 2010 and 2011, a fact that was verified by both, calculating the NDVI, see **Figure 7**, and information provided by the Agricultural and Livestock Service. Based on an initial study of one of these specific sectors, identified by the Agriculture and Livestock Service in 2011 as a new outbreak of *S. noctilio*, it was possible to conclude that the photosynthetic activity decreased in the study area during a period of time of 4 months (November 2010–February 2011). In a second sector, photosynthetic activity also decreased during the same period, but it was not possible to clearly determine its cause because the Agricultural and Livestock Service had not declared this sector infested by *S. noctilio*. Nevertheless, it is important to highlight that an attack by *S. noctilio* was likely for two reasons. First, the index of normalized difference vegetation was 0.624 in 2011, which in comparison to the other sector is only 9% higher. And second, in the nearby area (within the range of natural displacement capability of *S. noctilio*), two outbreaks of *S. noctilio* already had been registered.

So, due to the rapid development of the forest pest, it was possible to detect changes in photosynthetic activity of the vegetation as well as areas of new infections.

4. Weed detection in eucalyptus plantations

4.1. Background

Early weed control for forest plantations is a recurrent, fundamental, and critical activity that has to be carried out by any forestry company. It must be conducted applying serious strategies, correct treatment times, and reasonable application of herbicide. This control must be

variable and flexible in time and magnitude, as on the one hand weed emerges in spring and summer months due to soil moisture left by the winter and on the other hand, weed growth augments with higher temperatures and daylight hours. Therefore, and due to the fact that in Chile approximately 500,000 ha are forest plantations, it is of great importance to count with a control system to manage lots of very complex geospatial information.

4.2. Methodology

In order to particularize the problem and transform it into local scale, Forestal Mininco S.A., a Chilean company dedicated to timber production, plants and seeds, is constantly working on automation processes and efficient management of huge volume of geoinformation generated during weed control activities. It is expected that financial and human resources can be optimized, by assigning certain levels of priority to plantations with high potentials to be damaged by weed during spring and summer period.

The main objective of this case study is to quantify the area affected by weed within the forest plantation denominated Fundo Porvenir, located between Mulchén and Collipulli in the Biobío region, see **Figure 8**. Almost 400 ha of different species of eucalyptus, such as *E. globulus* Labill., *E. nitens* H. Deane & Maiden, and *E. saligna* SM. can be found in the study area.

SPOT-6 high resolution satellite images, see **Figure 9**, were acquired because of their ground sampling distance and capacity to make observations in the infrared band of the electromagnetic spectrum. These two properties allow detecting small vegetation species, such as weed.
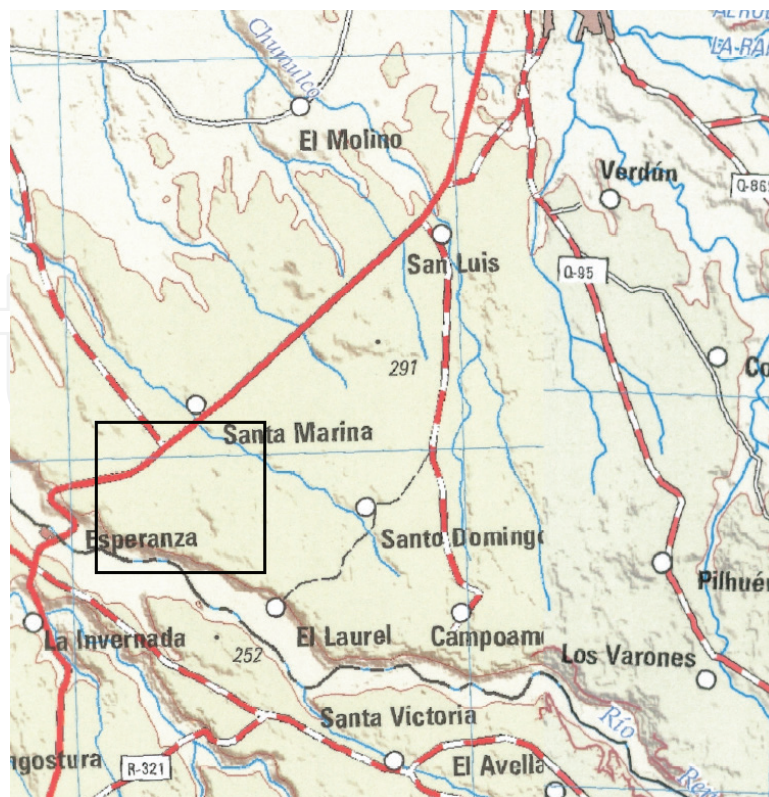

Figure 8. Study area with eucalyptus plantations (adapted from: http://www.geoportal.cl/Visor/).
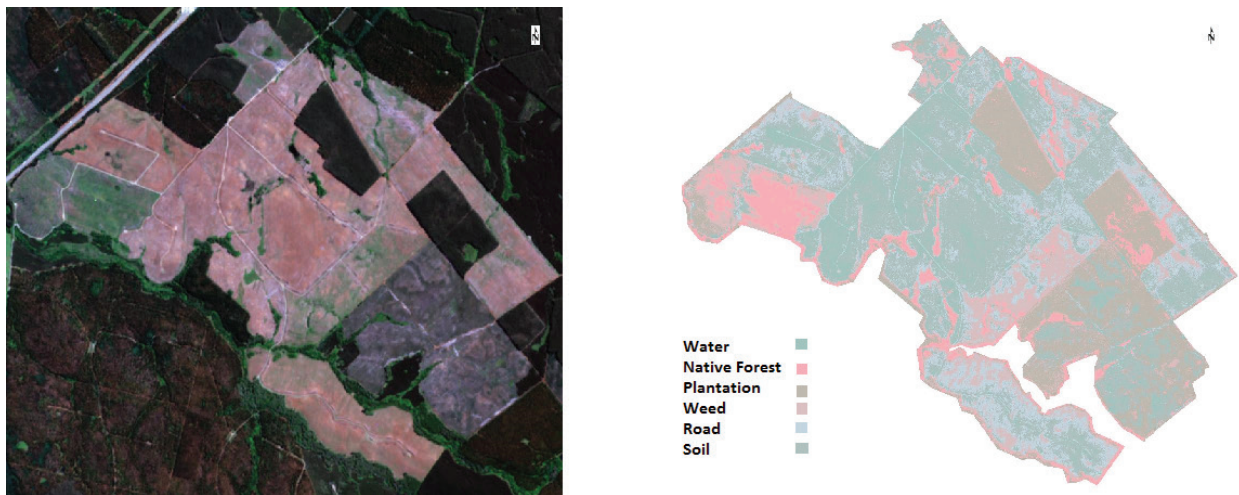
Figure 9. SPOT 6 image and result of supervised classification.

The most convenient date to select the image acquisition is closely coupled with the type of phenomenon that has to be studied according to [22]. So, image acquisition was during the last days of October.

First of all, a visible inspection of both, satellite image and terrain, for training site definition and subsequent ground truthing of the classification results, **Figure 9**, was carried out. Supervised classification was statistically analyzed using confusion matrix and Cohen's Kappa statistic.

4.3. Results and conclusions

Figure 9 shows the original SPOT 6 satellite image and the result of the supervised classification.

Table 1 summarizes information gathered regarding surface, species, area occupied by weeds, and the respective occupancy rate in the specific sectors (S1–S6), see **Figure 10**. Based on these percentages, control priority levels were established.

Name (Tree species)	Total [Ha]	Undergrowth [Ha]	Occupation %	Priority
S1 (*Eucalyptus nitens*)	46.2	28.7	62.1	1
S2 (*Eucalyptus nitens*)	35.9	18.6	51.8	2
S3 (*Eucalyptus nitens*)	48.3	15.7	32.5	3
S4 (*Eucalyptus nitens*)	66.2	19.3	29.2	4
S5 (*Eucalyptus globulos*)	193.7	26.4	13.6	5
S6 (Eucalyptus Smith)	24.3	2.1	8.6	6
Countryside Porvenir	414.6	110.8	26.7	

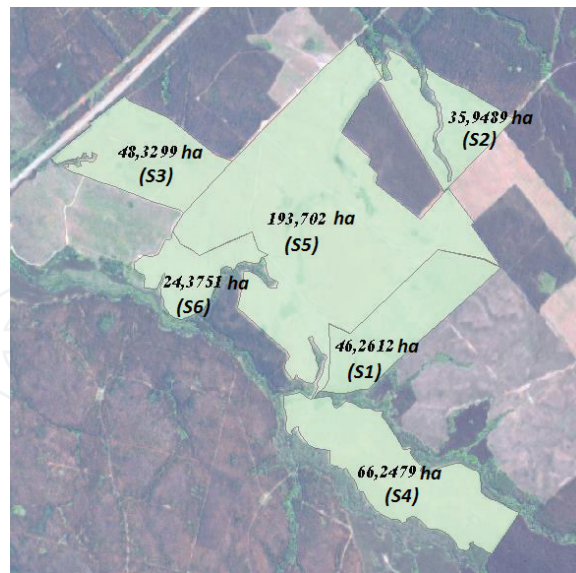**Table 1.** Undergrowth in forest plantation.

Figure 10. Specific sectors S1–S6.

Quality assessment based on field work, to compare classification results and vegetation found in the study area, provides the confusion matrix of the supervised classification. The result indicates that with 95% probability, the overall accuracy is 82%. The reliability to classify weed is about 90%. The results are shown in **Table 2**.

The Kappa statistic indicates that the classification is 76% better than expected to do so randomly. Field verification for 100% coverage was found.

As a direct conclusion, which can be drawn from the results, sector 1 (*Eucalyptus nitens* Sur 1) occupancy rate of 62% has to be treated first and with urgency. Sector 2 (*Eucalyptus nitens* Este)

	Water	Native forest	Plantation	Weed	Road	Soil	Total	Consumer's accuracy (%)
Water	20	0	0	0	0	5	25	80
Native forest	0	22	0	0	0	5	27	81
Plantation	0	0	35	0	0	1	36	97
Weed	0	0	2	37	0	0	39	94.9
Road	0	0	0	4	6	29	39	15.4
Soil	0	0	0	0	0	90	90	100
Total	20	22	37	41	6	130		
Producer's accuracy	100%	100%	94.6%	90.2%	100%	69.2%		
Overall accuracy: 82%								

Table 2. Confusion matrix of supervised classification.

with an occupancy rate of 52% also can be considered as critical. Occupation rate in all the other sectors is less alarming.

Nevertheless, it is recommendable to develop sustainable strategies, which allow weed control in order to guarantee tree growth and reduce tree death. As death of trees may imply considerable economic losses, it is even more important to count with relevant information. Satellite imagery and image processing can be used for trustworthy studies on weed growth and its extension.

5. Tree growth monitoring

5.1. Background

As mentioned by [23], in the Biobío region, forestry is one of the main economic activities. So, it has become necessary to perform serious analysis of growth in each plantation to have a record about its past and present development. In general, this task is poorly realized by a couple of experts employed by the forestry companies. Time and available financial resources are the two main limiting factors and therefore an alternative strategy, which allows reliable information generation that has to be envisaged in the near future.

5.2. Methodology

The area of interest corresponds to a part of the sector called Verdun of about 154.000 ha, owned by Forestal Mininco S.A., located south west of the city of Mulchén, see **Figure 11**. Plantations of *Eucalyptus globulus* Labill. and *Eucalyptus nitens* H. Deane & Maiden can be found there. The *E. nitens* plantation is under permanent treatment as an experiment for improvement of the species is carried out. It should also be noted that these types of plantations (Eucalyptus) around Mulchén have become the new landscape. For local residents, it is the main source of employment.

Red clay soil is dominant in the study area. Rainy weather during winter and dry during summer period are the main climate characteristics. Furthermore, the river Mulchén limits the area, what guarantees permanent water supply, and in consequence, better growth of the species. The study areas topography is almost plane with the exception of a small hill, which is located in the middle it.

The main objective of this case study was to demonstrate how remote sensing can help to carry out long-term studies on tree growth, in particular, using high resolution satellite imagery, which became more and more accessible during the last decade.

The images used for this study correspond to three aerial photographies with a spatial resolution of 30 cm (2009–2011), a SPOT 5 (2007), a QuickBird satellite image (2008) with spatial resolution of 5 m each, and an image taken from Google Earth, basically for visual image interpretation in 2007.

Beside the visual interpretation, a principal component analysis (PCA) and a RGB to HSV transformation were carried out.
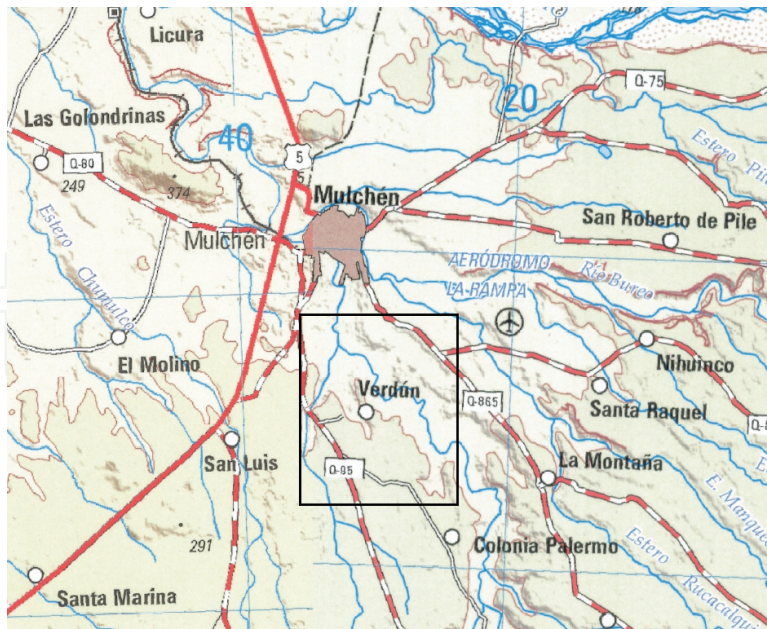
Figure 11. Tree growth monitoring study area (adapted from: http://www.geoportal.cl/Visor/).

5.3. Results and conclusions

With regard to the visual interpretation of the images, it was possible to clearly identify the transition phase between harvesting and reforesting. Horizontal growth of the vegetation cover and the newly planted eucalyptus species has augmented significantly.

The PCA method allows detecting vegetation cover that can be analyzed considering furthermore reflectance and in-situ gathered forest relevant information, such as the stand density. The resulting PCA components 1, 2, and 3 are shown in **Figure 12**. Tree growth can be observed in the first principal component as 98 and 65% of the information that can be found in the aerial photographies and the satellite image, respectively. The development of the eucalyptus plantations in the course of the years became detectable.

Figure 12. PCA components 1, 2, and 3 (left to right) for 2010 image of the study area.
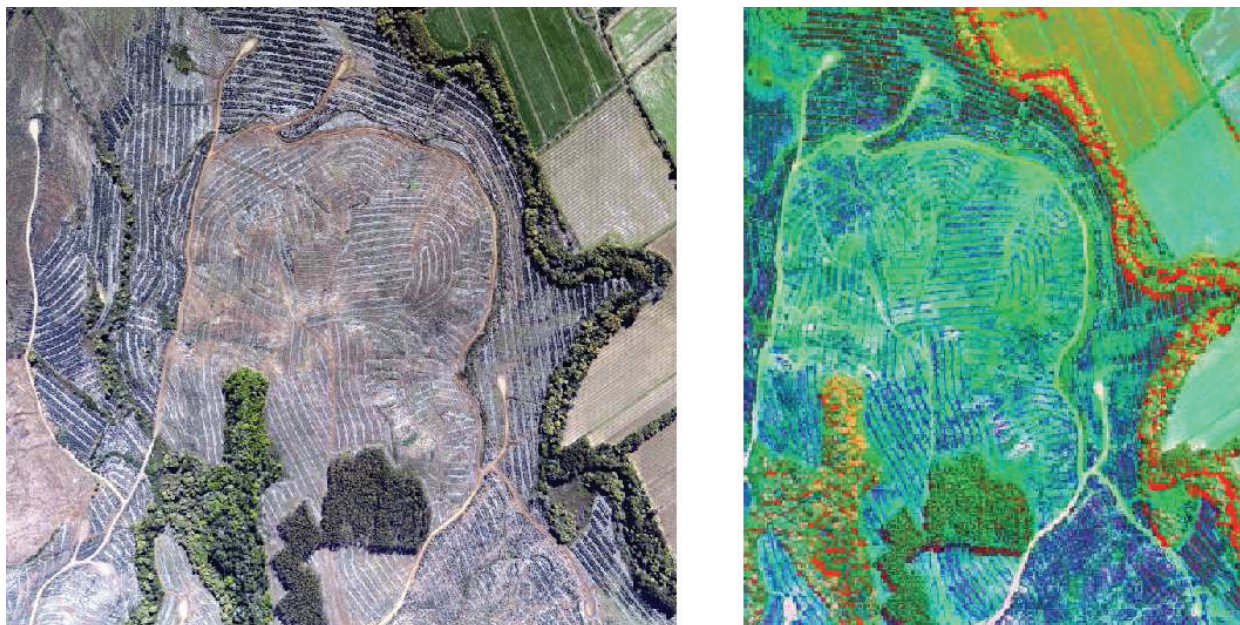
Figure 13. Original 2010 RGB image (left) and transformed IHS image (right).

In case of the RGB to IHS transformation, see **Figure 13**, mainly an estimation of tree growth through the comparison of soil covered by forest with soil covered by other type of vegetation was possible.

In particular, with this type of comparison, it was possible to highlight the importance of influencing factors such as water, soil, and temperature. They are fundamental characteristics for any plantation, which have to be studied. Nowadays, it is possible to make use of high resolution satellite imagery and determine surface characteristics in areas where tree plantations are planned.

6. Water stress detection and analysis in the Andean Precordillera

6.1. Background

The United Nations Organization (UNO) has recognized that desertification is a major problem of economic, social, and environmental concerns that affects many countries from all regions of the world. The United Nations Convention to Combat Desertification (UNCCD) defines desertification as: *land degradation in arid, semi-arid, and dry subhumid regions resulting from various factors, including climatic variations and human activities.* So, [24] indicate that desertification occurs as a result of long-term imbalance between manmade demand for ecosystem services and what ecosystems can provide. As a result of this degradation process, soil loses its fertility and in consequence, its production potential due to the destruction of vegetation cover and water shortages. Often, manmade interventions promote and enhance this process due to inappropriate and excessive activities such as cultivation, overgrazing, and deforestation.

In Chile, about two-thirds of the national territory is affected by soil degradation caused by desertification. The "Preliminary Map of desertification in Chile" prepared by the National

Forestry Corporation (CONAF) in 1999 and published in [25], is the only study of desertification in the country so far. The map, originally considered five principal indicators: erosion, poverty, xerophytism rate, length of the dry period, and a temporal trend indicator. It was concluded that of the 290 rural communes, 270 (93%) had some degree of desertification, of which 76 (27%) were severely affected and 108 (36%) were moderately affected by desertification.

In the central south of the Biobío region, the Biobío province limits the north with the Ñuble province, south to the Araucanía region, east to the Argentine border, and the west with the Arauco province. It is the only one of the four provinces within the Biobío region without coastline. Considering [26], it can be stated that the Biobío region has 353,315 inhabitants and covers an area of 16,226 km^2. According to the preliminary map, which was generated by CONAF in 1999 (the only study on desertification that covers the whole national territory), the Biobío province was classified as moderately affected by desertification.

The main objective of this case study is to quantify desertification process that took place during the last 15 years in the Andean Precordillera.

6.2. Methodology

Based on Landsat 5 and 7 satellite images, of the Andean Precordillera in the Biobio province, see **Figure 14**, preliminary identification of areas vulnerable to desertification were detected by moisture stress index (MSI) calculation. In general, MSI measures the water stress in plants and ranges from 0 to 3 (from excess to lack of water, as found in [27]). The satellite images were captured during March in 2000, 2005, 2010, and 2015. The results were statistically analyzed using the *Pearson* product–moment correlation coefficient, considering precipitation records of four climate observation stations within the study area.
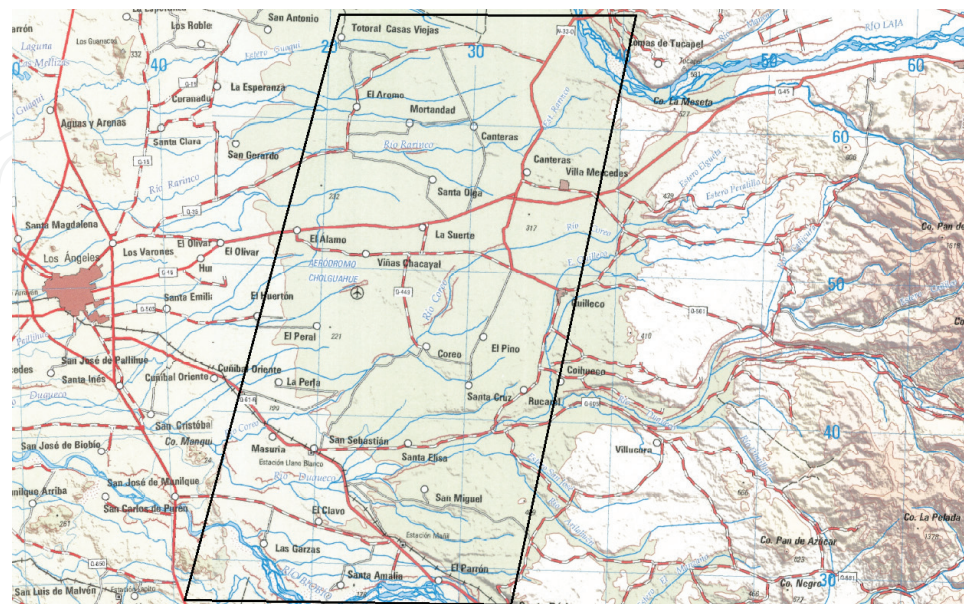

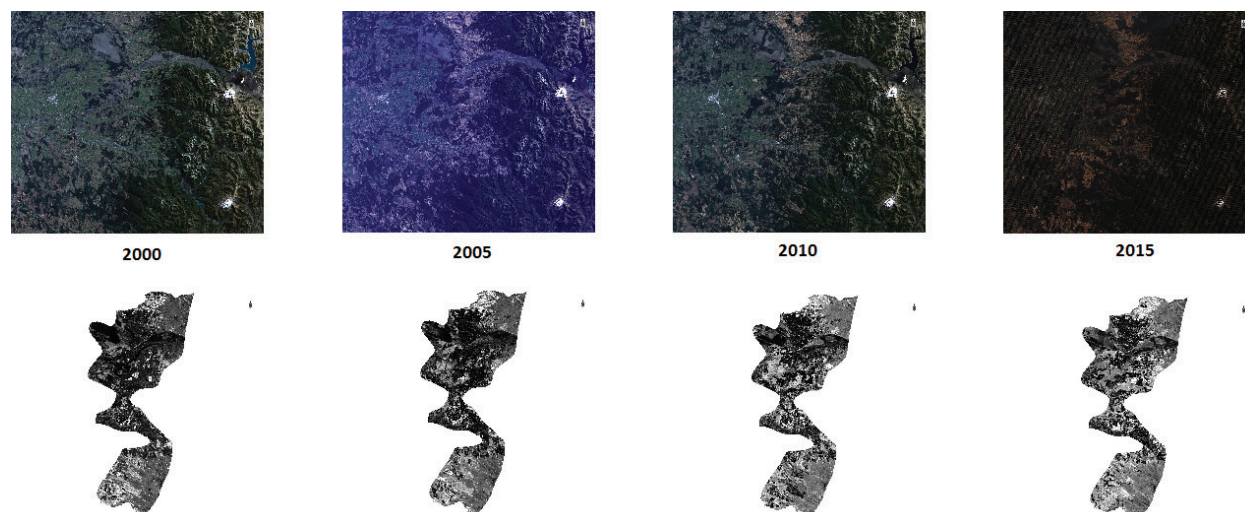**Figure 14.** Andean Precordillera in the Biobío region (adapted from: http://www.geoportal.cl/Visor/).

Figure 15. The original Landsat satellite images and the results of the MSI calculation are shown.

Year	Vulnerable surface (%)	Variation of vulnerable surface (compared to previous year) (%)	Precipitations (mm)
2000	28.50	-	1745.6
2005	36.02	7.52	1644.8
2010	49.36	13.34	1529.7
2015	16.19	−33.18	1792.3

Table 3. Vulnerable surface variation during the last 15 years.

6.3. Results and conclusions

In this particular study, areas vulnerable to desertification were identified where the MSI value did not reach a critical level (below 0.4 or above 2). The study reveals that these areas steadily increased every year except to 2015, due to an increase in rainfall during 2014, which temporally reduced the stress in the vegetation and in consequence led to a negative trend for possible desertification. The original satellite images and the results are shown in **Figure 15** and **Table 3**, respectively.

A negative correlation is observable between surface vulnerable to desertification and precipitation (−0.978). This means that a lack of precipitation leads to an augmentation of areas vulnerable to desertification processes.

At present, 16% of the Andean Precordillera of the Biobío province is vulnerable to desertification, a number that is significantly lower as in 1999 (28.5%). However, it is important to mention that this is something misleading because in the period from 2000 to 2010, a considerable increase of the area vulnerable to desertification can be detected. This means that in 2010, almost half of the Andean Precordillera was affected. The observed decrease in 2015 is due to the increased rainfall in 2014. The surface area vulnerable to desertification that is seen in 2015 decreased considerably in comparison to 2010, but still stays above 16% of the total study area surface.

It can be concluded that desertification is a long-term process, which has to be monitored. Short-term variations can be detected by the use of satellite imagery and image processing. Nevertheless, to identify trends in desertification, precipitation, and temperature records have to be considered within long-term studies.

7. Monitoring of vegetation recuperation after volcanic eruption event

7.1. Background

The emission of gas and ash during the eruption of the Volcanic Complex Puyehue–Cordón Caulle located 83 km northeast of the city of Osorno in the Los Lagos Region, **Figure 16**, in 2011 produced severe damage in the surrounding area of the volcano. For 10 days, an eruptive column with a height of approximately 9 km emerged and affected the Nahuel Huapi area with intense ash fall, at a distance of 100 km northeast of the crater. Furthermore, ash deposits affected flora and fauna in the southeast of the crater for a prolonged time period. Photosynthetic activity of vegetation decreased significantly as volcanic ash deposits affected old growth forest, which is predominant in the National Park Puyehue.

The objective of this case study was to monitor vegetation recovery after volcanic eruption. Of our particular interest, was the quantification of vegetation affected by ash deposits and to determine how and why it recovered.

Figure 16. Volcanic complex Puyehue – Cordón Caulle and area affected by ash fall after 2011 eruption (adapted from: http://www.geoportal.cl/Visor/). And identification of three particular study sites.

7.2. Methodology

Satellite imagery and in-situ data collection are used to carry out a three-step methodology. At first, a visual image interpretation is carried out, based on a visual analysis of Landsat 7 ETM+ satellite imagery acquired in 2011 and 2012. Landsat 7 ETM+ typical band combinations for true and false color visualization (3, 2, 1, 4, 3, 2, 5, 4, 2), according to [28]. The natural color band combination (3, 2, 1), is considered to visualize the landscape as it appears in reality. With the help of band 3, it is possible to discriminate vegetation slopes, band 2 allows assessing vegetation vigor, and band 1 permits to distinguish soil from vegetation. False color combinations such as 4, 3, 2 and 5, 4, 2 are employed to highlight biomass content in plants (band 4) and moisture content in vegetation and soils (band 5).

Second, an analytical image analysis based on NDVI calculation is carried to determine vegetation health and photosynthetic activity potential.

The final step consists of ground truthing of the generated results. Therefore, between the months of January and February 2012, and during December 7 and 8 in 2012, field work was realized to obtain reliable first-hand information about, for example, the percentage of ash-covered/dead/sprouting vegetation within the area of interest.

Three specific sectors were identified inside the Puyehue National Park, where dominating forests are evergreen and different landforms can be observed. They were chosen because they were accessible for research and because reference data for comparison was facilitated by Corporación Nacional Forestal – National Forest Cooperation (CONAF). The first (1) corresponds to a small area near Aguas Calientes (southwest of the crater) in hilly country, the second (2) encompasses the border crossing complex Cardinal A. Samoré (south of the crater) in the Gol-Gol valley, and the third (3) includes an area near Route 215 next to the side of Laguna El Pato (southeast of the crater) in the high mountains of the Andes. All these sectors are of almost equal size and cover an area of approximately 43 ha. In 2011, experts of CONAF had already carried out intensive fieldwork and studies to detect vegetation affected by volcanic ash deposits.

7.3. Results and conclusions

Figure 17 shows the original Landsat 7 satellite images and the calculated NDVI values inside each study area (deliminated by a white rectangle).

A quantitative analysis of NDVI-related statistical measures (**Table 4**) indicates that in all three sectors, the potential of photosynthetic activity increased steadily. Nevertheless, only for sector 2 a significant change in vegetation recovery was detected. This is mainly due to wind-terrain interaction, as sector 2 is in a valley, strong winds that are typically there, helped to clean ash-covered foliage. For sectors 1 and 3, such recovery was not possible due to external factors like prolonged snow cover during observation period. Furthermore steepness of the terrain is also of great importance. Vegetation is not exposed to strong winds that might help to reduce ash cover. In consequence, only rainfall might help to do so.

The calculated NDVI values were compared with data collected during field trips and it was possible to prove that ash fall in vegetation caused dryness of the leaves in evergreen trees.
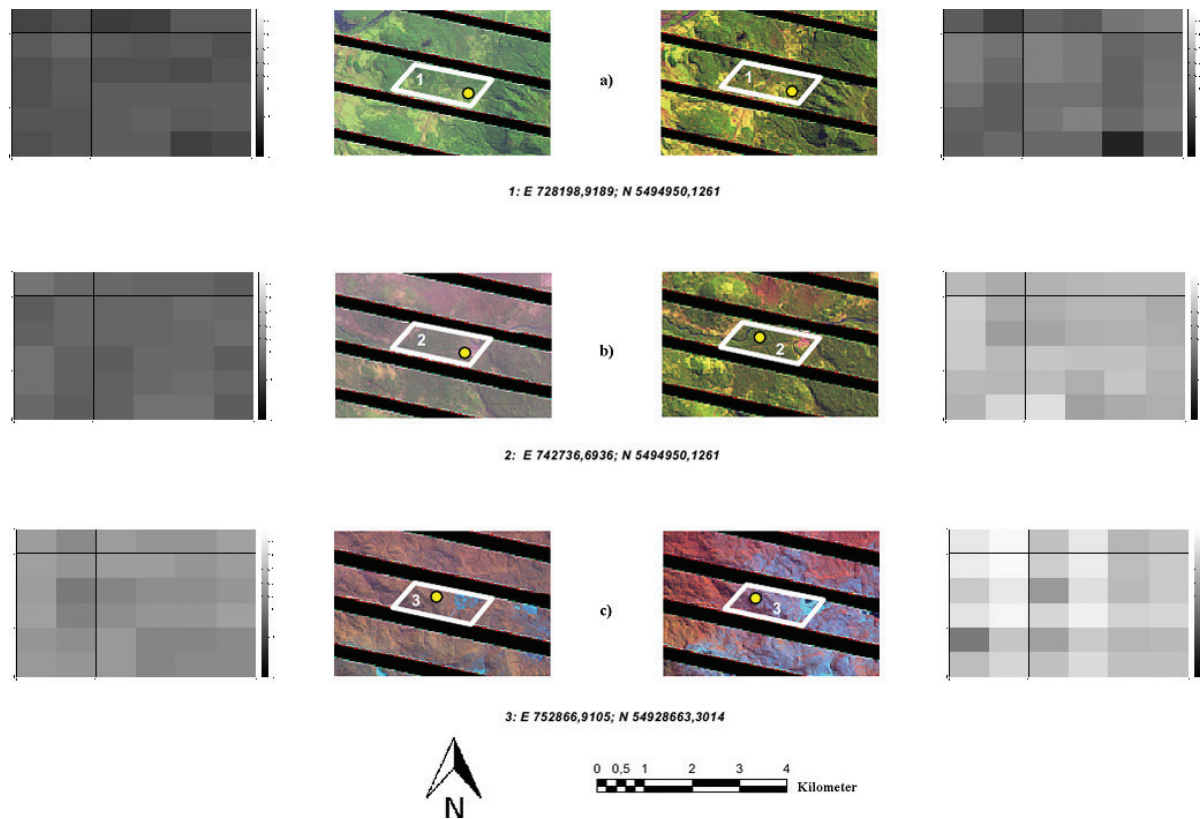
Figure 17. NDVI for each of the three study areas (middle) and for 2011 (left) and 2012 (right).

This led to a decrease in the potential of photosynthetic activity. Several reports published by CONAF allowed to proof the results and to identify the most affected vegetation during and after the eruption event.

Although the eruption of Cordón Caulle in 2011 did severe damage to Flora and Fauna, as indicated in [29, 30], a slow recuperation of the vegetation affected by ash deposits was observed. The decrease in contamination could be related to a combination of two phenomena: the cessation of volcanic activity and to climate (rainfall and prevailing winds in the study area). Recovery of photosynthetic activity started almost immediately after volcanic ash deposits were washed away by rain and wind.

	Mean	Variance	Year
Sector 1	0.236	0.002	2011
	0.486	0.011	2012
Sector 2	0.042	0.001	2011
	0.383	0.003	2012
Sector 3	−0.039	0.002	2011
	0.041	0.010	2012

Table 4. NDVI variations in the different sectors.

8. Conclusions

The use of geospatial tools for future management of trees is possible due to the characteristics of remote sensing and the ongoing development of image processing techniques. Nowadays, imagery is available on the Internet free of charge as well as some well-developed software suites for image processing. All over the world exists the necessity to carry out scientific studies on vegetation, migration processes, urban growth, and so on, to face climate change and to be aware of a changing world we live in. As shown, lots of investigation is ongoing at present and there is no limitation due to geographic location or data availability.

The five case studies presented in this chapter show that geospatial data, such as imagery and climate data is available, even in Chile. And that its study and analysis permit to develop strategies to monitor a wide range of natural phenomena. Desertification, weeds, forest plagues, and natural disasters are only some examples, which have to be studied in order to find answers on critical situations. As this works very well in rural sectors, it is possible to adapt them and to apply them in urban areas.

There is no doubt that once a suitable platform will be developed or established, for example, unmanned aerial vehicle (UAV) equipped with a multispectral camera, urban green areas can also be monitored. Its use will be vital for a number of strategic activities such as land use planning, installing green areas and urban parks, tree management plans, tree planning, fertilization, phytosanitary applications, removal, replacement, or gradual replacement tree in specific areas, among others.

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