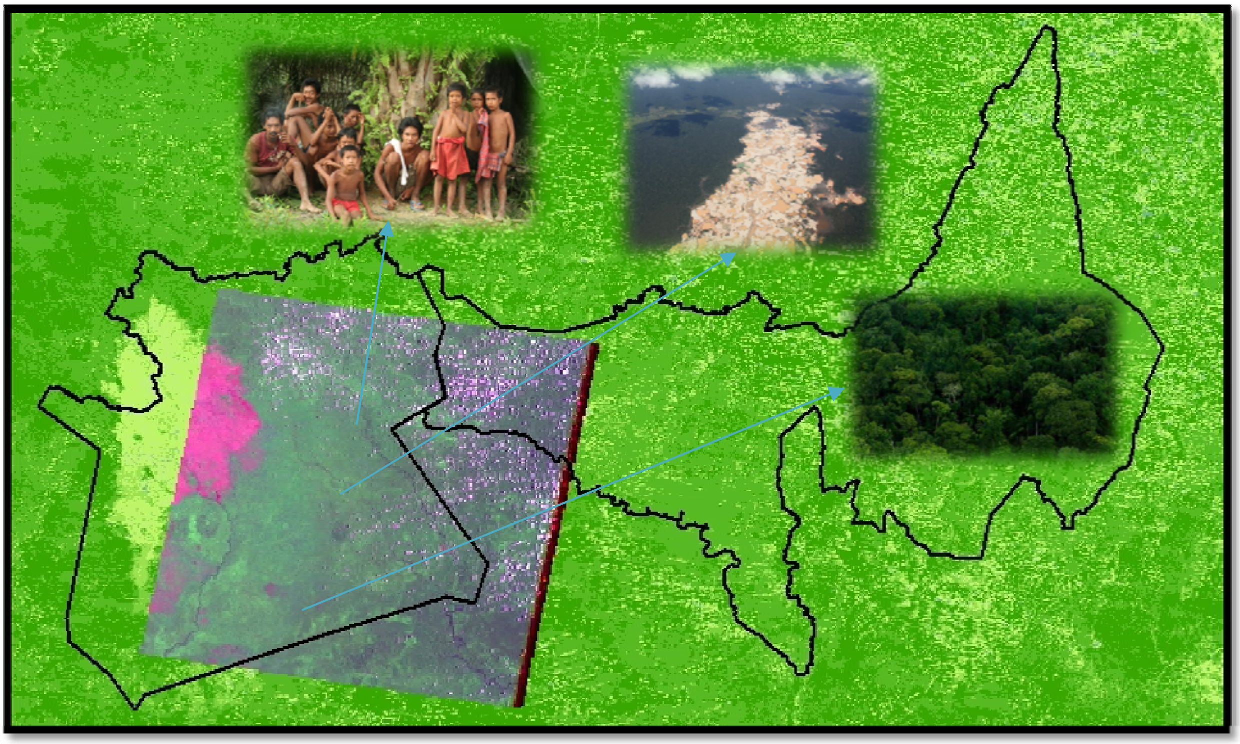
Application of Remote Sensing for Ecosystem Services Monitoring in Tropical Forest Conservation

A review



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Tropical Forestry and Nature Conservation
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and

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Front page showing a MODIS satellite image as a 16-day Vegetation Index with a 250m resolution downloaded from NASA LAADS, with a LandSat TM inset in false colour composition with a 30 meter resolution, downloaded from Earth Explorer. The black outline represents the approximate extent of the Tumucumaque area. Pictures show a local community, illegal gold mining and forest canopy respectively.

Abstract

Ecosystem services have become an important part of tropical forest conservation and provide important products for human being, as well as regulating our climate. However, many of the tropical regions are remote and often inaccessible to monitor the state of the ecosystems and its services. Remote sensing has become a very popular tool to 'access' these areas and developments of satellite sensors have increased their application possibilities. This study reviews these possibilities from the viewpoint of ecosystem services from a more holistic approach, rather than focussing on a single element.

The Tumucumaque area, located in the Guiana Shield, has been selected as a study area to determine requirements for monitoring ecosystem services. Elements are derived from selected ecosystem services as spatial proxies and will function as the criteria in the assessment of application possibilities. Additionally, pressures to the study area are described and included as complementing criteria. Subsequently, the current remote sensors are described as well as spectral reflectance from the ecosystem elements. Considering the importance of carbon sequestration in climate regulation the criteria set within REDD+ are summarised also and included in the assessment. The information about the spatial proxies and sensor properties is analysed and compared to provide insight in the possibilities, but also in the potential lack of information due to constraints.

This review concludes that tropical forest conservation cannot do without the involvement of remote sensing, but neither can remote sensing do without conventional field work. Remote sensing cannot provide the accuracy and level of detail necessary for tropical forest conservation, especially regarding carbon stock estimations. Constraints, mainly due to atmospheric constituents and clouds, limit application possibilities. This gap in remotely sensed data puts emphasis on involvement of local people, and by supporting them in protecting their environment, their involvement can fill in the gap and provide additional, vital information for tropical forest conservation.

Preface and Acknowledgements

This review is written as a final these to obtain the bachelor degree for the study tropical forestry and nature conservation at Van Hall Larenstein University. I choose the subject because remote sensing is becoming a very popular tool, also in tropical forests, and looks very promising for this purpose. Especially considering that nature conservation has become very broad in its scope due to all kinds of international agreements, it is a valuable contribution to the curriculum of the study. However, much of the information available on remote sensing is written in technical and engineering terms, and a clear overview of possibilities from a holistic approach was lacking. I therefore tried to review the possibilities in clear language that can be understood by many of those involved in nature conservation. However, the use of some technical terms is inevitable, but I tried to explain some of them in annex 6. I hope that this review can support those occupied with tropical forestry and nature conservation.

I would like to thank all who have helped and supported me. I especially thank Wouter Veening, director of the Institute for Environmental Security in The Hague, for his cooperation and enthusiasm in establishing this thesis assignment and efforts to achieve this result. I also thank Laurens Gomes from IUCN-NL who in the initial phase of this thesis helped me find a place to conduct this thesis, and Erika van Duijl (Van Hall Larenstein University) who guided me during the thesis and gave useful comments and notes to improve this review. Furthermore, I thank Niels Wielaard from SarVision who made time for an interview while being very busy and provided very useful information.

A very special thanks goes to my girlfriend, who supported me mentally and encouraged me throughout, while me being occupied with my final thesis.

Best wishes,

Arjan van Erk

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IV. Acronyms and Abbreviations

AATSR	Advanced Along-Track Scanning Radiometer
ALI	Advanced Land Imager
ALOS	Advanced Land Observing Satellite
ASAR	Advanced Synthetic Aperture Radar
ASTER	Advanced Space-borne Thermal Emission and Reflection Radiometer
AVHRR	Advanced Very High Resolution Radiometer
AVNIR	Advanced Visible and Near Infrared Radiometer type
CHRIS	Compact High Resolution Imaging Spectrometer
DEM	Digital Elevation Model
EO	Earth Observation
Envisat	Environment Satellite
ERTS	Earth Resources Technology Satellite
ETM+	Enhanced Thematic Mapper Plus (sensor on Landsat 7)
FAO	Food and Agricultural Organisation of the United Nations
GPG	Good Practice Guidlines
GSI	Guiana Shield Initiative
HRVIR	High Resolution Visible and Infra-Red
IPCC	Intergovernmental Panel on Climate Change
IRS	India Remote Sensing
LAI	Leaf Area Index
LIDAR	Light Detection And Ranging
LISS	Linear Imaging Self-scanning Sensor
MEA	Millennium Ecosystem Assessment
MERIS	Medium Resolution Imaging Spectrometer
Metop	Meteorological Operational Satellite
MODIS	Moderate-resolution Imaging Spectrometer
MRV	Monitoring, Reporting and Verification
NIR	Near Infra-Red
NOAA	National Oceanic and Atmospheric Administration
NDVI	Normalised Difference Vegetation Index
NTFP	Non Timber Forest Product
PALSAR	Phased Array-type L-band Synthetic Aperture Radar
Pan	Panchromatic mode

PES	Payments for Ecosystem Services
PROBA	Project for On-Board Autonomy
PSW	Priority Setting Workshop
RADAR	Radio Detection And Ranging
REDD	Reduced Emissions from Deforestation and Degradation
SAR	Synthetic Aperture Radar
SLC	Scan Line Corrector
SPOT	Satellite Pour l'Observation de la Terre
SRTM	Shuttle Radar Topography Mission
SWIR	Short-Wave Infra-Red
TIR	Thermal Infra-Red
TIROS	Television Infra-Red Observation Satellite
TM	Thematic Mapper (sensor on Landsat 5)
VGT	Vegetation (sensor on SPOT 4 & 5)
VNIR	Visible and Near InfraRed
WiFS	Wide Field-of-view Sensor
XSAR	X-band Synthetic Aperture Radar (flown on space shuttle)

1. Introduction

1.1. General

Tropical forests are very important for the provision of services and goods for many people. Moreover, they are important at a global scale as they take part in regulation of the global climate for example. These tropical forests provide in, for example, food and drinking water for many people, regulate many ecological processes, contribute to the mitigation of climate change, which are known as ecosystem services. However, these tropical forests are worldwide under heavy pressure and immediate conservation with accurate monitoring is of utmost importance to secure the deliverance of services and goods that are so important for people worldwide. Thereby, conservation of these tropical forests is important to achieve targets set in global agreements.

The Guiana Shield Initiative (GSI), initiated in 2000, is an initiative to conserve parts of the Guiana Shield by "*promoting the sustainable development of the Guiana Shield by means of an integrated eco-regional policy, institutional and financial management framework, designed to enable the six countries and their local communities to benefit from their natural resources*". Under this initiative several projects have started in the Guiana Shield countries, which are French Guyana, Suriname, Guyana, Venezuela, Colombia and Brazil. The Tumucumaque area, situated in Brazil and study area for this review, is one of the areas that have satisfied the selection criteria of GSI. Within a GSI-project a contract is made between the parties involved and guarding such a contract is important to see if agreements are met and to monitor the effect. More importantly is that the forest under such a project is 'watched' and thus intensively monitored to record the ongoing processes and identify pressures occurring in the area. On the other hand, monitoring ecosystem services is important for the development of Payments for Ecosystem Services (or PES-) schemes. Considering the structural complexity and remoteness of tropical forests, remote sensing might be the only feasible and efficient way to conduct the necessary monitoring (Solberg, et al., 2008; Kerr, et al., 2003).

The use of remote sensing as a monitoring tool for conservation of such extensive area seems therefore promising for active conservation and combating of the pressures. To counteract these pressures it is important to apply a monitoring system that provides information quickly so that within a shortest possible time span the pressure can be eliminated.

1.2. Problem description

The remote sensors have evolved rapidly in the last decades and increased the application possibilities within tropical forest conservation and monitoring. The popularity of remote sensing has also increased, although not sufficiently yet within this field of application, which is testified by a lack of translation abilities by scientists to translate an image into ecological characteristic of a remotely sensed area (Turner, et al., 2003). Another complicating factor is that many satellites are not built for use in biodiversity conservation and therefore miss environmental priorities (Loarie, et al., 2007). However, many studies have been conducted to understand the textural characteristics of tropical forests from satellite images, which can support tropical forest monitoring to a significant extent.

These studies are often focussed on landscape or vegetation class discrimination (Gond, et al., 2011; Mayaux, et al., 1998), habitat identification (Kerr, et al., 2003; Nazeri, et al., 2010), estimation of biomass and carbon stock (Clark, et al., 2011; Turner, et al., 2004) or estimating deforestation rates (Fraser, et al., 2005; Tucker, et al., 2000; Morton, et al., 2005). While it would be preferable to apply a more holistic approach in tropical forest conservation, many of these studies are focussed on just a single aspect. Thereby, many local studies are often context dependent and hence not accurate for mapping large trends in the variation of landscape elements, while regional studies are based on broad landscape characteristics (Gond, et al., 2011). To apply a more holistic approach, the focus of tropical forest conservation should shift towards the ecosystem services that are present in an area, also to synergise and integrate development and biodiversity conservation, and to increase public support (Tallis, et al., 2008). Such a holistic approach would include detecting and monitoring a wide range of ecosystem elements via remote sensing, together with the monitoring of pressures. It is thus focussed on many aspects regarding tropical forest conservation, while many studies are focussed on one or just a few. Although this is in itself not an issue, the methodologies used may differ so that a certain method is accurate for a single aspect, but is less suitable for another. Consequently, many methods are needed, which can be time consuming and prohibitively expensive.

Such an approach is also important in initiatives as the Guiana Shield Initiative. Within these projects it is important to collect data of ecosystem services frequently, at low costs and at high accuracy. These obligations cause the next set of constraints for application of remote sensing in ecosystem service monitoring. For effective monitoring it is important to receive images frequently and that are as near real time as possible. However, much data needs processing before it useful for monitoring or before it provides the accurate information that is wanted. Kerr & Ostrovsky (2003) even stated that satellite remote sensing data are subject to errors that, if uncorrected, substantially reduce their utility for ecological applications. On the other hand, remotely sensed data are the best way for monitoring large-scale human-induced land occupation and biosphere-atmosphere processes (Sano, et al., 2007). It is therefore useful to review the possibilities of remote sensing for monitoring of ecosystem services.

1.3. Research questions and objective

The problem description shows the lack of an overview of the possibilities of remote sensing regarding ecosystem service monitoring. Although many of the elements have been described separately, a more holistic approach involving most elements is preferred, especially regarding initiatives such as the GSI and systems as Payments for Ecosystem Services (PES) and Reduced Emissions from Deforestation and Degradation (REDD). Therefore, this study reviews the current possibilities of remote sensing for application in ecosystem service monitoring as part of tropical forest conservation.

The aim of the study is to provide an overview of the possibilities, but also the limitations, through a set of requirements that are related to ecosystem services. These requirements will also be based on cost and time efficiency to evaluate quick counteraction possibilities against pressures. The overall goal of this study is to give insight in remote sensing applications within tropical forest conservation and to provide a set of guidelines that need to be considered before actual implementation of the monitoring. Thereby this study tries to avoid the use of difficult language and jargon, although the use of specific terms is inevitable. Although the study is aimed at application of remote sensing for all tropical forests on earth, a study area (the Tumucumaque area) is chosen for a more specific review and because of its relation to the GSI, which has formed the basis of this study.

The main research question of this study is:

> **"What are the possibilities and limitations of remote sensing for tropical forest conservation from the perspective of ecosystem services and long term monitoring?"**

The hypothesis is that remote sensing supplies sufficient methods for accurate ecosystem service monitoring, albeit that for specific purposes still much research must be conducted, but that *in situ* information remains necessary for verification of the data for at least in the foreseeable future.

The main research question is answered through the following sub-questions:

1. What are the elements on earth that should be monitored regarding ecosystem services?
2. What are the current remote sensors, their characteristics and their availability?
3. How can these elements be monitored using remote sensors?
4. How can remote sensing contribute to measurements of the carbon storage and the possible carbon sequestration, considering the REDD-programme?
5. Which additional measures are necessary to overcome the limitations from remote sensors that will contribute to the monitoring of the area?

1.4. Methodology

Firstly, the definitions of ecosystems and ecosystem services are explained to focus on the important elements that are related to the services. Many services are difficult to detect because they may not always be visible. Relating to elements on earth will give a better foothold for monitoring of the services. Subsequently, important elements will be determined for the Tumucumaque area, as well as (potential) pressures and their relation to the elements.

Secondly, the current remote sensors are described. They will be selected according to their use in vegetation studies and their technical properties are described as well. Complementary, the satellites are also assessed by the support of the satellite programme on the long term. Furthermore examples will be given of application of these sensors in which also limitations will be discussed.

Thirdly, the elements that are determined in the first step will be compared with the remote sensors described in the second step. Also, a description of the spectral signature of the elements is given to understand the monitoring possibilities with remote sensing. Additionally, requirements will be determined based on the needs for efficient ecosystem service monitoring. It is expected that this step reveals most limitations of the application of remote sensing. This information will consequently be used in the conclusion.

Fourthly, the requirements for monitoring biomass in tropical forests will be determined. These will be based on the REDD-programme for which guidelines have been established by the IPCC. A translation is eventually made into remote sensing possibilities.

Finally, the results from the previous steps will be summarised and compared to show the possibilities and limitations of remote sensing of ecosystem services. Following the hypothesis of the research question, additional measures will be proposed when necessary, either to fill in the gaps in remote sensing possibilities, for verification needs, or for complementing the monitoring of ecosystem services.

This review is mainly based on literature research and much of the information and assessments in this study is related to scientific researches on ecological application of remote sensing. The gathered information is translated, compared and assessed in order to conclude about the possibilities. Additionally, an interview will be hold to gain understanding about SAR-systems, which will be used to assess the possibilities of SAR in ecosystem service monitoring. Complementary, the study will be supported with satellite images where possible to visualise possibilities and limitations.

2. Study Area

2.1. Location

2.1.1. Introduction

The Tumucumaque area is part of the Guiana Shield in South-America and is subject of this study through its relation with the Guiana Shield Initiative. It is one of the areas that satisfied the criteria of the GSI. However, due to a decision of the Brazilian government this area is up to now not a priority site within this initiative. Instead, Iratapuru was chosen, but the Tumucumaque area is still under interest. The areas were chosen on basis of their representativity, conservation priority according to PSW 2000, contractibility, identified ecosystem services, precedence, and replicability. The assessment of the Tumucumaque area is shown in table 1.

Proposed site	**Tumucumaque Indigenous Reserve**
Country:	Brazil
Representativity:	Area of 4,2 million ha located in the Brazilian State of Pará, bordering Suriname on the north, part of the east-west corridor of protected areas in the Guiana Shield eco-region. The indigenous population moves freely to relatives in Suriname and French Guyana. Area officially recognized as protected area since the 1960s and as indigenous reserve in 1999. Threats are illegal gold mining and construction of illegal roads from the south and west.
Conservation Priorities (PSW 2002[1]):	Highest priority
Contractibility:	Representation by two indigenous associations with recognized legal personality with current and past contracts with government and non-government funders. Officers are elected by the communities and trained staff (both indigenous and non-indigenous) can handle project accounting and official business.
Identified Ecosystem Servcies:	Carbon storage and sequestration potentially very high, well-mapped traditional biodiversity knowledge, upstream protection of Amazon tributaries.
Precedence:	Involvement of GSI's remote sensing partner SarVision in assisting local management with monitoring of area. Support of management and mapping by Amazon Conservation Team.
Replicability:	Throughout Brazilian part of Guiana Shield and adjacent areas

Table 1: Assessment criteria of the Tumucumaque area

[1] PSW 2002: Priority Setting Workshop held in 2002 as part of the Guiana Shield Initiative to identify priority areas.

2.1.2. Guiana Shield

The Tumucumaque Upland (hereafter also referred to as 'Tumucumaque') is located in the Guiana Shield in northeast South America. This Guiana Shield region covers 2.5 million km² of intact tropical rainforests and extends from Colombia in the East to the Amápa state of Brazil in the West, and includes all of the Guyana's (Guyana, Suriname, French Guiana), the Venezuelan states of Delta Amacuro, Bolívar and Amazonas, and the Brazilian states of Pará, Roirama and Amazonas (see figure 1 and annex 1).

The Guiana Shield is an eco-region of global significance; it contains more than 25% of the world's pristine tropical forests, 10-15% of the world's fresh water reserves, diverse ecosystems that provide habitats for amazingly rich, endemic biodiversity, and stores and sequesters vast amounts of carbon dioxide that is important to regulate the climate and to combat global climate change (Huber, et al., 2003). Despite a growing world economy, this region remained almost intact and rather undisturbed compared to other tropical forest regions, also due to a very low population density of 0.6-0.8 people/km^2. The natural resources of this region provide ecosystem services that are important for the livelihoods of the communities, but also for neighbouring countries. The fresh water reserves in the area feed the water consumption of surrounding countries, and in the form of wetlands they play a critical role in maintaining and improving water quality, mitigating floods, recharging aquifers, and providing habitat for fish and wildlife (Ustin, 2004).

The Guiana Shield has also many minerals covered in the Precambrian soil, which forms one of the main reasons for further commercial exploitation of the Guiana Shield. This will consequently affect the current, very important functions of this eco-region. Any conservation efforts are therefore important as currently only a small part is protected.

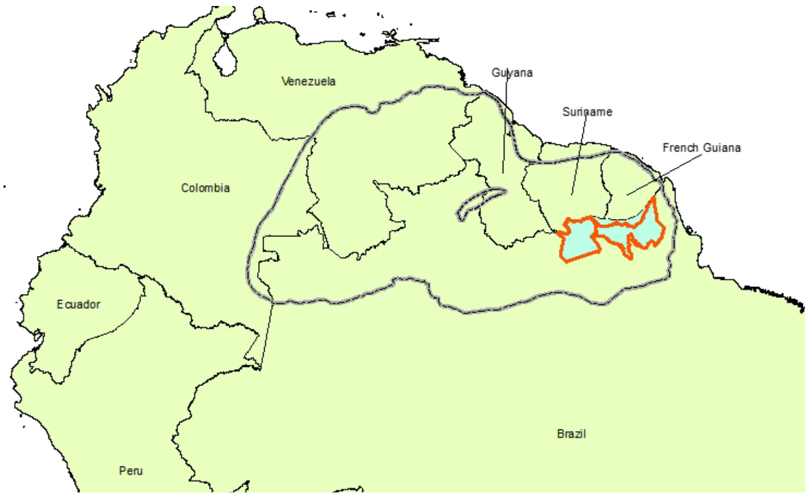

Figure 1: Situation Guiana Shield. The geological extent of the Guiana Shield is shown with a grey line. The study area is bordered with a red line. See annex 1 for a more detailed map.

2.1.3. Tumucumaque Upland

The major part of the Tumucumaque is located in Brazil, in the states of Amapá and Pará, and extends into French Guiana and Suriname. The exact extent of the area is not known, but large parts of the area are covered by parks: National Park Montanhas do Tumucumaque (Brazil, 3.8 million ha), Indigenous Area Parque do Tumucumaque (Brazil, 3 million ha), and National Park Guyane Parc Amazonien (French Guiana) (see figure 2 and annex 2). The latter covers also areas that are not part of the Tumucumaque Uplands. Considering that the Brazilian parks are part of Tumucumaque and that the area extends into Suriname and French Guiana to a limited extent, the total area is estimated to cover about 8 million ha in the three countries, which is twice the size of the Netherlands. The borders of the study area are thus arbitrarily selected due to this lack of information.

The area has derived its name from the Tumac Humac Mountains, which can be translated from the local language into “the mountain rock symbolizing the struggle between the shaman and the spirits”. These mountains are part of a mountain range from the Wilhelmina Mountains in South-Suriname, along the boundary of Suriname and Guyana, passing into the Acarai Mountains in the Pará state and Tumuc Humac mountains in the states of Pará and Amapá. Eventually this mountain range gently slopes downwards towards the Amazon River and the Atlantic Ocean. It forms a natural division between the Guianan and Amazonian drainage systems. Although the elevation does not exceed 800 meters above sea level, the area is remote and not easy accessible.

The Tumac Humac Mountains are very important for both Suriname and French Guiana as their main rivers have their origin in these mountains. These rivers are the Maroni (or Marowijne) River, which is the border river between Suriname and French Guiana, and the Oyapock River, which is the border river between French Guiana and Brazil. These rivers have an important function in the (local) economies of both countries; they provide a means of transport, fishing ponds, irrigation water for agriculture, etc. The area is described by the Priority Setting Workshop (PSW) (Huber, et al., 2003) as a largely intact area with a high ecological diversity with dry savannah, hill tops, inselbergs and granite outcrops, and with a high number of endemic plants and fragmented populations of plants and animals. The granite outcrops are sometimes so closely arranged that they form a special habitat for xerophytic (xero = dry; and phytic = plants) species among the rainforests. The area is important as a transition area for fauna, and is essential for species depending on rocky habitats.

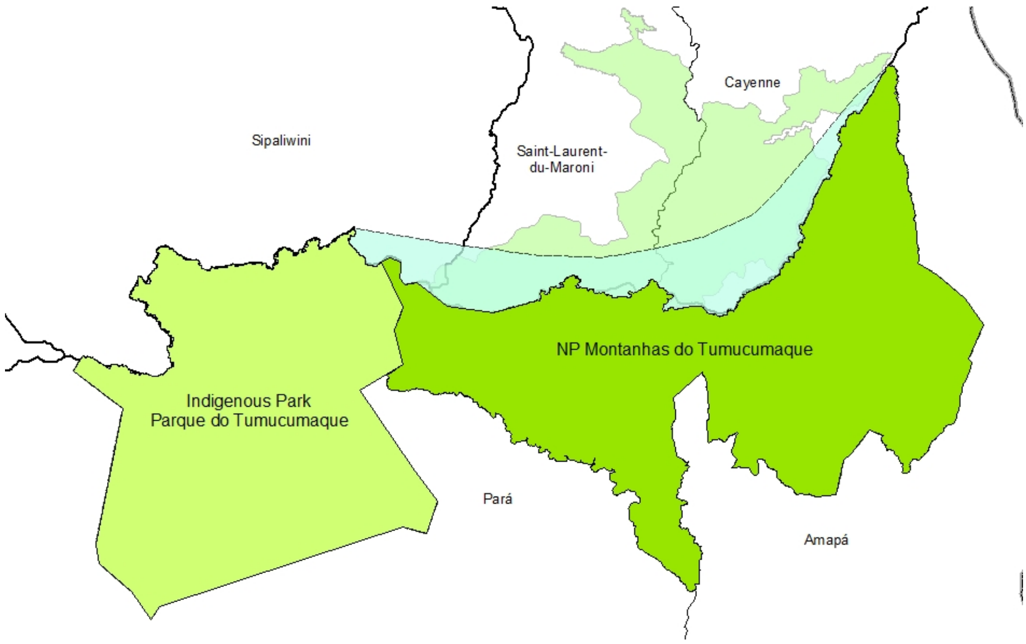

Figure 2: Situation Tumucumaque Upland showing the two parks located in this area and estimated extent into Suriname and French Guiana. See annex 2 for a more detailed map

Despite the fact that almost the entire Tumucumaque area is appointed as either a national park or indigenous reserve (home for indigenous people), much effort must be done to actually protect the area against illegal activities such as gold mining and logging. The legal status is thus not a guarantee for protection of the biodiversity, the ecosystems and the final services. Guarding such extensive areas is very difficult and many of the illegal activities remain under the radar and can continue unabated. Good application and understanding of remote sensing is likely to greatly improve the effectiveness of conservation.

2.1.4. Climate

According to the Köppen climate classification, the climate in Tumucumaque is classified as a tropical monsoon climate (Peel, et al., 2007). Although no exact figures of climate characteristics are known for the Tumucumaque area, the average annual precipitation is estimated to be between 2,500 and 3,000 mm and an average annual temperature of 26°C. Together with a relative high humidity these characteristics cause frequent cloud development above the area. The dry season is from September to November and the wet season the rest of the year.

2.2. Ecosystem services

2.2.1. Introduction

Ecosystem services have become an important issue in conservation and for that reason it was also included as a criterion for pilot site allocation within the GSI. Certain ecosystem services have been marked as important in the Tumucumaque area and must be focussed upon in a MRV programme. The monitoring of ecosystems, especially in an extensive area as Tumucumaque, can be enhanced by remote sensing. In addition, identification of ecosystem services can be simplified if one understands to which elements these services are related to. This chapter tries to give this insight by explaining the definitions and the relation of services to elements on earth.

2.2.2. Definitions

Ecosystem

An ecosystem can be described as "*a functional entity or unit formed locally by all the organisms and their physical (abiotic) environment interacting with each other*" (Tirri et al, 1998). The Millennium Ecosystem Assessment (2003) defines ecosystem as "*a dynamic complex of plant, animal, and micro-organism communities and the non-living environment, interacting as a functional unit. Humans are an integral part of ecosystems*." Both definitions emphasize the interaction between organisms and the environment, which suggests that within an ecosystem all elements depend on each other and affecting one of them will influence the other. This means that for monitoring the ecosystems all elements within a unit (water, soil, vegetation, human beings, etc.) should be taken into consideration as parameters to measure the state of the ecosystem. Also, the exact extent of an ecosystem is hard to define when considering these definitions and the focus for monitoring should therefore not be on these ecosystems as such but rather on the elements. While ecosystems can be as large as the Amazon basin and as small as a backyard, it is always related to the elements that it consists of. As an additional benefit, the elements that are monitored will also directly provide information about the ecosystem services that are found in the ecosystems.

Ecosystem services

The Millennium Ecosystem Assessment defines ecosystem services as "*the benefits people obtain from ecosystems*" (MEA, 2005 p. 1). The services can be grouped in provisioning, regulating, cultural and supporting services. Although standards for defining ecosystem services are lacking and some definitions might even be competing (Boyd, et al., 2007), this definition describes best the core function of an ecosystem service and the direct relationship with people and their well-being. This also reflects the importance of tropical forest conservation as it provides many services on which the human-being is dependent.

But Boyd and Banzhaf (2007) further defined the term as "*final ecosystem services are components of nature, directly enjoyed, consumed or used to yield human well-being*", and attempted to emphasize the importance of the end product of the service the ecosystem provides. Hence, the quality of a water body is, for example, not necessarily the end product as it relates to the fish stock, although the quality is a final service at the same time if for drinking water and irrigation (both benefits). This example also shows the relation of services to the state of elements.

2.2.3. Ecosystem services

Ecosystem services can be divided into 4 service categories according to their general functions, which are 1) provisioning, 2) regulating, 3) cultural and 4) supporting (MEA, 2005). Other categorisations have been adopted as well (e.g. Hyde-Hecker, 2011; Wallace, 2007), but this categorisation is generally used, although some related services mentioned by the MEA are considered 'means' rather than 'ends' (Wallace, 2007). Many ecosystem services are thus part of a process to provide an end product to benefit human well-being. All ecosystem services, thus the products of nature, can be categorised in at least one of these four groups. But these service groups do not necessarily directly relate to a particular element of the ecosystem, as the services are often results of the complex ecosystem processes. Ecosystem processes are the interactions between and among biotic and abiotic elements of the ecosystems that lead to a definite result (Wallace, 2007; Tirri et al, 1998). However, a service can be directly related to the presence of a certain ecosystem element. One can conclude that all ecosystem services eventually arise from the ecosystem elements (biotic and abiotic) as illustrated in figure 3.

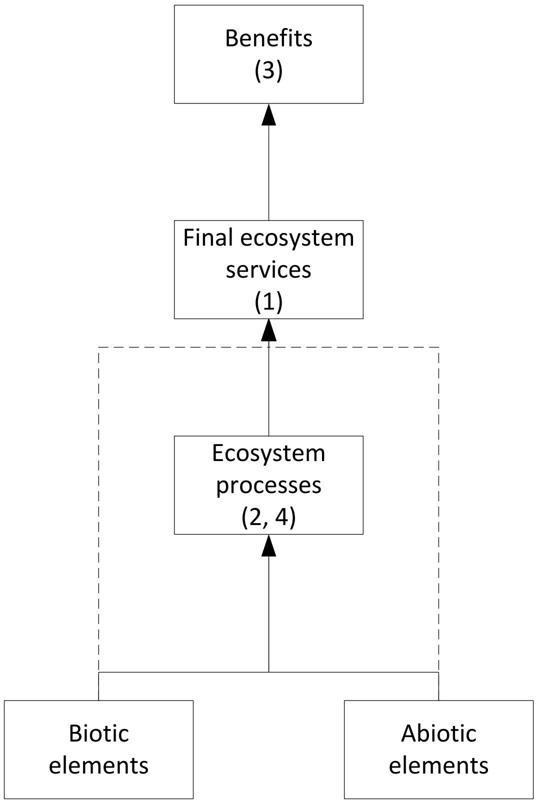

Figure 3: Relationships between ecosystem elements, processes and final products

Service categories

Provisioning services (1) are the products that can be obtained from the ecosystem. These products include wood, energy, medicines, fresh water, genetic resources, etc., and are the services directly consumed and/or enjoyed. Regulating services (2) are the benefits that can be obtained from the regulation of ecosystem processes.

These services include fresh air regulation, climate regulation, water regulation, soil protection, etc. that secure the provisions from ecosystems. Cultural services (3) are the non-material benefits that are obtained from the ecosystems. These benefits are spiritual and religious values, education, cultural heritage, but also recreation and eco-tourism, which can be an alternative source of income. This testifies of the relation with other service groups as, for example, tourism depends on the scenic beauty of the landscape. Supporting services (4) are the services that are necessary for the production of all other ecosystem services. These include soil formation, nutrient cycling and primary production. They differ from the other groups because their impacts are often indirect compared to direct impacts in changes of the other services (MEA, 2003).

In fact, according to the definition of services as a direct benefit, only the first group of provisioning services comprise the actual final products. The values of the ecosystem processes (including regulating and supporting services) are embodies in these final products. The cultural services often arise from an end-product or a combination of it and are therefore considered benefits. Taking into account the ecosystem as illustrated in figure 3, a change in the ecosystem elements is eventually visible in the availability of the final services and vice versa: a change in the availability can be related back to a change in the ecosystem elements. For monitoring it is thus important to focus both on elements (begin) and final products (end). This gives additionally also information about the state of the ecosystem and the effect on final products can be used as verification method of the remotely sensed data on ecosystem quality. However, most final services may not be able to be detected using remote sensing due to a lack of spatial proxies, which then would require additional methods that complement to the monitoring through remote sensing.

2.2.4. Ecosystem services Tumucumaque

The Tumucumaque area provides important services for the local communities, neighbouring areas and countries, and at world scale. Most services are related to the following ecosystem elements, which will need to be detected and monitored using remote sensing. Although it would seem logical, the element air is not included to narrow down the scope to elements that are on earth. As an additional 'element', biomass is included because of its strong relationship with combating climate change. Activities that pose a threat to the state of the elements are described in chapter 2.3.

Ecosystem elements:

- Water
- Vegetation
- Biomass
- Soil

Water

The Tumucumaque area is the source for two important rivers in the neighbouring countries of Suriname (Marowijne River) and French Guiana (Oyapock River), which supply many communities with fresh (potable) water, a means for transport, a source for fish, irrigation water for agriculture, etc., but both rivers also function as a natural border between involved countries, which can be considered a service as well. Also wetlands, with a very unique biodiversity and regulating characteristics, must be included in the water element. "For many wetlands, remote sensing is the only practical method of obtaining a synoptic view of wetland inundation and vegetative covers" (Ustin, 2004).

The water body itself can be a direct ecosystem service as well as being the source for many other products. This can be exemplified by fishing as a recreational activity (benefit) that needs a water body (end service) as it is necessary for angling. The water quality in this example is an intermediate product as it is strongly related to the target fish population (the final service), but in the case of drinking water (a benefit) the quality of the water is the final service (Boyd, et al., 2007).

Considering the above mentioned benefits and services, it can be concluded that most of the end services are dependent on the water quality, fish population (especially economically interesting species) and the water body itself (quantity). Therefore, for the element water these three parameters are to be monitored to determine its state.

Vegetation

The Tumucumaque area is covered with pristine tropical forests and hosts a rich and endemic biodiversity. The vegetation in the area provides habitats for several endemic species and is a vital element for the biodiversity. The natural biodiversity provides many products and services: timber, fruit, medicinal plants and other non-timber forest products, but also pollination, fresh air, soil protection, genetic resources, water infiltration, nutrients, energy, etc.

The vegetation cover can be classified in vegetation or landscape classes for estimation of the total forest cover. The detail with which this is conducted determines the level of distinction between forest types and ability to detect small forest cover changes, e.g. smart timber harvesting. This accuracy is especially important if monitoring is conducted within a contract to guard agreements on exploitation. Furthermore, vegetation classification is important to gain more insight in species habitats, but also in estimating the distribution of species and services across the study area. Gond et al (2011) stated that characterising the spatial organisation of the landscape is important to analyse changes and to sustainable management of the forest.

Biomass

Although biomass is strongly related to vegetation cover and can be considered a parameter of vegetation, it is dealt with separately because of its relation to climate mitigation through the amount of carbon embodied in the biomass, and hence its potential for financial benefits. This potential might also be very important in financing the conservation of the Tumucumaque area. As the Tumucumaque area contains some of the pristine tropical forests, it is a very important carbon sink and conservation is necessary to prevent a turnover to a carbon source, due to natural or human induced causes. The biomass in the forest is further discussed in chapter 4.

Topology and soil

Protection of the soil is important to sustain many of the ecosystem services. Hence, there is a strong relation with other ecosystem elements, for example, the vegetation cover protects the soil from erosion, and subsequently ensures water quality that can be affected by soil sediments. Thus a decline in the final services related to the soil has probably its roots in other ecosystem elements.

However, mapping the soil or surface is important to identify sensitive areas, e.g. areas that have steep slopes or are close to a water body. Any activities that are planned in these sensitive areas are likely to have more impact than when conducted in other, less sensitive, areas. Erosion can have a severe impact on the ecosystems and final services, while recovery can take many years. These (natural) occurrences relate to the topography of the area rather than the soil type.

2.2.5. Monitoring of ecosystem elements

Regarding the ecosystem services of the Tumucumaque area, the landscape characteristics or indicators mentioned in table 2 are important to follow by monitoring. Most of these indicators are directly related to the ecosystem elements and influence the availability of certain services and end products. However, some of these indicators are area-specific and need to be determined *in situ* before monitoring can take place and reflect the state of ecosystem elements.

Element	Indicator	Parameter
Water	Water quantity	Water body
		Water flow
		Watershed
		Wetland extent
	Water quality	Turbidity
		Water discharge
Vegetation	Vegetation cover	Land cover
		Vegetation cover/classes
		Forest cover
Carbon	Biomass	Biomass total area
		Biomass per vegetation type
		Carbon stock
		Carbon sequestration
Soil	Erosion	Altitude
	Sensitivity	Slope

Table 2: Overview ecosystem elements and parameters

2.3. Pressures

2.3.1. Introduction

Despite the protected status of the forest, certain activities are conducted that pose a threat to the biodiversity of Tumucumaque. From the perspective of ecosystems a threat can be defined as a phenomenon that negatively affects the availability of the ecosystem services. As humans are an integral part of the ecosystem and hence dependent on the services, they are affected by it, while they also are strongly related to the causes. These threats, or phenomena, often result in a forest cover loss and hence also in a loss of biodiversity. Measuring the forest cover loss or deforestation rate can therefore give a picture of the changed availability of ecosystem services, but in addition, the causes of this forest cover loss must be determined in order to effectively interfere with these with conservation measures. These causes are discussed in this chapter.

If the forest cover is compared with 1990, Brazil has lost approximately 8.1% of its forests (FAO Forest Resource Assessment). This might seem a relatively moderate deforestation rate, in absolute terms the deforestation is of high environmental concern as Brazil holds about one third of the world's tropical rainforests. However, the deforestation of Brazil mainly occurs in the other parts of the country and Tumucumaque (northwest) is relatively untouched due to its remoteness and low accessibility. The forest cover change for Suriname and French Guiana is for both countries very low as deforestation is not significant or not detectable. However, these numbers do not suggest that threats to Tumucumaque from both countries do not exist.

Although most activities that pose a threat to Tumucumaque are related to forest cover change in the area, other activities might pose threats as well. For example, illegal gold digging using mercury might go unnoticed as these activities can occur under canopies, but the impact on the environment can be very significant. Besides the threats that are now occurring, the concerned countries have planned certain activities, for mainly economic development, that might or will pose a threat for the availability of ecosystem services at some point in the future. These will be, for as far as possible, included for the benefit of the monitoring and for estimation of the quantity of its effect on the ecosystems and biodiversity.

Figure 4: Typical deforestation pattern in Rondonia, Brazil, as seen from space (LandSat TM)

Besides human induced pressures on ecosystems, an increasing problem nowadays in the Amazon is drought. This will threaten the carbon sink function of the Amazon rainforest and will even cause them to turn over in carbon sources, mainly through killing trees (University of Leeds, 2009). This will consequently accelerate global climate change. Although it may become a severe threat in ecosystem service availability, it is not further discussed in this review due to the large scale involved.

2.3.2. Main threats

Illegal small-scale gold mining

As gold is considered a reliable refuge in financial insecure times, the gold price has increased significantly over time. This caused an increased activity of illegal gold mining in mainly French Guyana and Suriname as these countries have interesting gold resources. However, this gold mining is very destructive for ecosystems because mercury is used to dissolve gold from the rough material. This has already caused severely polluted rivers.

This illegal gold mining occurs along rivers for the needed water availability and results in clear cuts along these rivers that become so polluted that recovery of the forest after abandonment is very difficult. This also causes erosion of the bare soil and subsequently high amounts of sediment in rivers besides the high amount of mercury. This destroys the ecosystems and its life. Animals found in and around these rivers have accumulated the mercury, which is also causing severe health problems among the local people. Drinkwater can hence not be collected from creeks and rivers and hunted food is dangerous because of the accumulation of mercury in animals. The situation in Tumucumaque according to the WWF is that the area has mostly remained violated by illegal mining activities. The Tumucumaque Mountains National Park is frequently pointed out as the supply base in Brazil of the illegal gold miners in the French bordering park.

Gold mining have distinct patterns as they follow most often rivers (see figure 5). It occurs near wetlands as well, but less frequent. Swenson et al (2011) found that gold mining patterns are independent of road networks, in contradiction to deforestation through settlements. Detection of river water sediment can be contributing to the overall detection and monitoring of illegal gold mining.

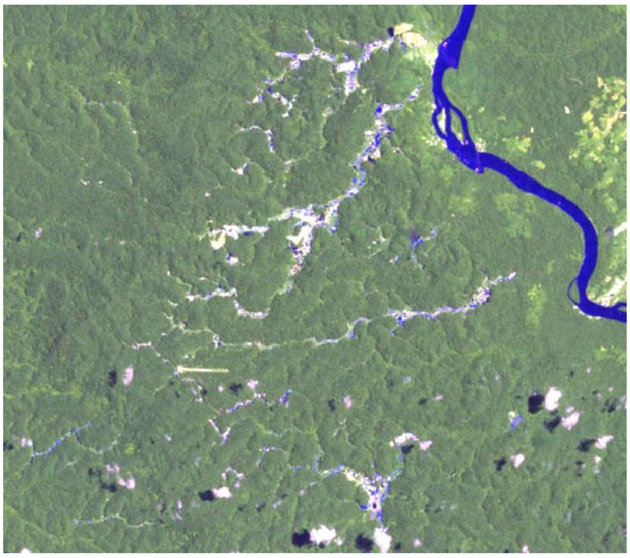

Figure 5: Typical pattern of illegal gold mining in southern Suriname, as seen from space (LandSat TM)

Mineral mining

The Guiana Shield is known for its, largely unexploited, resources of minerals, due to its geological characteristics. Although the Guiana Shield is largely impenetrable and therefore unattractive for exploitation due to high establishment costs, the ever increasing global demand and prices for minerals also increases the 'attractiveness' for exploitation. And once the infrastructure is established that is needed for the mining, this will attract even more investors.

The current issue with large-scale mining is the lacking attention for the environment. They operate often with limited environmental standards and pay little attention to the use of toxic materials. Consequently, it causes deforestation and pollution of the environment. Currently, regulation by law is also lacking and therefore environmental legislation is needed urgently, as well as the capacity to enforce the law (Haden, 1999).

In view of the future, it is expected that mining activities will increases and without sufficient regulation regarding safety and environment, deforestation, and even destruction, of the biodiversity and environment is inevitable. This will consequently cause a drop in the availability of ecosystem services.

Belo Monte hydro-electric dam

Brazil has proposed to build an immense hydro-electric dam in the Amazon basin, near Altamira, southeast of the Tumucumaque area. Although it is situated a far end form the study area, this proposal is considered to be a first step for the development of another 60 hydro-electric dams in Brazil. Although the locations of these future constructions are unknown, one close to the Tumucumaque area might possibly severely affect the biodiversity in the area and also subsequently the ecosystem services.

Highway from Suriname to Brazil

Suriname is not yet economically connected with Brazil by land. In perspective of the on-going economic development in Brazil, it is very interesting for Suriname to establish such a connection. For this reason both the Brazilian and Suriname government have proposed to construct a highway running from Paramaribo to Macapá through the Tumucumaque National Park.

Although it will probably bring economic benefits to both countries, the numerous negative impacts the highway will bring to the environment are a serious threat to local economies. This highway will unlock a vast area in the Guiana Shield for (illegal) exploitation of natural resources, e.g. logging, mining, etc. Furthermore, it will encourage migration of people, open up ways for illegal gold miners, consequently land conflicts (Ven, 2010). Eventually, deforestation will take place and severely decrease the availability of ecosystem services in the Tumucumaque area. It is found that 80% of the deforestation occurs within a 30 kilometre buffer from the roads (Asner, et al., 2006; Barreto, et al., 2006).

3. Remote sensors

3.1. Introduction

Currently many satellites are operative and scheduled for launch with a wide range of different sensors. Certain satellites are especially designed for environmental studies and others carry one or more (experimental) instruments for this purpose. The field of application of the instrument, which is described in this chapter, is determined by its properties; temporal resolution, spatial resolution, and detectable radiation. These properties are used to group the sensors in this chapter. The optical sensors are subdivided according to the spatial resolution. Although there is no global standard for this subdivision, the following is used:

Spatial resolution:		Satellite systems
Low	>1,000m	SPOT VGT, MERIS, AVHRR, MODIS
Moderate	<1,000m and >100m	MODIS, MERIS
High	<100m and >10m	Landsat, SPOT, IRS, ASTER
Very high	<10m	IKONOS, QuickBird, Orbview

Table 3: Overview satellite system according to their spatial resolution

The most important current remote sensors are listed below, both space-borne and airborne, that are suitable for application in vegetation studies. The listed sensors are amongst others related to the findings of Jones and Vaughan (2010), who have created a list with the following requirements:

- It must provide data suitable for vegetation studies
- It must be currently operational
- The data must be readily available

There are of course many more remote sensors and hence the list is completed with older, still operational sensors, but also with the newest available sensors. Other sensors may not give a complete annual coverage of the Tumucumaque area. For each of the sensors (series) a short description is given to give little insight in its purpose and continuation of the programme. The latter is important to be able to obtain continuous data over the period of monitoring. Technical information about these sensor are summarised in table 4 and more extensively in annex 4.

Sensor	Spatial resolution	Spectral resolution (um) (number of bands)	Temporal resolution
Vegetation	1.15 km	0.45 - 1.66 (4)	daily
MODIS	1000m - 250m	0.41 - 14.34 (36)	1-2 days
AVHRR	1.1 km	0.61 - 12.0 (5)	12 h
Meris	1200 - 300m	0.41 - 0.90 (15)	3 days
ASTER	90m - 15m	0.56 - 11.3 (14)	16 days
ETM+	60m - 15m	0.48 - 11.5 (8)	16 days
TM	120m - 30m	0.45 - 12.5 (7)	16 days
HRG	20m - 5m	0.5 - 1.66 (6)	27 days
ALI	30m - 10m	0.43 - 2.35 (10)	16 days
Hyperion	30 m	0.40 - 2.50 (242)	On request
LISS-3	70m - 24m	0.55 - 1.65 (4)	24 days
IKONOS	4m - 1m	0.45 - 0.90 (5)	11 days
Quickbird	2.44m - 0.61m	0.45 - 0.90 (5)	1 - 3.5 days
Orbview	4m - 1m	0.45 - 0.90 (5)	Up to 3 days

Table 4: Concise overview of current satellite systems

Data catalogues and costs

Most common satellite products are easy accessible, although only a few are free of costs. However, it is likely that soon most satellite products are freely available for everyone, especially data from non-commercial satellites. But until then, the costs of the satellite products determine significantly the quality and its application, and hence the effectiveness and efficiency of nature conservation.

In the table below an overview is given of the most common satellite products with their catalogue services and the costs per unit. The prices are given for level 1 satellite products or similar, which is pre-processed data with geometric and atmospheric corrections. Prices are estimates as total costs will depend on the area that must be covered, but also on the amount of detail (spatial resolution). Most free scenes need further processing before use, while these additional services can be obtained from commercial ordering services at costs.

Satellite	Catalogue service / ordering service	Costs/unit (level 1)
Landsat 5 & 7	USGS Global Visualisation Viewer USGS New EarthExplorer	Free
Spot	SPOT catalogue (spotimage) EOLI-SA (ESA)	€ 1,900 / scene (20m C)* € 2,700 / scene (10m C)* € 5,400 / scene (5m C)* € 8,100 / scene (2.5m C)*
Aster	Warehouse Inventory Search Tool	
MODIS	USGS Global Visualisation Viewer	Free
AVHRR (NOAA)	NOAA CLASS	Free
Vegetation (SPOT)	Vegetation Image Catalogue	€ 260 / <1 million km2 Free (older than 3 months)
XSAR (TerraSAR)	Infoterra	€ 2,750 / scene (SC)** € 3,750 / scene (SM)** € 6,750 / scene (HS/SL)**
ASAR (Envisat)	EOLI-SA (ESA) Eurimage	 € 400 / scene
SAR (RadarSat-2)	CEOCat MDA Geospatial Services Eurimage	 $ 3,600 CAD*** / scene (wide) € 2,540 / scene (wide)
Quickbird	Eurimage	€ 3,808 / scene
* 20m C stands for a spatial resolution of 20m and a colour image ** SC = ScanSAR; SM = StripMap; HS = High Resolution SpotLight; SL = SpotLight *** Canadian Dollars		

Table 5: Catalogue services of the satellite systems

3.2. Optical: Low and moderate resolution satellite sensors

Mapping large areas without much processing costs due to large amounts of data is possible with low resolution satellite sensors. These sensors have a low spatial resolution, but often a high temporal resolution, which allow obtaining images of the entire area (e.g. the Tumucumaque area or even whole of the Guiana Shield) frequently at low costs. Also, due to the high frequency of revisiting the probability of collecting cloud free images of the Tumucumaque area is much higher than with medium resolution sensors. Furthermore, cloud free images can be obtained by combining several images taken within a time span from a few days up to a few weeks to compensate for the lack of information due to cloud coverage, and still allow for quick response actions in contrary to medium resolution images. The low resolution sensors are commonly used to classify broad land cover types, deforestation, drought monitoring, estimation of leaf area index, etc. at near real-time, although dependent on the frequency adopted and amount of processing involved. The most interesting possibility is the classification of land cover types. Frequent classification allows detecting changes in land cover and hence points out the place where intervening actions are required. The question is to what detail the changes can be detected with this type of sensors.

However, a disadvantage of the high temporal resolution is that not much detail can be seen on these images for ecosystem inventory and reporting (Fraser, et al., 2005), while many illegal activities start at a small scale that might therefore be hard to detect using coarse resolution images. Another problem is that errors arise regarding the discrimination between the vegetation types, so that boundaries cannot be defined correctly as pixels are identified as mixed forests (Foody, et al., 1997). This would also limit the detection of forest cover change. This requires additional, more detailed images to identify the exact activities for more efficient response actions. Hence, analyses from these images can be considered as a 'first pass' (e.g. (Fraser, et al., 2005) to identify areas that require detailed studies with more detailed satellite imagery. This is also an obligation to prevent errors in the final products based in the coarse scale resolution sensors (Achard, et al., 2010; Scepan, 1999), or by other means (e.g. (Townsend, et al., 1987).

Toukiloglou (2007) assessed the three most commonly used coarse resolution (1 km) remote sensors, which are AVHRR, MODIS and VEGETATION, for land cover mapping and drought monitoring. He concluded that MODIS provides the beast quality in these products, followed by the VEGETATION sensor. The AVHRR sensor has the advantage of a larger historical NDVI-dataset, but AVHRR data are known for their poor geometric accuracy and their absence of radiometric calibration (Meyer, 1996; Cihlar, et al., 1998; Mayaux, et al., 2000). Another advantage of MODIS is that it can also achieve higher classification accuracies if only the first seven bands of MODIS are used (Toukiloglou, 2007).

AVHRR

The AVHRR sensors are mounted on the NOAA satellite series and have been collecting data since 1981, although the first sensor was carried on TIROS-N, which was launched in 1978. There are at least two NOAA satellites in orbit at all times that provide global coverage twice a day, ensuring continuation of data collection. The primary purpose of the AVHRR is to monitor clouds and to measure the thermal emission of the Earth, but is also used for other purposes, e.g. vegetation monitoring. Due to the long history of AVHRR data, it is frequently used for global vegetation history mapping.

VEGETATION

The VGT sensors are mounted on the SPOT satellite series. The first VGT sensor is mounted on SPOT-4 and launched in 1998 and the second VGT sensor is mounted on SPOT-5 and was launched in 2002. This sensor is especially developed for vegetation studies and has global coverage. The minimum lifetime expectancy is 5 years, but the Vegetation programme will continue on Proba-V satellite (V = Vegetation) and its launch is scheduled for 2012. A study conducted by Mayaux et al (2000) to create a near-real time forest cover map of Madagascar showed that a forest cover map could be produced within three weeks after acquisition date based on a 10-day synthesis. However, images were still too contaminated by clouds and haze to allow for direct classification.

MODIS

The MODIS sensor is mounted on both the Terra and Aqua satellite, which were launched by NASA in 1999 and 2002 respectively. Both MODIS sensors can capture the earth in 1-2 days at a spatial resolution of 250-1000 meters, and are designed for global monitoring of cloud cover, radiation budget and processes occurring in the oceans, on land and in the lower atmosphere. The design life is 6 years, which means that there is an increased risk of failure of the satellite system. MODIS is amongst others used for creating global vegetation indices, which are already automatically created and made available in the catalogue service.

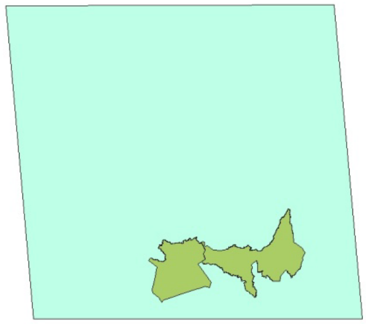

Figure 6: MODIS footprint (in blue) in relation to the study area

MERIS

The MERIS sensor is mounted on Envisat, but is not commonly used in vegetation studies. This satellite was developed to overcome the gap that existed between the low spatial and high spatial resolution satellites, thus provides medium resolution imagery.

3.3. Optical: High resolution satellite sensors

High resolution satellite sensors currently operative have often a spatial resolution of approximately 10 to 100 meters and allow creating more detailed images when compared to low and medium resolution sensors. These types of satellite images are particularly useful to cover a smaller area (e.g. National Parks); large areas would involve the processing of much data which can consequently become rather expensive. High resolution imagery is suitable for vegetation studies. The first Landsat satellite was developed especially for this purpose.

The higher spatial resolution of the satellite images, compared with the coarse resolution images, allow better discrimination between forest types and forest structure. Classifying landscape types is also much more accurate as the pixels cover an area of only 30x30m or even smaller, which significantly reduces the errors. Estimating land cover change and actual deforestation becomes therefore much more accurate, and the resolution also allows identifying the underlying cause of deforestation of a specific area as related patterns are clearly visible on the images. Furthermore, calibrating, validating and correcting products derived from coarse spatial resolution data can best be done using such high spatial resolution data sets (Mayaux, et al., 1998).

The disadvantage is the trade-off between spatial resolution and temporal resolution. While coarse resolution satellites provide near real-time images with a minimum of detail, the high spatial resolution images provide detailed images, but at a low frequency. The revisit time at the equator is generally 20-30 days, which significantly reduces the probability of obtaining cloud-free data. In combination with the atmospheric constituents that decrease the quality of the scene, these types of images can forsake to provide the data needed, but is dependent on the climate of the study area.

Although high resolution images can be useful for the classification of land cover, it still misses detailed spatial information. Estimating the biomass in a forest is therefore rather inaccurate if these types of satellites are used (Gibbs, et al., 2007).

SPOT

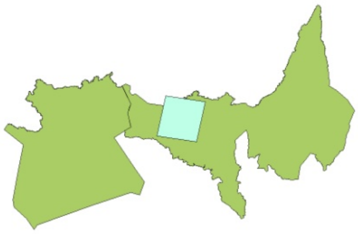

Figure 7: SPOT footprint (in blue) in relation to study area

The SPOT satellite series are of French origin, and the programme was initiated in the 1970s. Currently, SPOT 4 (launched in 1998) and SPOT 5 (launched in 2002) are working and providing high resolution images of the Earth. The programme is to be extended with SPOT 6 and SPOT 7 to ensure continuity until 2023. The SPOT system is designed for land-use studies, assessment of renewable sources, exploration of geologic resources, and for cartographic work. Both SPOT satellites carry a HRVIR instrument. The temporal resolution is 27 days, but the sensor is pointable, which provides a temporal resolution of 4 days. This mode provides images mainly used for cartography. Images from the SPOT satellites are available at costs.

LANDSAT

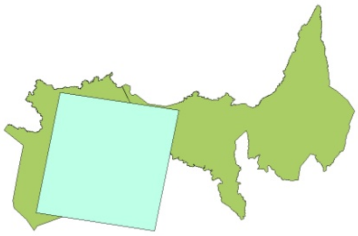

Figure 8: LandSat footprint (in blue) in relation to study area

The Landsat series is the oldest series that provide global coverage of the Earth's surface, which can benefit studies of vegetation history of a certain area. At present, Landsat 5 (launched in 1984 and thus far beyond its design life) and Landsat 7 (launched in 1999) are operative. Landsat 5 is equipped with MSS and TM instruments, but the MSS has been turned off. The TM instruments still collects images of the earth and is at present the only Landsat satellite that provides undisturbed satellite images.

Landsat 7 is equipped with the ETM+ instrument, which is highly accurate compared to other Earth observing satellites. However, the SLC component failed in 2003, which affects the quality of the image. Approximately 22% of each scene is lost due to this failure and only a 22 km wide band in the middle of the scene has very little duplication and provides similar quality as SLC-on products.

TERRA-ASTER

The ASTER-sensor is mounted on the Terra-satellite and was launched in 1999 to obtain detailed maps of land surface temperatures, reflectance and elevation. The ASTER-sensor also provides stereo viewing capability to generate digital elevation models. ASTER data is generally available within 5 days after collection. However, the SWIR detectors are currently not operating due to high detector temperatures that caused severe disturbances of the images. All attempts for recovery have failed and only images from the VNIR and TIR are available, still providing high quality images. Also, ASTER data is not collected continuously, so that some areas have better coverage than others.

EO - ALI

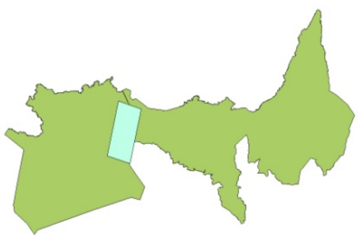

Figure 9: EO-ALI footprint (in blue) in relation to study area

The ALI-sensor is mounted on EO-1 satellite, which was launched in 2000 and designed to experiment with new developments. The design life was 18 months, but that has been greatly exceeded. The images from ALI are available at no costs, but the sensor operates upon requests. Hence, requests can conflict with each other and maintenance, and also increases the risk of unwanted images. It does not provide continuous coverage of the earth.

EO - HYPERION

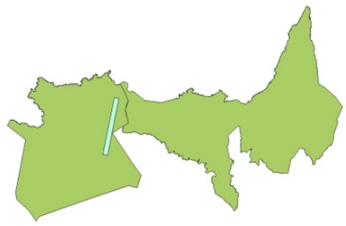

Figure 10: EO-HYPERION footprint (in blue) in relation to study area

The HYPERION-sensor is ALSO mounted on the EO-1 satellite and is a hyper-spectral sensor. It has a capability of resolving 220 spectral bands. The disadvantage of this sensor is the enormous amount of data that it obtains, which makes image processing a time intensive task and can be prohibitively expensive. The advantage of this sensor is its ability to identify a lot more vegetation classes compared to multispectral sensors due to the small spectral bands that allow for detecting more unique spectral signatures from vegetation. Also, it is useful to assess the water quality of many open water aquatic ecosystems, and to classify vegetation characteristics if wetland ecosystems (Govender, et al., 2006). A study from Thenkabail et al (2004) in African rainforests established the advantage of using Hyperion data over IKONOS, ETM+ and ALI sensors; they were able to increase land cover classification accuracies by 45-52% and could explain 36-83% more of the variability in biomass. Govender et al (2006), however, concluded that due to some practical issues multispectral sensors are preferred above hyperspectral sensors.

ALOS – AVNIR-2

The AVNIR-2 sensor is mounted on the ALOS-satellite, a Japanese satellite and launched in 2006. Unfortunately, this satellite recently stopped working. The successor ALOS-2 is scheduled to be launched in 2012, but will only carry a SAR-instrument (PALSAR).

3.4. Optical: Very high resolution satellite sensors

Very high resolution sensors have a spatial resolution of less than 10 meters and have a significantly lower swath width, thus covering a small area. Mapping the Tumucumaque area would therefore become prohibitively expensive due to the amount of data and time needed for processing. Furthermore, also these types of sensors are sensitive to cloud cover. But the relative fast revisit time (up to 10 days) and the pointing ability of the satellites increases the change of obtaining low cloud cover images.

A useful application would be the utilisation of such images to validate coarser images, e.g. Landsat forest cover maps (Wang, et al., 2005), as these sensors are able to resolve single tree crowns (Read, et al., 2003) and to enable measurements of crown sizes (Asner, et al., 2002). However, this would involve plot determination, which can lead to errors in the overall estimates in, for example, forest cover change.

Unfortunately, research in the application of such sensors has been lacking, although high expectation were raised. However, it seems that the high spatial resolution might also cause difficulties; if the pixel size is smaller than the size of the object, then the variability increases dramatically. Hence, very high spatial resolution sensors appear to be less sensitive to plant diversity and total species richness when compared to high resolution satellites (e.g. Landsat) (Nagendra, et al., 2010).

IKONOS/ ORBVIEW

IKONOS is a commercial satellite launched in 1999 and is owned by GeoEye. It provides images in a very high resolution: 4m-resolution in multispectral mode and 1m-resolution in panchromatic mode, which can also be combined. IKONOS images can be obtained through ordering an acquisition time in a certain period of a certain area. OrbView-3 is also a commercial satellite launched in 2003 and owned by GeoEye as well. It provides images in the same spatial resolution as IKONOS. This satellite however does not produce usable imagery as it decayed in 2011. GeoEye-1 and -2 can be considered the sequels with 1 launched in 2008 and 2 is scheduled for launch in 2011 or 2012. GeoEye-1 provides images at 0.41-meter (panchromatic) or at 1.65-meter (multispectral). Unfortunately, not many studies in tropical forested regions have been conducted yet.

QUICKBIRD

QuickBird is a commercial satellite launched in 2001 and is owned by DigitalGlobe. It provides images at 60-70cm resolution in panchromatic mode and at 2.4-2.8m resolution in multispectral mode. It is the first in a constellation of very high resolution satellites; the others are Worldview-1 (launched in 2007) and Worldview-2 (launched in 2009). The mission life of Quickbird is through early 2014. The 'successors' to the Quickbird satellite provide images at an even higher resolution. Worldview-2 is also equipped with additional spectral bands that can aid in vegetation classification. However, application examples in tropical forested regions of these new satellites are not yet available as well.

3.5. Synthetic Aperture Radar sensors

SAR sensors are based on Radar-technology and consist of low frequency electromagnetic radiation, which are generally send out by the satellite and received back to obtain an image from the earth. Hence, these are called active sensors. Passive, radar-based sensors capture the natural radiation that the earth sends out, but these are too weak to provide high resolution images. The advantage of SAR is the independence of weather, in contradiction with optical sensors that are easily affected by atmospheric conditions. It can see through clouds, which is the main constraint in optical satellite imagery, and is capable of obtaining images at day and night. This weather independence, however, does not count for every spectral band that is used within SAR-imagery; the shorter-wavelengths are often too much attenuated by the atmosphere (X-band) (Jones, et al., 2010). The C-, L-, and P-band penetrate the clouds and interact with the canopies of the forest.

The different bands that are used in satellite SAR imagery have different utilisations. Mapping the Tumucumaque region would hence probably require a composite image of different satellite images to identify most of the objects related to ecosystem services. C-band and X-band interact with the canopy providing information about vegetation types, while L-band and P-band SAR penetrate deeper into the forest and can give information about the standing biomass. Furthermore, the polarisation is an important feature in radar imagery. It denotes the orientation of the signal that is emitted and received by the antenna. The signal can be emitted horizontally or vertically, but features on the ground may alternate this orientation. Especially dense forest canopies tend to be depolarising (Jones, et al., 2010). The ability of sensors to receive the different, multiple polarisations is important for a better discrimination of ground objects and hence for more accurate mapping of tropical deforestation (Rigot, et al., 1997; Campbell, 2006).

Due to these advantages, the SAR-satellites have become immensely popular (Jones, et al., 2010). Although SAR is used already for over a decade, only recently the developments have increased the application possibilities with more advanced sensors and processing techniques, and have reduced the suite of shortcomings (Kerr, et al., 2003; Asner, 2001; Jones, et al., 2010). The processing requirements are the main differences with optical imagery; whereas the reflection of the wavelength from green leaves depends on the amount of chlorophyll or greenness with optical imagery, microwave radiation is sensitive to the size, shape and water content of the leaf (Jones, et al., 2010). Also, the spatial resolution is determined by the bandwidth of the radar system and is not related to the distance of observation as is the case with optical imagery (Hoekman, 2000).

ASAR

The ASAR-sensor is mounted on the Envisat-satellite, which was launched in 2002. This sensor operates in the C-band and has 5 polarisation modes. Furthermore, it can operate in several modes with different spatial resolution; images, wave and alternating polarisation modes is approx. 30x30m, wide swath mode is approx. 150 x 150m, and global monitoring mode is 1,000 x 1,000m. Its applications are mainly in ocean and coast studies, snow and ice studies, and land studies (mainly landscape topography). The ASAR will eventually be followed up by Sentinel-1, which is planned for launch in 2013.

SAR

The SAR-sensor is mounted on Radarsat-2, which is of Canadian origin and developed to contribute to monitor environmental change and to support resource sustainability. It was launched in 2007 as the successor of Radarsat-1, which is still operative. This sensor operates also in C-band with multiple polarisation modes, and has an image swath from 45 – 500km, with resolution from 8 – 100m. The temporal resolution is 24 days, but using the 500km wide swath it can provide images at the equator every six days. The Radarsat satellite series will be followed up with the Radarsat constellation, involving three satellites that are scheduled for launch from 2014 onwards.

XSAR

The XSAR-sensor is mounted on TerraSAR-X, a German Earth Observation satellite, and was launched in 2007. It acts as a pair with its sister satellite TanDEM-X, which was launched in 2008, for digital elevation models. The sensor operates in the X-band and has four acquisition modes, providing a spatial resolution of 1 – 18m, with alternating swath width. The temporal resolution is 11 days, but due to swath overlay, the whole Earth can be covered in 2.5 days. The successor to this satellite is the TerraSAR-X/2, which is scheduled to be operative in 2015; 2 years after the design life of TerraSAR-X/1.

PALSAR

The PALSAR-sensor is mounted on the ALOS satellite, a Japanese Earth Observation satellite and was launched in 2006. Unfortunately, the ALOS satellite failed and the operation was completed. This sensor operated in L-band. The successor to this satellite is ALOS-2, which will also carry an L-band SAR sensor and is planned to be launched in 2013.

3.6. Other sensors

LiDAR

Lidar, or laser altimetry, is used in a wide field of applications. The sensors used in forestry are all airborne sensors, meaning that a survey has to be conducted especially for the purpose of forest management, but provides detailed data. The system is rather similar to radar systems; a laser sends out a beam in certain wavelength and receives the signal back due to reflection of the object. The time delay can be used to determine the distance between the sensor and reflecting surface. The wavelength used depends on the objects that are subject to the observation. For vegetation studies wavelengths in the range of 900 – 1064 nm are generally used, but the disadvantage is the absorption by clouds (Lefsky, et al., 2002). However, the time of data collection can be chosen as an airborne sensor is not in an orbit.

Laser scanners are able to provide a 3D model of the forest due to the small footprint of the scanning system and can hence provide information about tree height, biomass, timber volume, etc. This 3D image is generated by sensing the parts of the beam that are reflected by the different layers of the forest.

3.7. Electromagnetic spectrum and reflectance

The elements (vegetation, water, soil) have specific components that determine the nature of reflectance and absorption of the radiation. This phenomenon is logically of utmost importance for distinction of the elements on a satellite image, and hence understanding the interactions of the radiation with vegetation, soil and water is important for interpretation of the final satellite image in order to infer the properties of a land surface. The reflecting and absorbing components depend on the type of radiation used: visible, infrared (both considered 'optical') or microwaves (see figure 11 for place in electromagnetic spectrum). The principle of the reflectance (or backscatter with microwave sensors) is that the components of the elements reflect a certain frequency or combination of certain frequencies (and absorb others) of the electromagnetic spectrum, which is called a signature. This signature can be detected by the sensor, but the ability of distinguishing between different features depends on the capabilities of the sensor itself. Most sensors operate in certain bands that detect a certain range of the spectrum (bandwidth), meaning that not all reflectance will be recorded. However, the sensors described in this chapter have been chosen according to their ability to capture reflectance from vegetation (see annex 4 for the place of the spectral bands in the spectrum).

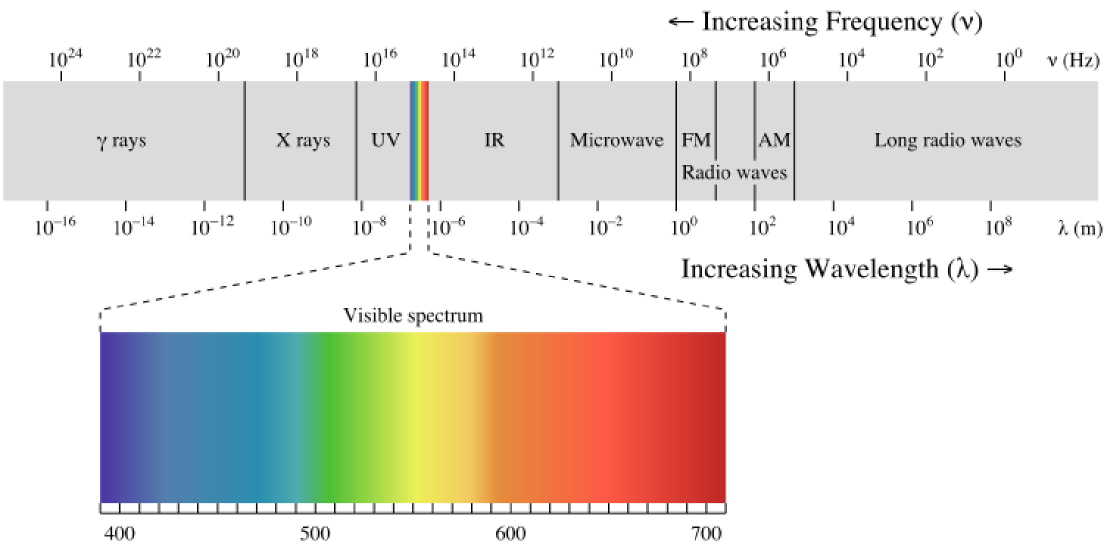

Figure 11: Electromagnetic spectrum

Absorbance is also important for identifying features on the ground. A certain element may almost completely absorb a certain frequency, which results in very dark pixels on the satellite image. Furthermore, spectral transmission is a third form of interaction of radiation that occurs at certain features (e.g. leaves and water). This transmission gives rise to absorption profiles and characteristic scattering that are useful in diagnosing surface characteristics (Jones, et al., 2010), but is not further discussed here.

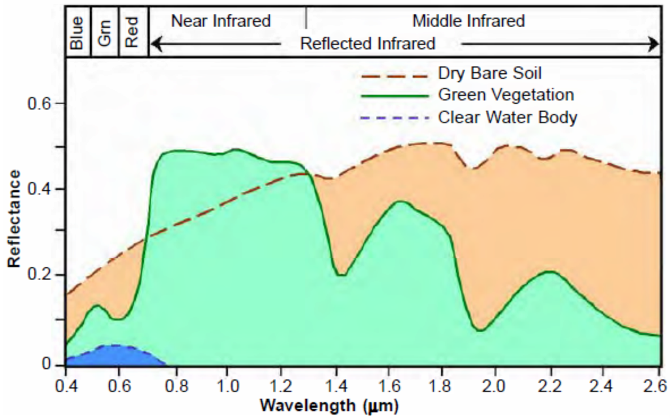

Figure 12: Spectral signature of dry bare soil, green vegetation and a clear water body

3.7.1. Vegetation

Optical

The most important elements of vegetation determining the ‘detectability’ are the leaves (from both trees and plants) and the canopies as a system. Additionally, stems reflect and absorb also a significant amount of radiation, but for simplicity it is common to ignore the contributions made by stems (Jones, et al., 2010). The amount of radiation detected by the satellite sensor depends on the interactions of radiation with plant leaves and their chemical and structural characteristics (see table 6). Understanding these characteristics will give scope on distinguishing species based on reflected radiation. However, many additional factors complicate this distinction, e.g. plant growth, stresses and the arrangement of leaves.

Wavelengths				Chemical
0.43,	0.46,	0.64,	0.66	Chlorophyll
0.97,	1.2,	1.4,	1.94	Water
1.51,	2.18			Protein, nitrogen
2.31				Oil
1.69				Lignin
1.78				Cellulose and sugar

Table 6: Absorption features in visible and near infrared related to leaf components

The main plant characteristics that determine the absorptance are the water content and chlorophyll, with water as the dominant contributor to the observed radiative properties in the infrared, where most pigments do not absorb significantly. Generally leaves absorb a large proportion of radiation in the visible, though with a dip in the green, and absorb relatively little radiation in the infrared, except in the water absorption band, which relates to the water content in the leaves (Jones, et al., 2010) (see figure 15). The most important plant characteristic determining radiation absorption and transmission by canopies is the Leaf Area Index (LAI) (Jones, et al., 2010).

The interactions of radiation with plant leaves occur through the angle of incidence and the arrangement of leaves (e.g. canopies), as shown in figures 13 and 14. This results in radiation scattering and secondary and tertiary interactions between the leaves at different levels in the canopy, as well as between leaves and the underlying soil (Jones, et al., 2010). These interactions determine the magnitude of spectral reflectance, spectral absorbance and spectral transmission, as the radiation intensity decreases with increased numbers of interactions. As a consequent the canopy reflection alters from the reflection from individual leaves.

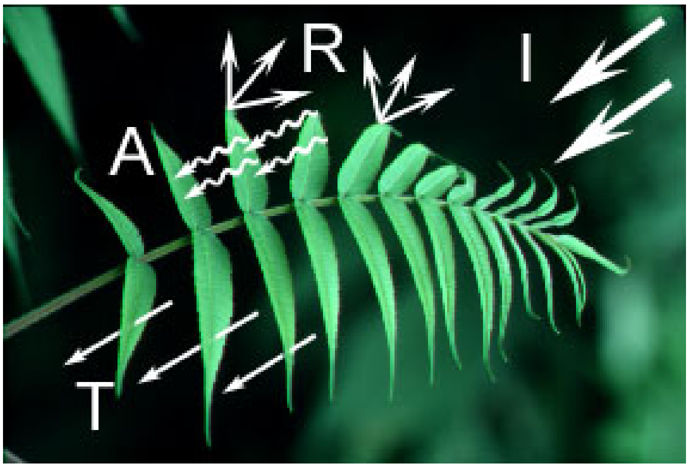

Figure 13: Leaf interaction with radiation; I = incidence, R = reflectance, A = Absorption, T = Transmission

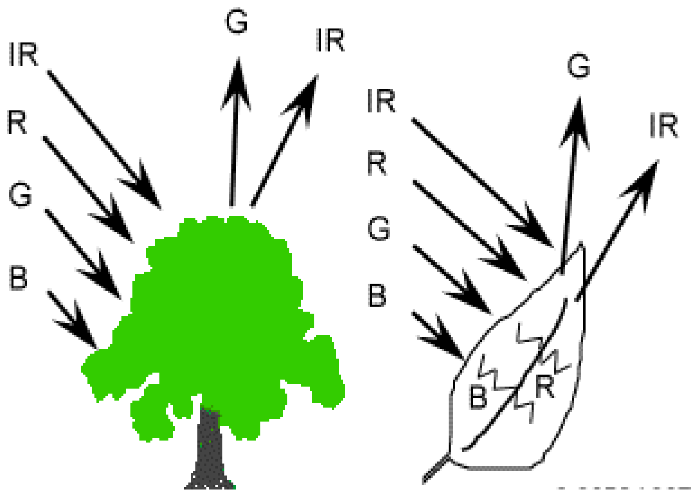

Figure 14: Canopy interaction in the visible and infrared region (from: Canadian Centre for Remote Sensing)

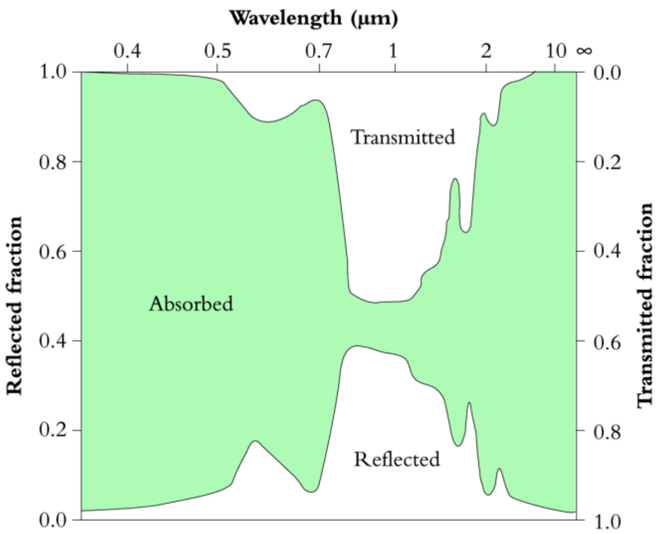

Figure 15: Typical patterns of radiation absorption, transmission, and reflections for plant leaves

Microwave

Microwaves interact with mainly the physical structure and the moisture content and not with chemical components or pigmentation of leaves. A vegetation canopy forms a heterogeneous volume consisting of different components (Jones, et al., 2010) and these individual components (leaves, stems, branches, trunks, soil) determine the volume scattering. The volume scattering by leaves and canopies is larger for shorter wavelengths (C- and X- band) and compared to soil surface scattering it is usually greater and hence suitable for detecting changes in forest cover (Jones, et al., 2010; Wielaard, 2011). Longer wavelengths (L- and P-band) penetrate the canopy and give also information about trunks and larger branches are therefore suitable for vegetation classification as more information can be collected about the texture of the vegetation classes. Also, the longer wavelengths are suitable for estimating biomass, albeit with a medium uncertainty (see chapter 4.3.). Figure 16 shows the individual scattering processes that together create the overall scattering behaviour of the forest. These scattering processes are dependent on the type of microwave radiation used: process 1 will dominate the backscatter of the shorter wavelengths, while process 4 is the most important contributor to the backscatter of the longer wavelengths (van der Sanden, 1997).

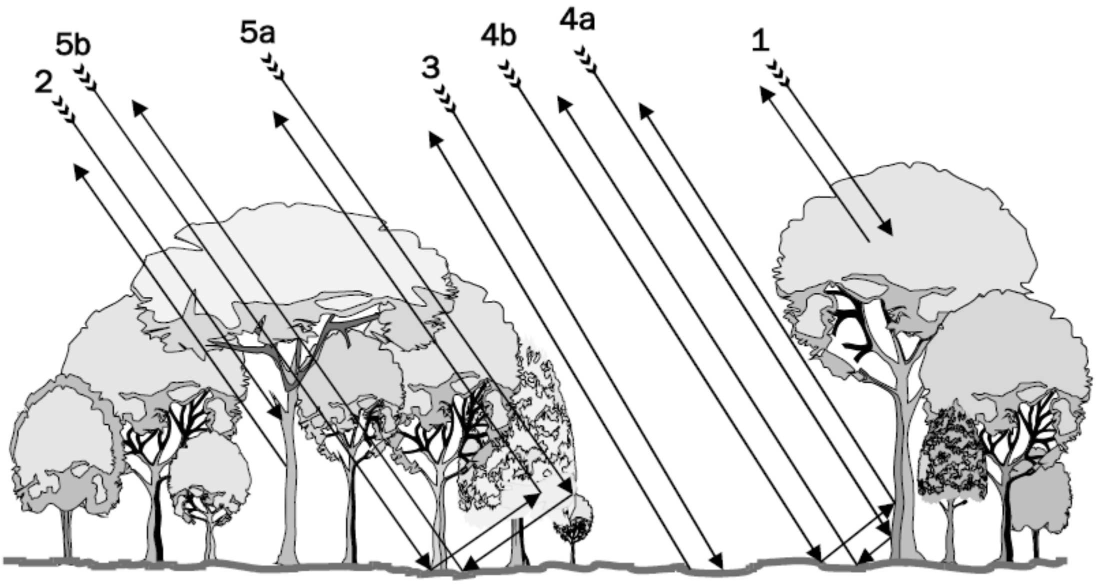

Figure 16: : Dominant backscattering sources in forests: (1) crown volume scattering, (2) direct scattering from tree trunks, (3) direct scattering from the soil surface, (4a) trunk – ground scattering, (4b) ground – trunk scattering, (5a) crown – ground scattering (van der Sanden, 1997)

3.7.2. Water

Optical

The nature of reflectance and absorption of the radiation by water is strongly determined by the characteristics of the water and its contents, which are (i) water turbidity, (ii) chlorophyll content, (iii) surface roughness, (iv) water depth, and (v) nature of substrate below the water body (Jones, et al., 2010). The colour of the water is determined by the water volume, known as volume reflection that occurs over a range of depths rather than at the surface (Campbell, 2006).This colour changes according to an increasing water depth or due to impurities or sediments. Clean water absorbs almost all radiation (see figure 17), especially in the NIR and MIR where water would than appear very dark and stand out in complete contrast with surrounding elements. Optical sensors are thus suitable for delineation of water bodies, as long as it is not covered by vegetation.

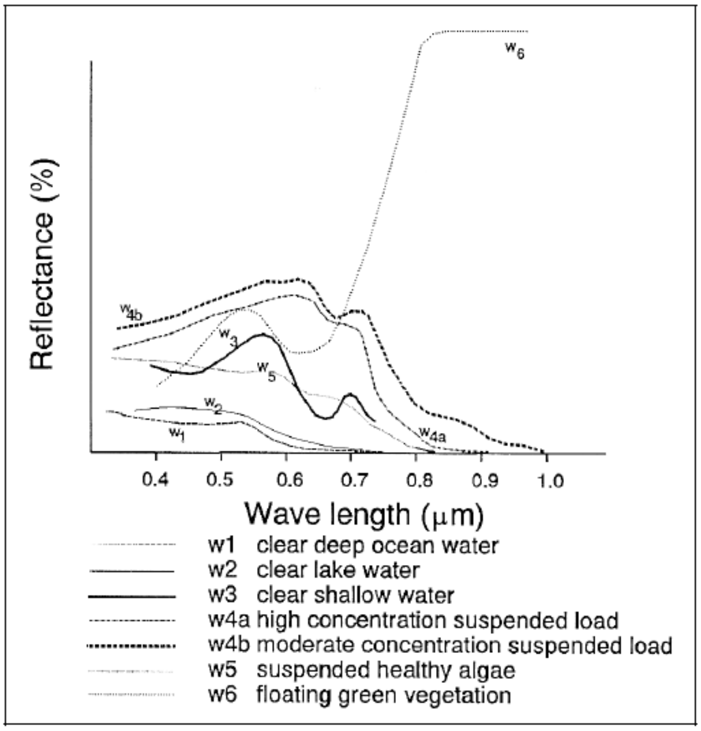

Figure 17: Reflectance properties of different water types

The difficulty in detecting water with optical imagery is that shade (from clouds and vegetation) and water are almost similar in their spectral reflectance. This may complicate, for example, the estimation of the water quantity and land cover classification, and is particularly the case in a frequent cloud covered area such as the Tumucumaque area. Hence validation is necessary to prevent over- or underestimates.

Microwave

The reflected radiation from water depends on the roughness of the surface (surface scattering); a smooth water surface will reflect the signal specularly away from the sensor, while a rough surface will diffusely reflect the signal with some of the diffuse radiation scattering back to the sensor. The roughness of a water surface depends on the wave heights in comparison with the incidence radiation (type of band); X- and C-bands are sensitive to centimetre surface wave heights and L- and P-bands are sensitive to decimetre surface wave heights (Schultz, et al., 2000). Microwave signals are not altered due to sediments or high levels of chlorophyll, as is the case with optical imagery, and are therefore not suitable for water quality detection.

The specular reflection of the radiation makes microwave sensors also suitable for water body delineation, with the advantage that they are not affected by cloud coverage. This delineation can best be done with longer incidence angels to reduce the backscatter response. (Schultz, et al., 2000).

4. Biomass, REDD+ and remote sensing

4.1. Introduction

Currently, estimating biomass in a forest has become a valuable aspect of nature conservation as a financial resource through, for example, the REDD+ scheme. REDD+ stands for Reduced Emissions from Deforestation and Degradation and enhancement of forest carbon stocks, and is a proposal to provide financial incentives to encourage developing countries to voluntarily decrease their deforestation and degradation below a certain baseline. Countries that succeed to reduce emissions below the baseline can sell their carbon credits on the international carbon market. Consequently, this reduction of emissions will also contribute to climate change mitigation, biodiversity conservation and ecosystem goods and services protection. This chapter attempts to clarify the requirements within the REDD+ scheme for estimating the biomass (and thus carbon stock) and relates that to remote sensing.

4.2. REDD+ requirements

The REDD+ mechanism is designed to be implemented at national scale. This logically involves a national monitoring protocol that is in accordance with the IPCC Good Practice Guidelines (GPG) (IPCC, 2006). The guidelines are developed to support countries in the development of a national monitoring scheme that provides neither overestimates nor underestimates, and reduces the uncertainty as far as practicable. Furthermore, internationally agreed rules for monitoring, reporting and verification (MRV) are needed for crediting REDD+ activities (Angelsen, et al., 2008). Subsequently, project based biomass inventories should match the national protocol of the concerned country. Considering the location of the Tumucumaque area in Brazil, Suriname and French Guyana, this might involve three differing monitoring protocols. However, at local/project scale additional monitoring requirements must be set for verification and implementation of payment schemes. Detailed verification of biomass estimates from remote sensing can best be done through field work, although this depends on available capacity and capabilities and can become rather expensive.

The IPCC GPG distinguishes three levels (called: ‘Tiers’) of detail and accuracy. The use of these levels depends on the data that is available at national scale, but it is good practice to adopt the most detailed Tier (Tier 3) when possible. Tier 1 uses the basic method with default emission factors and spatially coarse (nationally or globally) data, e.g. deforestation rates and global land cover maps. Tier 2 is similar to Tier 1, but applies emissions factors that are defined by the country for the main land uses. Tier 3 uses higher order methods specific for each country and repeated through time, and driven by high-resolution activity data and disaggregated at sub-national to fine grid scales (Teobaldelli, et al., 2010; Gibbs, et al., 2007; Aalde, et al., 2006). For the sub-national approach of the Tumucumaque area applying Tier 3 is thus recommended. The carbon stock estimates should be transparent, consistent, accurate, complete, comparable, and reduce uncertainties (IPCC, 2006; Herold, et al., 2009; Herold, et al., 2011). However, the degree of these requirements depends on capabilities and capacities at national or implementation scale.

Within REDD+ two variables must be monitored: forest area change and carbon stock change estimation (Herold, et al., 2009). The latter is generally calculated by estimation of the biomass. For an accurate estimation of the biomass and the carbon stock, the IPCC GPG requires to take into account the following carbon pools:

- Aboveground living biomass;
- Belowground living biomass;
- Dead wood;
- Litter;
- Soil organic matter.

Although it would be ideal to monitor all five carbon pools, it likely consumes much effort and can hence be expensive. Therefore, most carbon pools can be estimated using their relation with the total aboveground living biomass. Besides these pools, the forest carbon stock change should be estimated as well according to the IPCC GPG. This will give insight in the transfer of carbon between the pools and removals due to certain causes (IPCC, 2006). Changes can be caused by:

- Human activities (establishing and harvesting plantation, commercial felling, fuel wood gathering and other management activities);
- Natural losses (fire, windstorms, insects, diseases, other disturbances).

Furthermore, as the carbon stock can change according to differences in the landscape, it is considered good practice to stratify the forest land into various sub categories (IPCC, 2006). The stratification should lead to fewer errors in estimations and reduces uncertainty.

4.3. Quantification of biomass

The biomass is strongly related to the carbon stock and the total carbon stock of a forest is embodied in several distinctive pools; aboveground living and dead biomass, root biomass and soil biomass. The most important and largest carbon pool in a forest is the aboveground living biomass, which is often directly impacted by deforestation and degradation. The aboveground dead biomass (e.g. dead standing trees, broken branches and leaves) is estimated to be ~10–20% of the total estimated aboveground biomass in a mature forest (Harmon, et al., 1996; Delaney, et al., 1998; Houghton, et al., 2001; Achard, et al., 2002; Gibbs, et al., 2007). The root biomass is generally estimated to be ~20% of the aboveground forest carbons stocks (Houghton, et al., 2001; Achard, et al., 2002; Ramankutty, et al., 2007; Gibbs, et al., 2007). The soil carbon stock is typically dependent on the soil type, e.g. the peat swamp forests in Southeast Asia are a massive carbon stock. In many cases the total carbon stock in a forest can be adequately derived from the aboveground biomass. The IPCC GPG (IPCC, 2006) provides default factors for estimating the carbon in the aboveground biomass and the belowground biomass in relation to the aboveground biomass, specified per climatic region.

The most direct way to estimate the carbon stored in the aboveground living forest biomass is to cut down all the trees, dry them and weigh the biomass. The carbon content of this dried biomass is approximately 50% (Westlake, 1966; Gibbs, et al., 2007). However, this is, besides being very destructive, expensive and impractical. Hence it is important to use a method that enables quantification of carbon stock on a large scale in a rather direct way and accurate at the same time for inclusion in the REDD+ scheme. This is where remote sensing can play a very important role. Much effort has therefore been put in the development of an accurate method (Brown, 1997; Chave, et al., 2005; Saatchi, et al.).

Currently, the following tools can be used for estimating biomass (Gibbs, et al., 2007):

- Biome averages
- Forest inventory
- Optical remote sensors
- Very high resolution airborne optical remote sensors
- Radar remote sensors
- Laser remote sensors

In annex 5 is an extensive overview added that gives advantages and limitations of these tools. Concisely, these tools have the following characteristics:

Tool	Description	Uncertainty
Biome averages	Estimates of average forest carbon stocks for broad forest categories based on a variety of input data sources	High
Forest inventory	Relates ground-based measurements of tree diameters or volume to forest carbon stocks using allometric relationships	Low
Optical remote sensors	Uses visible and infrared wavelengths (e.g. Landsat, SPOT) to measure spectral indices and correlate to ground-based forest carbon measurements	High
Very high resolution airborne optical remote sensors	Uses very high resolution (~10-20cm) images to measure tree height and crown area and allometry to estimate carbon stocks	Low to medium
Radar remote sensors	Uses microwave or radar signal (e.g. SAR) to measure forest vertical structure	Medium
Laser remote sensors	LiDAR uses laser light to estimate forest height/vertical structure	Low to medium

Table 7: Biomass estimation tools and characteristics (after Gibbs et al, 2007)

4.4. Conclusions

The REDD+ programme has currently no specific requirements, but has yet mainly guidelines based on the IPCC GPG. Choosing a methodology is therefore not restricted to just a few methods, but the methods that will be adopted should be harmonised with national protocols for REDD+ and the related MRV. For sub national scale implementation Tier 3 should be adopted as determined by the IPCC GPG. This is the most detailed tier and requires high resolution and detailed data and should be repeated through time. This repetition depends on the capabilities and capacities available, but following the Iwokrama contract, this should be determined at twice a year plus an additional independent third-party check.

The elements that must be monitored under REDD+ are at least the following:

- Forest area;
- Carbon stock;
- Human activities;
- Natural losses;
- Vegetation classes as part of the required stratification.

The estimates should meet the requirements of transparency, consistency, accurateness, completeness, comparability and should reduce uncertainties. The latter means the utilisation of tools (remote sensors) that have a high resolution as also is part of Tier 3. Remote sensors or tools that have a relatively low uncertainty are listed in table 7; currently these are forest inventories, laser remote sensors, radar remote sensors and very high resolution airborne remote sensors (the last two have a higher uncertainty compared with the first two). Biomass estimation through biome averages and optical remote sensors have a high uncertainty and can therefore be considered unsuitable for utilisation within Tier 3, unless improved, more sophisticated methods are available. Validation of the estimates gained from remote sensing can best be done through field work (forest inventories).

5. Limitations

5.1. Introduction

The limitations in applying remote sensing are determined by the region, time of acquisition, level of detail, the budget of a project and the set of requirements and criteria as determined on beforehand by the goal of the project. Understanding and considering these limitations on beforehand will benefit directly the efficiency and effectiveness of the monitoring. Therefore they are described in this chapter as they will influence the overall possibilities of application of remote sensing.

Regarding the GSI-project in Tumucumaque it is important that the monitoring of ecosystem elements is efficient and effective in means of counteracting abilities. It is thus important to obtain satellite data frequently that requires little processing time and thus quick availability, and at the other hand data that is accurate and detailed enough for discrimination of sufficient vegetation types, accurate detection of ecosystem elements (as discussed in chapter 2.2), and accurate estimation of the standing biomass. This chapter will thus assess the limitations regarding these two types of criteria sets.

5.2. General limiters

5.2.1. Atmospheric constituents

Atmospheric constituents are the main limiters of collecting accurate earth data as natural phenomena may interfere with the reflections of the earth's elements that are received by the satellites. Most limitations that affect data collection for the Tumucumaque area are due to weather conditions and most of the other constituents do not or rarely occur in the area. The atmospheric constituents are the following (EUMETSAT, 2011):

- Water vapour
- Dust and aerosols
- Volcanic ash plumes
- Smoke (from fire)
- Ozone
- Industrial haze

Both optical and radar satellite instruments are affected by the weather conditions, but radar sensors might be affected less. The main factors that may affect the image quality are excessive clouds (see 4.2.2.), the variability in moisture content in the forest and leaves, and ozone. The variability in moisture content is a limiting factor when comparing different years and occurs mainly at radar (SAR) images (Lucas, et al., 2004) and need to be corrected for in order to map large areas and provide consistent time-series (Wielaard, 2011). Both cloud cover and moisture content are least limiting in the dry season, suggesting that imagery taken in the dry season are of best quality, e.g. for discrimination of vegetation types (Huete, et al., 2006; Bonal, et al., 2008; Pennec, et al., 2011; Gond, et al., 2011). It must also be noted that rain interferes with SAR, especially in X-band, but in practice rarely occurs (Wielaard, 2011).

5.2.2. Cloud cover

Tropical regions and especially tropical rain forests are frequently covered by clouds, also the Amazon basin in South-America. At regional level the cloud cover varies: the south-eastern Amazon basin is relatively cloud free during the dry season, while the northern Amazon basin (Guiana Shield) was even in the dry season covered with clouds (Asner, 2001). Asner (2001) considered that a cloud cover of 30%, although arbitrarily selected, is the maximum allowable in order for analyses of land cover to be effective. Cloud cover can be very misleading in estimating forest loss, even though cloud cover might be very small and can therefore not be ignored or simply dropped out (Butler, et al., 2007). The Tumucumaque is situated in the northern Amazon basin and therefore obtaining cloud-free data is expected to be difficult with a maximum threshold of 30% cloud coverage. The highest changes of collecting cloud free data are in the dry season. Besides this higher probability of obtaining cloud-free data in the dry season, this season also allows better distinction between vegetation types due to the increased photosynthetic activity of the vegetation (Huete, et al., 2006; Bonal, et al., 2008; Pennec, et al., 2011; Gond, et al., 2011). It must however be noted that cloud cover can be significantly lower in less humid areas and hence cloud cover constraints must be assessed for each project separately in order not to exclude possibilities based on general assumptions.

Options to overcome cloud cover constraint

Overcoming the limitations regarding cloud cover associated with optical and thermal sensors is possible by using SAR as microwave can penetrate clouds and contaminated atmospheres (Saatchi, et al., 1997). Another method to obtain cloud free data is sub-scene compositing. This approach consists of integrating two or more scenes with a different cloud cover pattern into a cloud-free composite image (Sano, et al., 2007). With applying this method only images can be used that are taken within the same time span as the base image as seasonal behaviour may change the appearance of the vegetation. Within this method alternative satellites can be used that have a similar spatial resolution (Sano, et al., 2007). However, this system is considered to become prohibitively expensive (Lucas, et al., 2004).

FAO (1996) introduced as method in which the data was randomly selected as wall-to-wall (an analysis that covers the full spatial extent of the forested areas) data was often too expensive. However, Tucker and Townshend (2000) found in their study that these methods had a much higher standard error. They concluded that wall-to-wall data sets are essential if deforestation is to be estimated to a reliable degree. Furthermore, random sampling of tropical deforestation using, for example, Landsat or SPOT sensor data provided inadequate estimates of actual deforestation, due largely to the spatially concentration of this process (Strategies for monitoring tropical deforestation using satellite data, 2000) (Lucas, et al., 2004).

5.2.3. Effect cloud coverage on availability

Optical remote sensors are particularly sensitive to the cloud coverage over a certain area, e.g. the Tumucumaque area. Consequently, it is likely to be hard to obtain images that are useful for accurate land cover estimation. To visualise this constraint, images from the SPOT and Landsat satellites are assessed on their data availability with the threshold of 30% cloud coverage for the study area for two randomly selected years (2007 & 2010). Their coverage does also reflect to some extent the availability of cloud free images from similar sensors. It appeared that SPOT-4 (20m resolution multispectral) could not provide a complete coverage of the study area for both years (see figure 18).

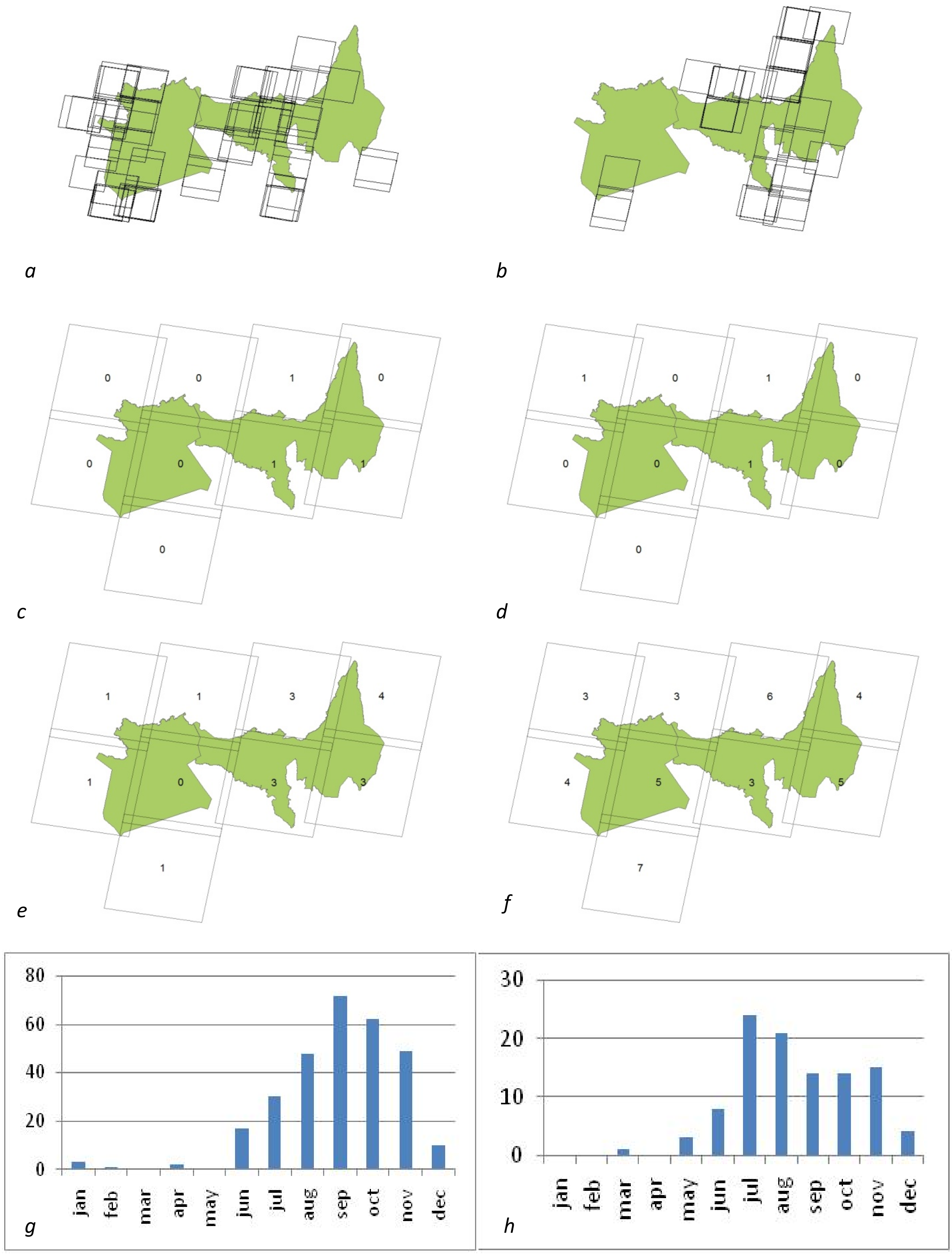

Figure 18: Cloud cover constraint with a 30% threshold in optical imagery for randomly selected years; *a* and *b* show scenes available for SPOT 4 of 2007 and 2010 respectively (data available from SPOTimage). Figures *c* and *d* (Landsat TM) and *e* and *f* (Landsat ETM+) show coverage for these sensors for 2007 and 2010 respectively. Figures *g* and *h* show total number of scenes available for Landsat ETM+ and Landsat TM per month (data available from New Earth Explorer).

The coverage of the Landsat 7 (ETM+) satellite seems much better, probably due to a larger footprint (and also a lower spatial resolution), but only for 2010 a complete coverage could be obtained; 2007 lacked in one footprint. Landsat 5 (TM) has in contrary a much lower coverage; for both years it appeared that from only a few footprints a <30% cc-scene could be obtained. This is probably due to the low storage capacity of the satellite, which consequently deletes images even before they are sent to the earth's receiving stations.

If we look at the time of acquisition of these relatively cloud free images for both Landsat TM and ETM+, then it appears that the highest change of acquiring these images is in the dry season, from July until November. Figure 5.1*g* and *h* shows the total number of images with <30% cloud coverage for all footprints covering the Tumucumaque area for Landsat ETM+ (*g*) from 2000-2010, and for Landsat TM (*h*) from 1985-2010. This suggests that it is difficult or simply not possible to create overview maps of the entire area twice a year, a frequency that should at least be used for monitoring purposes. It must also be noted that the footprints covering the study area are not always entirely within the area, which allows for utilisation of other scenes as well that have relatively low cloud coverage in the part that does cover the area. However, this will significantly increase the time needed for image selection and processing, and the benefit may not be very significant.

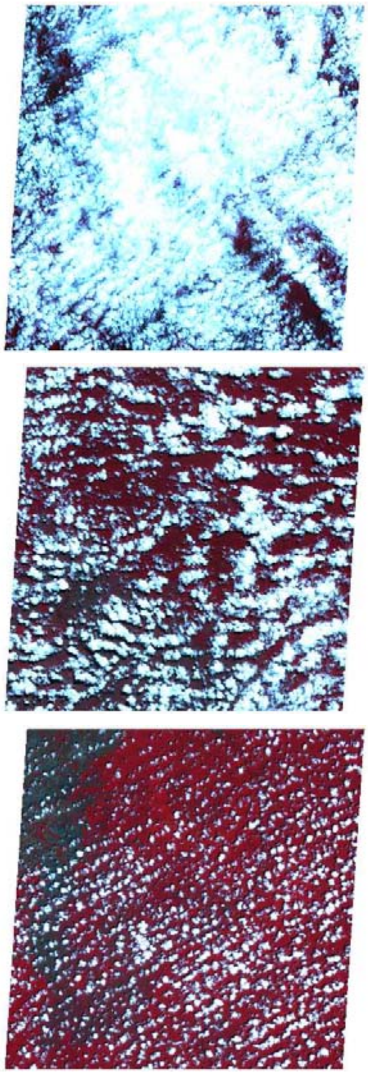

Figure 19: ASTER data showing cloud cover constraint (90%, 50%, 30% cloud cover respectively)

5.3. Monitoring requirements

5.3.1. Frequency and continuation

The frequency with which the data sets can be collected and processed is important to keep up with the changes in the forest. A low frequency will cause a drop in the effectiveness of the response actions in the case of pressures and therefore the data sets must be delivered twice a year, following the Iwokrama contract, which requires monitoring to be conducted on a regular basis and reporting of the state of the ecosystem services twice a year (UNDP, 2008). This frequency is also necessary to avoid errors due to climatic and seasonal variability, and to follow forest regeneration in which the spatial signature can be rapidly changing (GOFC-GOLD, 2010). Considering the extent of the study area, twice a year is probably the limit. Additionally, these data sets must be delivered within the shortest time possible after images have been taken.

The data sets that are used for the monitoring should be uniform throughout the duration of the contract, i.e. using images from the same sensors will contribute to efficiency through quicker (automated) processing and interpretation. Satellite programme continuation is thus important to consider when choosing the sensors for monitoring. This continuation is described in chapter 3 per satellite if information was available. However, even between different scenes from the same sensor radiometric correction might be necessary to unify reflectance and classification.

5.3.2. Detail and accuracy

A highly detailed satellite image will logically enable accurate estimation of forest cover change, biomass estimation and other important changes. The amount of detail on an image is related to the spatial resolution and an increasing spatial resolution also increases the costs and processing time. It is therefore important to consider also how much detail must be on an image. This decision will depend on the current status of the forest. If an area is a so called 'hot-spot' (an area with increased threatening activities) a higher detail is necessary to map the occurring pressures as well as the consequences, but won't be needed for an undisturbed area. Several methods have been researched and proposed to integrate high resolution data in monitoring in combination with coarser spatial resolution images (Wang, et al., 2005; Fraser, et al., 2005; Hyde-Hecker, 2011); this reduces the costs and provides sufficient detail when and where necessary.

The overall accuracy is also determined by the spatial resolution. While in mapping some of the elements a medium accuracy will do, for biomass estimation it is considered good practice to use data that is as accurate as possible. But also in monitoring forest cover change, especially small changes as small scale gold mining, slash and burning and smart logging, accurate data is needed for detection and counteractions.

5.4. General sensor limitations

5.4.1. Optical imagery

Optical datasets are probably easiest to interpret, but are sensitive to certain limitations that influence final products if not held into account or corrected for. One of these limitations is cloud cover, which is already discussed in chapter 5.2. Another limitation is that it is unable to penetrate the forest canopy and lacks hence in the provision of ecosystem elements data below the canopy, as well as distinguishing between plantations and forest. These limitations can be overcome with the use of or synergism with SAR data (Wielaard, 2011).

Other limits are the inability of sensors to distinct between shade and water, which are almost similar in their spectral signature. Shade is often a result from the cloud cover on an image, which is one of the reasons to adopt the 30% threshold. Shade can obstruct the quantification of water in the area and should be corrected for, especially if the classification of a scene is automated. If cloud free images cannot be obtained or created, then visual interpretation is preferred, but can increase the total costs (GOFC-GOLD, 2010).

5.4.2. SAR imagery

Although SAR seems promising in overcoming optical sensor limitations, it has its own shortcomings and difficulties as well. SAR imagery is affected by topography and relief as it is 'side-looking', which can be corrected with ortho-rectification and relief-correction. Furthermore, the SAR-signal is strongly influenced by moisture levels of the soil and can be affected by heavy rain, although the latter rarely occurs, and should be considered in image selection and corrected for if used to map large areas and/or to provide consistent time-series (Wielaard, 2011). Due to the fundamental difference in sensors, SAR is less suitable for mapping land cover/ vegetation classes. Currently a problem is the absence of space-borne long wavelength radar sensors (L- and P-band). If validation is needed of SAR-imagery, then very high resolution optical data is needed, e.g. from aerial overflight data or IKONOS, which can be expensive. Although Radar has been demonstrated to be useful, it is yet not widely used operationally for forest monitoring over large areas (GOFC-GOLD, 2010).

5.5. Conclusion

Most of the limitations that in general influence the monitoring programme come forth from the scope of the project itself. For monitoring ecosystem services and occurring pressures as proposed for the Tumucumaque area it is important to use accurate and detailed data, especially if REDD+ is included. Setting high requirements will definitely contribute significantly to accurate maps that allow for effective monitoring. However, this will also inevitably involve limitations that are mentioned above and in combination with other natural limitations, monitoring may become not so cost efficient as sophisticated methods will be necessary to overcome most of the limitations. Currently, studies are being conducted to improve the efficiency and already solutions have been found, but the main constraint is still the lack of large scale implementation (GOFC-GOLD, 2010).

The choice that must be made involves some trade-off in the requirements. If maps must be delivered in near-real time, the maps will be in coarse spatial resolution. Although this would allow for quick counteraction, many small scale activities cannot be seen until sub-pixel information is extracted, or higher resolution images are used. Using finer scale resolution images will compromise on the rapid availability, but allows for better recognition of forest cover changes. Furthermore, there is logically a trade-off between budget and effectiveness and efficiency.

In summary, the following requirements are used to assess the remote sensors for application in the long term monitoring of the study area, although not exhaustive as a combination of sensors can be used to detect different aspects of the ecosystems:

- Long-term annual monitoring, preferably twice a year;
- Detection of major landscape changes;
- Detection of minor landscape changes;
- Ability to detect driving forces of deforestation/degradation;
- The ability to follow carbon sequestration;
- Maximum cloud cover of 30% for analyses;
- Wall-to-wall datasets.

6. Monitoring of elements

6.1. Water

6.1.1. Water quantity

Locating water bodies, e.g. lakes, rivers, creeks, etc., requires delineation of the extent of these water bodies. With optical imagery the colour that is seen on the image depends on the chemical composition of water and its contents, e.g. chlorophyll (see chapter 3.7). Clean water absorbs almost all radiation in the infrared region (NIR and MIR) and hence stands out in complete contrast with surrounding elements with very clear boundaries. However, optical imagery is subject to atmospheric constituents causing difficulties in the exact definition of the water boundaries due to cloud cover. Delineation of water bodies can hence better be done using SAR in areas as Tumucumaque. SAR sensors with a high incidence angle (> 45°) and HH-polarisation are most suitable for the delineation (Schultz, et al., 2000). VV-polarisations are much more sensitive to small-scale surface roughness causing water to appear bright on an image and reducing the contrast between water and surrounding elements (Barber, et al., 1996; Khalili, 2007). Another advantage of SAR is that it is able to penetrate the canopy to sense rivers and creeks that are underneath it.

Due to the sensitivity of SAR to moisture content of the soil (and vegetation) it is highly suitable to measure the extent of flooded areas (Wielaard, 2011). However, SAR relies on its backscatter which can be affected by the surface roughness and can reduce the accuracy (Jones, et al., 2010). It is therefore important to map the surface so that it can be corrected for, using other data sources. Because SAR can map flooded areas even beneath a canopy, it is also very well suited to monitor many types of wetlands (Melack, 2004). But mapping wetlands can best be done with multi-source data, as concluded by Bwangoy et al (2010). They managed to create the most spatially detailed Congo Basin wetland map to date using optical and SAR imagery, together with derivations from the topography. Each data source contributed to the overall characterisation of the wetland. However, optical imagery is subject to persistent cloud cover limiting its application possibilities, while it was considered a very important contributor. The indices derived from the topography, e.g. elevation, were used as a primary discriminator, emphasising the importance of landscape structure in wetland mapping and the potential of multi-source data for application in tropical forest conservation.

It is possible to measure the water discharge of a river remotely. The accuracy of these measurements are however dependent on the relationship between increasing discharge and area covered by the flow; the smoother the relationship, the more accurate the measurements. Logically, ground data is necessary for calibration. MODIS and AVHRR are in particular useful because of their frequent image acquisition and regional coverage (Mertes, et al., 2004).

6.1.2. Water quality

It is possible to detect water quality using remote sensing. The properties that may be estimated includes concentration of total suspended matter, chlorophyll content and coloured dissolved organic matter (Mertes, et al., 2004). Water quality can best be measured from optical and near-infrared data; SAR is not suitable for this purpose (Wielaard, 2011). Most properties can be detected through the colour as seen on the satellite image such as shades of red due to algae. Turbidity is another parameter, although still related to colour, and refers to the amount of sediment dissolved (in mg/L). Techniques used to measure turbidity are based on spectral signatures in combination with field data. This *in situ* data should be collected frequently for both the calculation as well as validation to increase accuracy. Hyperspectral data is in particular useful in remote sensing of water quality due to its ability to distinguish different spectral signatures that relate to water constituents (Govender, et al., 2006).

The disadvantages in remote sensing of water quality are firstly its dependence on optical imagery; cloud cover will play an obstructing role in the measurements. Although coarse resolution images (e.g. MODIS) can be used in such studies, the resolution misses many properties and will not be able to map all rivers in a certain area. Another disadvantage is that certain constituents are completely dissolved in water and are hence not detectable using remote sensing. One example is the river pollution due to illegal gold mining. Although the sediment is visible, no estimation can be made of the amount of mercury released in the rivers. Water quality measurements will hence remain dependent on conventional field data.

6.2. Vegetation

Monitoring the vegetation cover can be considered the most important element as it relates directly to activities that are either human induced or occur naturally. Thereby, it contributes to identification of habitats for specific species and aids in biomass estimation for which forest stratification is very important (see chapter 6.3.). A regular update of the vegetation map is important to detect changes and to counteract with pressures when necessary. Change detection is described in 6.2.2.

6.2.1. Vegetation cover

There are multiple methods to classify the vegetation. A prerequisite is a detailed stratification as advised within REDD+ to aid carbon stock estimation. This involves inclusion of layers related to topology, soil types, climate, etc. and can become an extensive job. However, after this map has been created, a regular update is not necessary if this one is separated from change detection. A highly detailed forest/vegetation classification requires the use of high spatial resolution images, but is accompanied with some constraints:

- Such detailed maps should be free from cloud cover, but this part of the Amazon basin is subject to persistent cloud cover (Asner, 2001);
- SAR would hence be the better option due to its weather independency, but is less suitable in forest type separation than optical imagery (Wielaard, 2011);
- Highly frequent, but coarse spatial resolution imagery is also less suitable as it lacks in detail, although it could provide cloud-free data.
- Very high resolution imagery are generally too detailed for vegetation class discrimination

Considering that SAR is less suitable, vegetation class discrimination is hence dependent on optical imagery. Many studies have been conducted to improve classification; too much to mention and to compare in this review, and it is hard to say what the best method is. Normalised Difference Vegetation Index is a common method and correlates directly with vegetation productivity. Hence it is useful for mapping vegetation distribution (Pettorelli, et al., 2005), but has its limitations as well. Considering also the extent of the Tumucumaque area, data sets similar to Landsat are most suitable (e.g. Landsat, SPOT, IRS, etc.). These data sets have sufficient spatial resolution to distinguish between vegetation types, a generally high probability to obtain an annual cloud free composite image, and can be improved with additional data sets. However, for Tumucumaque the cloud cover may be too persistent (see chapter 5.2.) and coarser resolution must be used instead.

An example of application of coarse resolution sensors is the study conducted by Gond et al (2011) in which they identified, characterised and mapped distinct forest landscape types in French Guiana. They collected data of the Vegetation sensor onboard the SPOT-4satellite for a year and created a composite image. This yearly synthesis was necessary to compensate for the lack of information due to cloud cover and to take into account the climatic seasonality and was proposed by Vancutsem et al (2007). Subsequently they classified the VGT data and collected and matched aerial photographs for selected sites (plots) together with additional field data for interpretation of the vegetation classes. The result was an observation of a spatial patterns similarity between climatic and forest landscape types. Although rather broad, these patterns are still very useful for management and conservation strategies, and for habitat identification through their relation with these landscape types.

Improvements and increased detail observing can be achieved, amongst others, through the use of MODIS instead. MODIS is most likely achieving better results in land cover mapping and can even achieve higher classification accuracies (Toukiloglou, 2007). A second improvement possibility is to synergise optical and SAR imagery. Although SAR is less suitable for vegetation classification, it provides additional information about forest structure and moisture levels and subsequently adds vegetation classes based on this information (Wielaard, 2011). Other alternatives can be the synergism with hyperspectral data sets that are able to identify more spectral signatures and hence more detail that can contribute to a more detailed vegetation classification. However, the cloud cover remains a constraint also for these datasets, which reduce application possibilities to the utilisation on plot level.

6.2.2. Change detection

Change detection is necessary for both detection of threats (and subsequently counteraction) and carbon emission estimation. Data collected can be used to adapt the overall estimated forest carbon stock and vegetation map, rather than obtaining new accurate maps. A prerequisite for detecting changes caused by pressures is near real-time data for quick and effective counteraction. This consequently limits the possibilities to utilisation of coarse spatial resolution imagery, which is too coarse for identification of the type of threat and might even miss out on small scale changes that occur below canopy or cause small gaps in the canopy (smart logging). An often suggested method is to use the coarse image as a first pass to identify so-called hotspots and subsequently use a very high resolution images to identify the type of threat (Hyde-Hecker, 2011; GOFC-GOLD, 2010).

If one deviates from the prerequisite of quick detection, than a finer resolution sensor can be used to map the entire area in order to find changes based on SAR. Using Landsat like optical data is still not an option due to persistent cloud cover. The backscatter signal of the SAR instrument increases in intensity and variability in selectively logged areas (Kuntz, et al., 1999) and texture increases, but texture decreases again if deforestation increases in scale and becomes more homogeneous (Lucas, et al., 2004). Deforestation maps from SAR and Landsat are often similar in accuracy and both techniques are improving. Such analyses must be conducted at least annually, preferably twice a year, as forest recovery generally takes place very fast. Detection of past changes will become hard when the canopy will close again for both optical as SAR sensors. SAR is not yet operationally used in forest monitoring over large areas, although it has proved to be useful in project studies (GOFC-GOLD, 2010).

6.3. Carbon

6.3.1. Biomass

The carbon stock is directly related to the amount of biomass in a forest. The carbon pools that are required to be measured according to the IPCC GPG are the aboveground living biomass, the below-ground living biomass, dead wood, litter, and soil organic matter. Most remote sensors can only measure the aboveground living biomass leaving other pools to be estimated through their relation with the aboveground living biomass, which is permitted within REDD+. Estimation of forest carbon stocks must be done for each forest type. Hence it is important to stratify the forest as much as possible; even within broadleaf tropical forests, stocks will vary greatly with elevation, rainfall and soil type (GOFC-GOLD, 2010). It is therefore important to accurately classify the vegetation of the area (see chapter 6.1).

Referring to table 4.1, the best method to estimate the biomass is through forest inventory. However, this can become prohibitively expensive and it is unlikely that the right amount of plots can be measured to achieve a representative estimation in time for an extensive area as Tumucumaque. Besides that, allometric relationships must be determined which is time consuming, expensive and destructive as it requires harvesting a large number of trees (Gibbs, et al., 2007). Allometry[2] includes tree stand characteristics as variables, of which tree height is very important to achieve high quality measurements (Koch, 2010). Many other options produce often a higher uncertainty. One option is to use optical remote sensors (e.g. AVHRR, MODIS, LANDSAT, etc.), but these cannot yet be used to estimate carbon stocks of tropical forest with certainty (Thenkabail, et al., 2004; Gonzalez, et al., 2010). Koch (2010) stated that visual interpretation and digital classification methods of such sensors often cannot fulfil the information requirements in regard to timeline and quality. Better methods to estimate the carbon are based on LiDAR, SAR, hyper-spectral sensors or very high resolution (air-borne) optical sensors. These methods provide low to medium uncertainty (see table 4.1) (Gibbs, et al., 2007), acceptable for carbon stock estimation within REDD.

Synthetic Aperture Radar

The advantage of SAR is its weather independency, but SAR measurements that are based on back-scatter values or on coherence are, however, subject to clear limitations: the roughness of the objects compared to the wavelength, the weather influence at different data take times, the exact co-registration and the saturation (Koch, 2010). Saturation point[3] is generally at 150m³ stem volume, while many forested areas have a higher stem volume per hectare. Also, SAR is generally not able to measure tree heights, so that it requires additional field data. An exception is shown in the study by Baltzer et al (2007) in which they used L-band for measuring ground height and X-band for measuring

[2] Allometry is, in this context, the study of the relationship of relative sizes of plant parts, e.g. between canopy size, tree diameter and biomass.

[3] Saturation point is the amount of stem volume after which an increase in stem volume cannot be observed as an increase.

canopy height in different polarizations. They achieved a relative error to LiDAR canopy height of around 29% (Koch, 2010). However, currently no space-borne L- or P-band is operational and forest conditions used in this study are not comparable with tropical forests. Considering the fact that SAR is of limited use of vegetation class discrimination, an accurate vegetation map is also additionally needed. These shortcomings result in either expensive methods and high costs, or compromises on biomass estimation accuracy. But due the advantage of weather independency, much effort is currently put in the development of new, more sophisticated sensors and methods to increase possibilities and accuracies; PolInSAR (Polarimetric Synthetic Aperture Interferometry) systems will be of increasing relevance.

Very high resolution optical sensors

Optical sensors generally only sense the canopy of the forest and without additional data it is difficult to model the structure in order to directly estimate the biomass. Pearson et al (2005) in contradiction yielded success with a three dimensional airborne optical sensor that uses laser to collect height data in tropical dense forests in Belize. But increasing topography in the area can reduce the certainty significantly as height measurements will become less accurate. However, this method must be tested more to show its application possibilities and overall accuracies. Studies with very high resolution spaceborne optical sensors as IKONOS and QuickBird showed application possibilities for biomass estimation with a very acceptable certainty (Gonzalez, et al., 2010; Clark, et al., 2004). On the other hand, Thenkabail et al (2004) found that IKONOS had an overall accuracy in estimating biomass in African tropical forests of only 48%, but did not apply any textural analysis in their study. Gonzalez et al (2010) conducted a study to compare uncertainties in biomass estimation from LiDAR and QuickBird in California and found that QuickBird produced estimates of forest carbon density that were lower and estimates of uncertainty that were higher than LiDAR, with LiDAR providing carbon estimates with uncertainties that are lower than most other existing remote sensing systems. Although the uncertainties were still very low for some study areas, QuickBird showed a systematic undercount of trees and underestimation of carbon density resulting in inaccurate estimates.

However, very high resolution optical sensors, especially those operating from space, are constrained by the cloud cover in the area reducing its possibilities. Also, extensive and detailed field data remain necessary to validate and calibrate the digital data and to perform allometric analyses in order to estimate biomass stocks with a high accuracy.

Hyperspectral sensors

The advantage of hyperspectral sensors is the ability to identify a wide range of spectral signatures of objects through a very high number of bands in the electromagnetic spectrum. This can result in highly detailed forest stratifications that are necessary within REDD+. However, directly relating forest biomass stocks from this stratification data is not possible. The main reason is the poor relationship between stem biomass and the vegetation indices (Schlerf, 2006; Koch, 2010). Clark et al (Clark, et al., 2011) researched the possibilities of biomass estimation with small-footprint LiDAR and hyperspectral sensors. Their study supported the conclusion that LiDAR is a premier instrument for mapping biomass and carbon stocks across broad spatial scales and found that hyperspectral metrics provided no additional benefit for biomass estimation in their study site. However, they also concluded that "hyperspectral sensors may be best suited for adjusting LiDAR-based biomass estimation equations for vegetation phenology or stress, as long as the sensors are flown simultaneously or close in time". This conclusion is also supported by Koch (2010) and is confirmed by the findings of

Thenkabail et al (2004) that Hyperion explained 36-83% more of the variability in biomass when compared to IKONOS, ETM+ and ALI sensors.

LiDAR

Amongst others based on the description of abovementioned sensors for application in carbon stock estimation, LiDAR seems to be the best instrument currently available for biomass estimation and related carbon stock (Koch, 2010; Gonzalez, et al., 2010; Clark, et al., 2011; Gibbs, et al., 2007). LiDAR can extract information about tree height and structure of forests with high quality at single-tree level. Knowing this information, especially tree height, the wood volume can be modelled and finally biomass can be estimated (Straub, et al., 2009). This is an indirect approach, but a direct approach is also possible (Latifi, et al., 2010; Wu, et al., 2009). Wu et al (2009) achieved accuracies of 73% with the direct approach, which are generally lower than the ~80% with indirect measurements. However, Gonzalez et al (2010) stated that only field measurements make possible the calibration and validation of the remote sensing data and the quantification of the 3-30% of total aboveground biomass in shrubs, dead trees, coarse woody debris, and litter. Both approaches will thus, especially in tropical forest regions, under- or overestimate the total carbon stock and increase the overall error and uncertainty if not correctly validated.

LiDAR has unfortunately some constraints. Firstly, it cannot sense through clouds, so cloud cover remains a limiting factor. Secondly, no spaceborne laser sensors are available at current for application in tropical forests and carbon stock estimations are hence dependent on expensive airborne sensors. And even spaceborne sensors would still require extensive field measurements of trees for validation and calibration (Gonzalez, et al., 2010). Lastly, Koch (2010) mentions that for biomass, the natural variation during the year should also be considered in carbon stock estimation, but currently no publications are available that describe the application possibilities of LiDAR for these variations.

6.4. Topography

There are multiple methods to create overviews of the topography. The main parameters are elevation, slope and watershed. Data about these parameters can be collected using Digital Elevation Models (DEM's) or from the Shuttle Radar Topography Mission (SRTM). The latter was a single-time mission in 2002 with a specially modified radar system onboard the Space Shuttle Endeavour. DEM's are created more frequently by different satellite systems. Of particular interest are DEM's created by Interferometric Synthetic Aperture Radar (InSAR), which achieve a spatial resolution of around 10 meters. SPOT, for example, is designed so that it can create DEM's from optical imagery, but provides coarser images. Airborne sensors, especially LiDAR, are able to provide DEM's with a resolution of up to 1 meter. Automated processing is available and provides the data necessary to map areas that are susceptible to erosion or contain important watersheds. Furthermore, this information can contribute to multi-source approaches in, for example, forest stratifications.

7. Conclusions and discussion

Remote sensing is a tool that yields increasing success and interests for application in tropical forestry and nature conservation. Many studies have been conducted to research the possibilities, but are often focussed on one or a few aspects of conservation, while conservation of tropical forests is complex and involves often many aspects; e.g. identifying and monitoring threats, sustainable exploitation, species habitat identification, water quality control, land cover discrimination, carbon sequestration, and ecosystem protection. This study is focussed on many of these aspects to review the possibilities and limitations of remote sensing for a more holistic approach of tropical forest conservation. This study took ecosystem services as the most important point of view.

The possibilities for application of remote sensing depend primarily on the region and climate. The Tumucumaque area is located in the northern part of the Amazon basin, which is known for its persistent cloud cover almost throughout the year. A quick assessment regarding cloud cover and availability of LandSat data for two randomly selected years showed a severe lack in information and is representative to other similar optical imagery. Over areas with a less persistent cloud cover it is likely that possibilities will increase and availability should be checked for every project individually. For Tumucumaque this constraint leads to a greater dependency on coarse spatial resolution optical imagery or Synthetic Aperture Radar, the latter being weather independent.

Coarse spatial resolution optical imagery is in many cases too coarse to sufficiently distinct between element characteristics. It is in certain cases suitable for first pass detection of changes in vegetation cover, but requires additional fine scale resolution optical imagery such as IKONOS or QuickBird to identify the cause of the change. However, those are expensive and still subject to the cloud cover constraint. SAR imagery has the benefit to be weather independent, but is not suitable for specific purposes, e.g. water quality control and detailed vegetation classification. The fundamental difference between these two sensor types causes them not to be suitable for replacing the other. It has been frequently stated that synergism should be established between SAR and optical imagery as a more accurate method and that can distinguish more details. But, again, also this synergy is still dependent on optical imagery.

Taking into consideration the criteria for remote sensing of biomass as determined by IPCC for Tier 3 level, remote sensing cannot stand alone unless expensive methods are applied that rely on LiDAR. Almost all methods rely on the inclusion of extensive field data to establish allometric relationships between remotely sensed data about forest structure and biomass of the tree species. Without this field data estimations of biomass can be considered inaccurate and probably have high uncertainties. To support accurate biomass estimation, detailed forest stratification is required. The best method to acquire accurate and detailed forest stratification is through field data, although multi-source data (using optical imagery, SAR and DEM's) will provide acceptable results as well. The issue with multi-source data is again the dependence on optical imagery.

Remote sensing is a very handy tool in tropical forest conservation and can be used for a wide variety of applications. However, when it comes to detail, remote sensing might not be as suitable as sometimes is assumed. It must be noted that this study took only into account satellite imagery and not the possibilities from airborne sensors, apart from the LiDAR sensor. Airborne sensors can be operated when climate conditions are optimal, but are relatively expensive compared to satellite imagery, so that expenditures quickly exceed the potential benefits that can be generated from the REDD+ scheme, for example. Also considering the fact that most remotely sensed data is advised to be validated with *in situ* data, tropical forest conservation will still rely to a significant extent on conventional field work. Despite the shortcomings of current remote sensing methods, it is indispensable for tropical forest conservation. Large areas, such as the Tumucumaque area, are too extensive to rely on field data alone. Future satellite missions with more sophisticated sensors will provide improved and better methods and higher accuracies. New studies that will be conducted relying on these new satellite sensors will also reveal new and improved application possibilities.

The need for field data creates possibilities for active involvement of local people in tropical forest conservation. This is interesting for both parties as they are dependent on the services provided by the ecosystems for their livelihood. Local people can be trained, equipped and funded through REDD+ scheme implementation or other initiatives. This creates support and the involvement will contribute to the threat detection and counteraction. Also, while remote sensing is useful for mapping ecosystem elements, local people can also provide information about the availability of the actual final products they enjoy.

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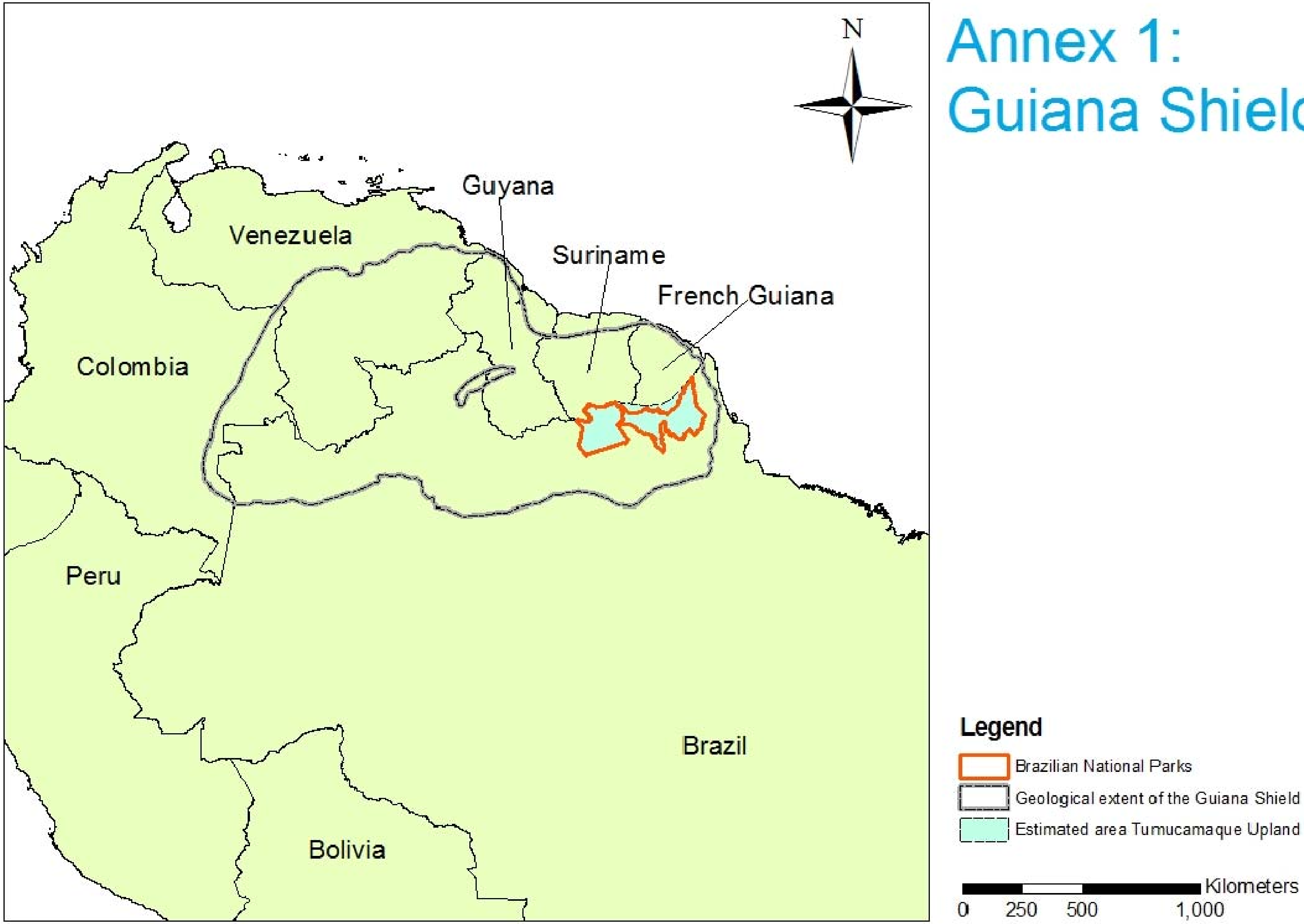
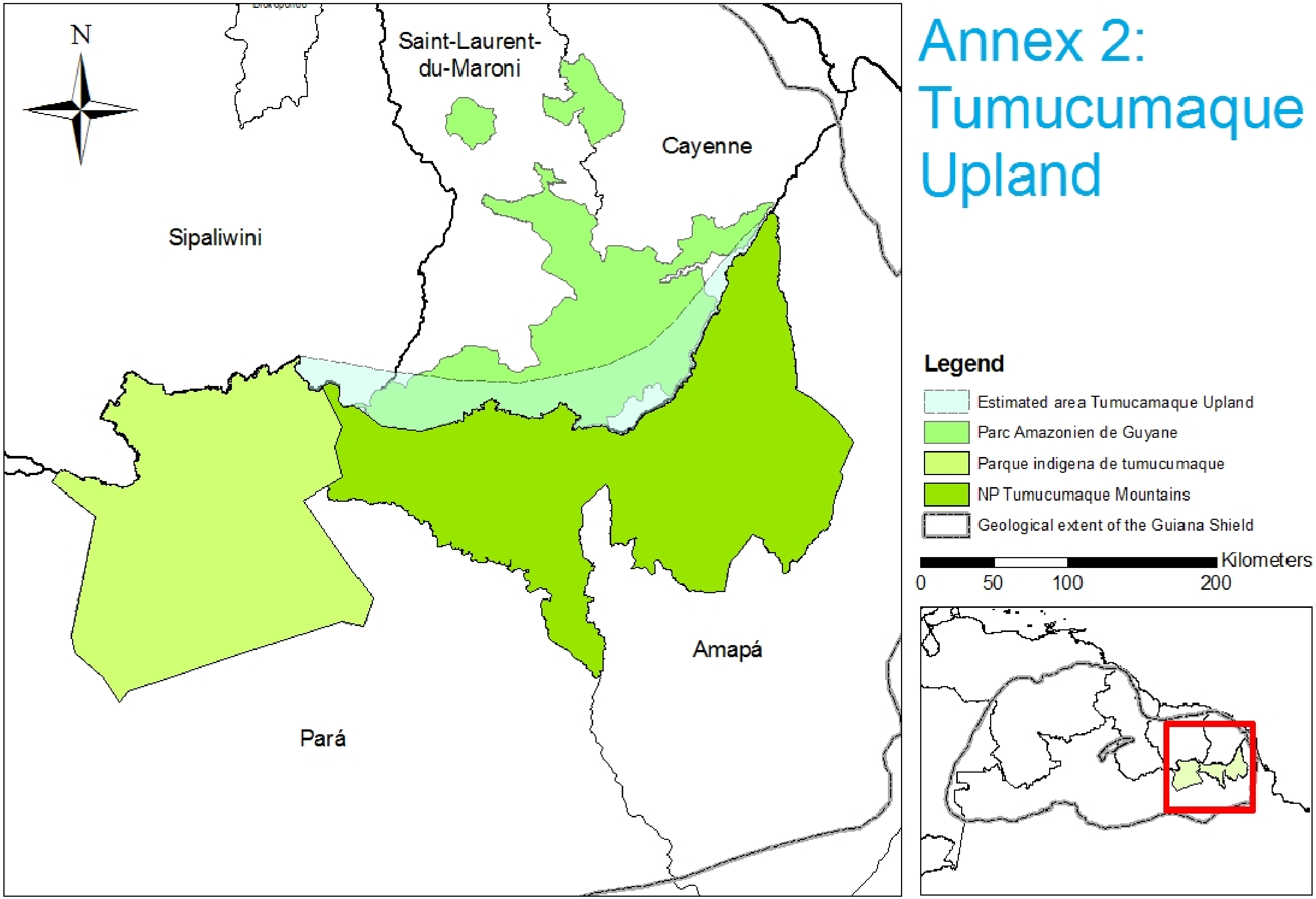
9. Annexes

Annex 1: Guiana Shield



Annex 2: Tumucumaque Upland



Annex 3:
Extensive overview satellite sensors

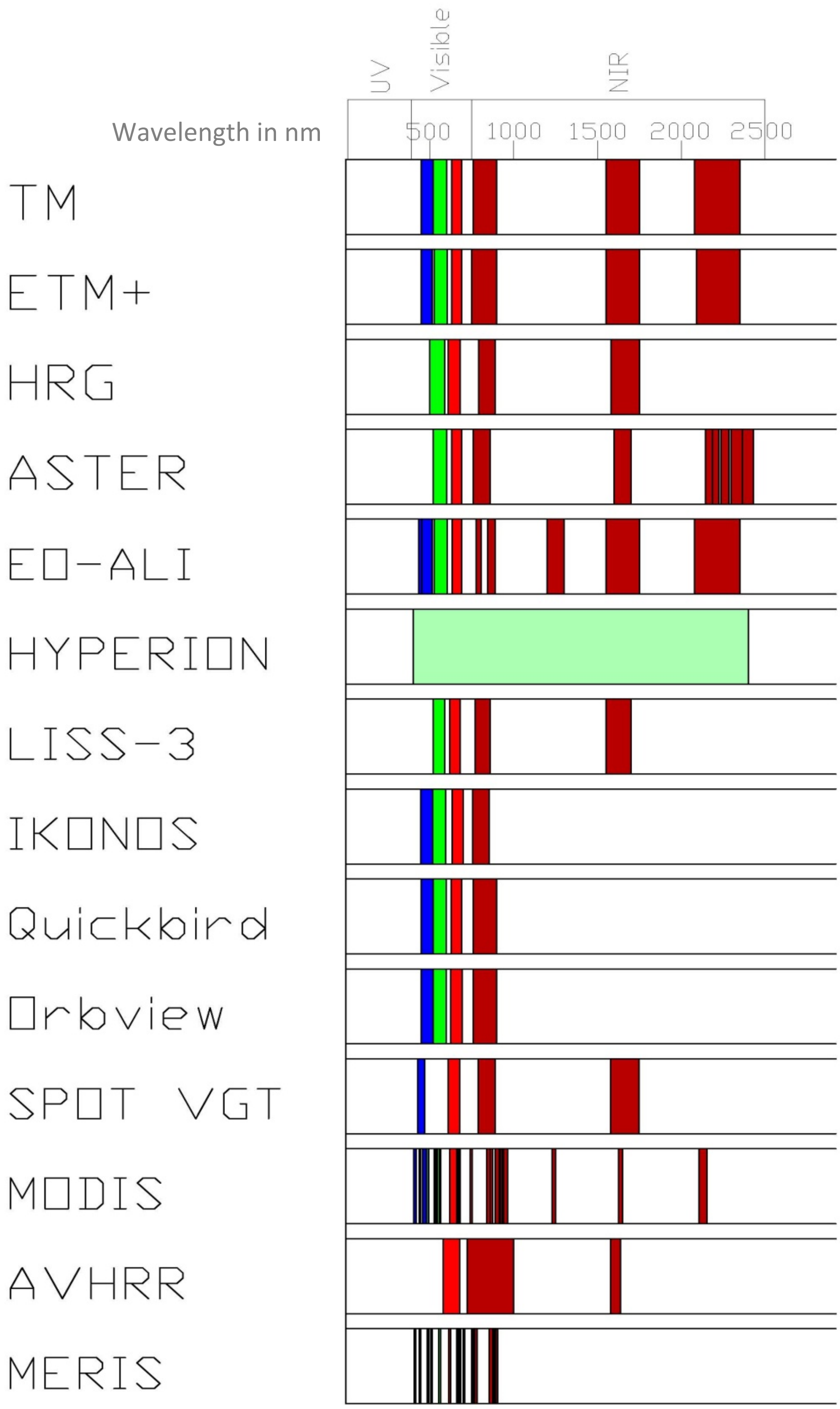
Optical sensors

Sensor	Satellite	Spatial resolution	Swath	Spectral bands (um)	Temporal resolution
Vegetation	SPOT 5	1.15 km	2200 km	0.45, 0.65, 0.83 1.66	daily
MODIS	Terra/Aqua	250 m (bands 1-2) 500 m (bands 3-7) 1 km (bands 8-36)	2330 km	36 bands in range 0.41 - 14.34	1-2 days
AVHRR	NOAA/Metop	1.1 km	2400 km	5 bands in range 0.61 - 12.0	12 h
Meris	Envisat	1.04 x 1.20 km 260 x 300 m	1150 km	15 bands in range 0.41 - 0.90	3 days
ASTER	Terra/Aqua	15 m 30 m 90 m	60 km 60 km 60 km	0.56, 0.66 0.81 (N and B) 11 bands in range 1.65 - 11.3 for 90m resolution	16 days 4 days pointable
ETM+	Landsat 7	15 m 30 m 60 m	185 km	Pan 0.48, 0.57, 0.66 0.74, 1.65, 2.22, 11.5	16 days
TM	Landsat 5	30m 120m	185 km		16 days
HRG	SPOT 5	5 m 10 m 20 m	120 km	2 pan images 0.55, 0.65, 0.83 1.66	27 days
ALI	EO-1	10 m 30 m	37 km	Pan 9 multispectral bands 0.43 - 2.35	16 days
Hyperion	EO-1	30 m	7.5 km	242 spectral bands 0.40 - 2.50	On request
LISS-3	IRS-1D	24 m 70 m	142 km 148 km	0.55, 0.65 0.82, 1.65	24 days 5 days pointable
OSA	IKONOS 2	1 m 4 m	13 km	Pan (0.45 - 0.90) 0.49, 0.56, 0.68, 0.72	11 days (pointable)
BGIS 2000	Quickbird 2	0.61 m 2.44 m	16.5 km	Pan (0.45 - 0.90) 0.48, 0.56, 0.66 0.72	1 - 3.5 days
OHRIS	Orbview 3	1 m 4 m	8 km	Pan (0.45 - 0.90) 0.48, 0.56, 0.66, 0.83	Up to 3 days

Synthetic Aperture Radar sensors

Sensor	Satellite	Wave-band	Modes	Polarisation	Spatial resolution	Swath
ASAR	Envisat	C-band	Image	VV, HH	28 m	Up to 100 km
			Wide swath	VV, HH	150 m	400 km
			Alternating polarisation	VV/H, HV/HH, VH/VV	30 m	Up to 100 km
			Wave	VV, HH	30 m	5 km vignettes
			Global	VV, HH	950 m	400 km
SAR	Radarsat-2	C-band	Ultrafine	Single, H or V	3m	10 or 20 km
			Fine	HH, HV, VV	11 x 9 m	25 km
			Standard		25 x 28 m	25 km
XSAR	TerraSAR-X	X-band	Spotlight 1	H and V in all modes	1 x 1.2 m	10 km
			Spotlight 2		2 x 1.2 m	10 km
			StripMap		3 x 3.2 m	40 km
			ScanSAR		15 x 15 m	100 km
PALSAR	ALOS	L-band	High resolution	HH or VV	7 - 44 m	40 - 70 km
				HH/HV or VV/VH	14 - 88 m	
			ScanSAR	HH or VV	<100 m	250 - 350 km
			Polarimetry	HH/HV + VV/VH	24 - 88 m	30 km

Annex 4:
Spectral bands remote sensors



Note: Hyperion has too many band too closely together that is cannot be visualised in this table and is therefore shown as on single band covering the spectral extent of the sensor.

Annex 5:
Overview biomass estimation methods

Method	Description	Benefits	Limitations	Uncertainty
Biome averages	Estimates of average forest carbon stocks for broad forest categories based on a variety of input data sources	• Immediately available at no cost • Data refinements could increase accuracy • Globally consistent	• Fairy generalised • Data sources not properly sampled to describe large areas	High
Forest inventory	Relates ground-based measurements of tree diameters or volume to forest carbon stocks using allometric relationships	• Generic relationships readily available • Low-tech method widely understood • Can be relatively inexpensive as field-labour is largest cost	• Generic relationships not appropriate for all regions • Can be expensive and slow • Challenging to produce globally consistent results	Low
Optical remote sensors	Uses visible and infrared wavelengths to measure spectral indices and correlate to ground-based forest carbon measurements Ex: Landsat, MODIS	• Satellite data routinely collected and freely available at global scale • Globally consistent	• Limited ability to develop good models for tropical forests • Spectral indices saturate at relatively low C stocks • Can be technically demanding	High
Very high-res. airborne optical remote sensors	Uses very high resolution (~10-20cm) images to measure tree height and crown area and allometry to estimate carbons tocks Ex: Aerial photos, 3D digital aerial imagery	• Reduces time and cost of collecting forest inventory data • Reasonable accuracy • Excellent ground verification for deforestation baseline	• Only covers small areas (10,000s ha) • Can be expensive and technically demanding • No allometric relations based on crown area are available	Low to medium
Radar remote sensors	Uses microwave or radar signal to measure forest vertical structure Ex. ALOS PALSAR, ERS-1, JERS-1, Envisat)	• Satellite data are generally free • New systems launched in 2005 expected to provide improved data • Can be accurate for young or sparse forest	• Less accurate in complex canopies of mature forests because signal saturates • Mountainous terrain also increases errors • Can be expensive and technically demanding	Medium

Laser remote sensors	LiDAR uses laser light to estimate forest height/vertical structure Ex: Carbon 3D satellite system combines vegetation canopy LiDAR (VCL) with horizontal imager	• Accurately estimates full spatial variability of forest carbon stocks • Potential for satellite-based system to estimate global forest carbon stocks	• Airplane-mounted sensors only option • Satellite system not yet funded • Requires extensive field data for calibration • Can be expensive and technically demanding	Low to medium

Annex 6: Terminology

Allometry

The study of the relationship of relative sizes of plant parts, e.g. between canopy size, tree diameter and biomass.

Interferometry (SAR)

Combining two or more SAR images of the same area to generate elevation maps and surface change maps with unprecedented precision and resolution

Level 1 satellite product

Satellite images that are systematically correct for their geometry and radiometry

Polarimetry

The measurements and interpretation of the polarisation of electromagnetic waves

Polarisation

The orientation of the electromagnetic wave (either horizontally or vertically)

Remote sensing

The acquisition of information about an object or phenomenon, without making physical contact with the object

Spatial resolution

Refers to the ability to distinguish between two closely spaced objects in an image

Spectral band

A well-defined, continuous wavelength range in the spectrum of reflected or radiated electromagnetic energy

Spectral signature

The specific combination of reflected and absorbed electromagnetic radiation at varying wavelengths which can uniquely identify an object.

Spectral resolution

Refers to the ability to separate independent spectral emissions

Temporal resolution

Refers to the revisit time of the satellite sensor over a certain area