Effectiveness of Colombia's protected areas in preventing evergreen forest loss: A study using Terra-i near real-time monitoring system

Mike Harvey Salazar Villegas

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By

Mike Harvey Salazar Villegas

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Degree Assessment Board

Prof. Dr. habil. Elmar Csaplovics

First Supervisor, Technische Universität Dresden

PD Dr. rer. nat. habil. Ulrich Walz

Second Supervisor, IOER

TECHNISCHE UNIVERSITÄT DRESDEN

INSTITUTE OF INTERNATIONAL FORESTRY AND FOREST PRODUCTS,
FACULTY OF FOREST, GEO AND HYDRO SCIENCES

Abstract

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"Agricultural development within the rural-urban continuum"

Evaluate effectiveness of protected areas PAs and indigenous reserves IRs in preventing deforestation is becoming more important given the crucial role of forest conservation in climate change mitigation. Monitoring deforestation using near real-time remote sensing is an effective tool for detecting forest cover change trends and identifying protection levels.

Information on how effective PA network in Colombia represent global and national conservation priorities is essential for developing and implementing policies for conserving forest habitats and development benefits. In this research, I evaluate the effectiveness of 80 Colombia PAs preventing forest loss under three forest conservation management strategies: 22/II—IV, 10/VI IUCN categories and 48/IRs. I mapped annual forest cover change from 2005 to 2011 using near real-time remote sensing Terra-i (250 m resolution) joined to GlobCover 2005 (300 m resolution) inside and in a 10-km buffer outside the PAs. I used GlobCover re-classified to identify the extent of evergreen forest cover as base map. Based on these data I develop an effectiveness index including percentage of loss inside PAs, the comparison of loss inside and outside PAs, annual rate of loss inside PAs and the comparison of annual rate of loss inside and outside PAs. The total forest cover area lost between 2005 and 2011 comprised 1.1% nationwide and 0.3% of the PA network, equivalent to 57.000 ha. Inside PAs, loss of forest occurred in 20% of those located in the category II—IV, 9% in the VI and 55% in the IRs, while 23%, 11 % and 60 %, experienced lost outside, respectively. Moreover, we identify four effectiveness categories: very-satisfactory, satisfactory, dissatisfactory and very-dissatisfactory. More than 50% of PAs were effective, described as satisfactory and very-satisfactory protection level. Particularly, strict PA's (categories II-IV) were found more effective than multiple-use PA's (categories VI-IRCC).

These findings suggest that loss of evergreen forest cover in Colombia PA network is substantially low in comparison with countries in Central Africa, South and Southeast Asia. These results hardly explained the factors (elevation, slope and socioeconomic) that have contributed with the performance of individual and effectiveness levels of protection. Hence, the application of another empirical method such as matching techniques controlling for bias is recommended to control for landscape characteristics that can influence deforestation. Finally, forest protection strategies can contribute both to biodiversity conservation and climate change mitigation goals.

Keywords: Effectiveness protection, forest cover loss, indigenous reserves

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Acronyms

BA(s)	Buffer Area(s)
CBD	Convention on Biological Diversity
CIAT	International Centre for Tropical Agriculture
GADM	Global Administrative Areas
GIS	Geographical Information Systems
IGAC	Instituto Geográfico Agustín Codazzi
IR(s)	Indigenous Reserve(s)
IUCN	International Union for Conservation of Nature
IUCN- WCPA	IUCN- World Commission on Protected Areas
LSWI	Land Surface Water Index
MODIS	Moderate Resolution Imaging Spectro-radiometer
NASA	National Aeronautics and Space Administration
NDVI	Normalized Difference Vegetation Index
PA(s)	Protected Area(s)
RS	Remote sensing
SIG-OT	Sistema de Información Geográfica para la Planeación y el Ordenamiento Territorial
SRTM	The Shuttle Radar Topography Mission
Terra-i	Near Real Time Monitoring of Habitat Change Using
TRMM	Tropical Rainfall Measuring Mission
WDPA	World Database on Protected Areas
WorldClim	Global Climate Layers

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1 Introduction

1.1 Research background: an overview of tropical forest and Protected Area conservation issues

Tropical rainforests cover more than 1600 million hectares of the Earth's surface and support approximately 60% of the world´s known terrestrial biodiversity (MEA 2005; Gardner et al., 2009) and a large number of undescribed species. Many rainforest species are important to local economies and have the potential for greater use by the whole world´s population (Primack 2010). Forests provide a wide range of ecosystem services such as regional and local climate regulation, water supply, soil conservation and habitat provision for biodiversity (Simula and Mansur 2011). They also have a disproportionate role as a significant global carbon sinks (IPCC 2002) a vital ecosystem services, storing from 70 to more than 300 tonnes of carbon per hectare, depending on their structure and location (Pan et al., 2011). Despite the importance of their multiple values, today, forests and their biodiversity are under increased threat from activities associated with land-cover change, principally deforestation and forest degradation (Simula and Mansur 2011). Globally, tropical deforestation continues apace, at an alarming speed of around 13 million hectares of forest lost each year (FRA 2010). This rate has not changed markedly in recent decades (FAO 2005). The fundamental drivers of deforestation are human population growth and accessibility due to increased prevalence of roads and other infrastructure (Angelsen and Kaimowitz 1999). Other immediate drivers, however, are changing – from mostly subsistence-driven deforestation, in the 1960s through 1980s, to far more industrial-driven deforestation more recently (Geist and Lambin 2002). This crisis has key implications for forest conservation. The only forests that remain will be in protected areas (referred to herein as PAs) and remote terrain.

In light of the increasing crisis of global deforestation, an effective PA network is the prominent strategy for conserving viable, representative, remaining areas of forest habitats (Chape et al., 2005). Therefore, PAs are meaningful, measurable indicators of status to decrease the rate of forest cover loss (Myers et al., 2000; MEA 2005; Chape et al., 2005; Nelson and Chomitz 2011). Recognizing the importance of PA networks, IUCN World

Commission on Protected Areas created a system of classifying PAs by management goals (IUCN 1994), with six categories (Table 1). The number of PAs and their surface of coverage have tripled over the past two decades. As of 2010, more than 108.000 terrestrial PAs have been designated worldwide, officially covering some 17 million km^2, or 12.7% of the world´s terrestrial area (Bertzky et al. 2012; Primack 2010). However, studies have confirmed that the PAs establishment, especially in the tropics, frequently does not correlate with identified conservation priorities (Naughton-Treves et al., 2005; Bonham et al., 2008; Bruner et al., 2001), leading to largely ineffective 'paper parks' (Bruner et al., 2001). Consequently, 'paper parks' had lost much of their forest cover through logging, conversion to agriculture and settlement (Naughton-Treves et al., 2005). Thus, a critical question is whether the PA network is actually effective in protecting natural forest cover.

PAs are considered to be effective at one conservation strategy level (Saterson et al., 2004), if there is no forest cover loss or if these changes are less in PAs than comparable surrounding or 'buffer areas' (Naughton-Treves et al., 2005, DeFries et al., 2005). However, the controversy partly originates from the fact that evaluations based on comparisons between PAs and buffer areas (BAs) in many countries are not randomly distributed across the landscapes (Andam et al., 2008; Joppa and Pfaff 2009, 2010), overestimating or biasing the protective effect of PAs. On the one hand, PAs under strict protection are sometimes viewed as effective in protecting biodiversity at the expense of excluding local people from access to forest resources (Joppa and Pfaff 2010; Nelson and Chotmiz 2011). On the other hand, the location of strict PAs tends to be biased toward uninhabited remote lands that are unattractive to agricultural conversion, even in absence of protection (Joppa et al., 2008).

Geographical Information Systems (GIS) and remote sensing (RS) tools represent the latest development in conservation analysis techniques to evaluate such spatial information (DeFries et al., 2005; Liu et al., 2001). Satellite imagery from several PAs makes it possible to highlight forest cover loss at the pixel level that needs to be used in the comparison with surrounding landscapes, in an unbiased manner. Over the past decade, studies using remotely sensed data across tropical forests have examined the impact of PAs in conserving forest cover (e.g., Naughton-Treves et al., 2005; Nagendra 2008; Defries et al., 2005), or deforestation implementing and comparing incremental buffer zone approach, focusing on forest cover changes over time (Sanchez-Azofeifa et al., 2003; Bruner et al., 2001). These studies emphasize that PAs are associated with lower deforestation rates and loss of forests are less inside PAs than in comparable sites.

These findings add to the accumulating evidence about protection success at a broad level, but they have important limitations. The quality and relevance of analysis with remote sensing measures depends on the accuracy and resolution of PA boundaries (Chape et al., 2005). Additionally, the type of natural forest habitat is relevant, because intact natural forests are an important signal that PAs are having significant results (Naughton-Treves et al., 2005). Furthermore, it is important that consistent effectiveness evaluations are set at national level. Unfortunately, existing PA data held by IUCN-WCPA do not indicate exactly if PA national networks “as a Colombian set” are actually effective in achieving the forest conservation and biodiversity goals.

1.2 Forest conservation and the PA network in Colombia

This study focuses on Colombia and it attempts to provide insight at national levels on how PA network might perform effectiveness conditions as forest cover changed. Colombia is a mega-diverse country that contains close to 14% of the world's biodiversity (Butler 2006). It also has one of the largest continuous forest areas in the tropics, with forests covering at least 0.55 million km^2 or 49% of the national territory (Archard et al., 2009). Therefore, Colombia has the potential to enact conservation strategies that are regionally and globally significant (Forero-Medina and Joppa 2010). Nevertheless, Colombia is one of the tropical countries where both fundamental and immediate causes of land-use change play a major role contributing deforestation (Etter et al., 2006). Since the 1950s, fundamental causes of deforestation have been associated with increased population density and economic activity as a result of agricultural activities and, currently, expansion of illicit crops and mining (Etter et al., 2006; Armenteras et al., 2011). Increased accessibility of forested areas by the development of the road network to supply agricultural markets has also catalyzed the process of forest cover change (Armenteras et al., 2011). However, Colombia’s spatial patterns of deforestation differ among forest habitats as well as among political regions.

It has been estimated that deforestation reached rates of 600.000 hectares per year, accounting for 37.7 million ha of forest lost between 1960 and 1984. This loss represented approximately 41.5% of all forested areas (DNP 1989). During the same period, Colombia began to build a network of PAs in order to combat deforestation and protect biodiversity. For the period of 1985 to 2000, rates of forest loss (0.83% per year) were consistent in the Colombian Andes, representing 1.5 million ha of total area deforested, although with higher rates of loss in lowland forest than in montane forest (Armenteras et al., 2009). Recently, Sanchez-Cuervo et al. (2012) reported that 1.1 million ha of forest were lost over the first decade of 2000s. Beside these historical trends and considering that currently there are 107 National PAs in Colombia (12% of the national's territory), it cannot simply be assumed PAs are effectively reducing forest clearing. Furthermore, these areas have been little studied and many information gaps exist about the effectiveness of the PA network in reducing deforestation (Armenteras et al., 2009; Rodriguez et al., 2012).

Regional-scale analyses have been performed in Colombia to assess effectiveness of PAs. For instances, Armenteras et al., (2009) provide examples of PAs and IRs effectiveness with high and minimal rates of deforestation inside and outside under similar conditions (matching paired method). They found that strict PAs reduce deforestation better than IRs, although along the outside borders of both, deforestation levels were four times higher than inside PAs but only 1.5 times higher than within IRs. However, the geographical scale of the assessment was limited to the Guyana shield region, including only five PAs. Despite the significance in effectiveness protection of PAs, a current dataset of protection status in the PA network in Colombia is still incomplete. Because the incomplete PA network evaluation to measure ongoing conservation strategies over the last ten years – through measure avoided deforestation – analysis of their effectiveness based on Terra-i MODIS sensors can provide the level of detail necessary to take action and slow the effect of deforestation drivers, at a national scale.

1.3 Research objectives

The objectives of this study are:

(i) To quantify how effective PA strategies network have been in preventing forest-cover loss (extent) annually over time since 2005 to 2011.

(ii) To identify effective and ineffective PAs (IUCN categories) compared with their contiguous 10km buffer areas, across the PA system.

This study considers PAs under the categories identified by IUCN I to VI, which include areas from the Colombia Natural National Parks (categories I to IV), the National Protected Forest Reserves system (category VI) and indigenous reserves, which are sometimes categorized as IUCN categories V and VI (Table 1). Moreover, GIS and spatial analysis of MODIS-NDVI RS techniques were used as an integral component of the (Terra-i)[1] near real-time monitoring of habitat change project by the International Centre for Tropical Agriculture (CIAT). The study asks three main questions:

(1) How much forest-cover loss (or deforestation rate) has there been in the PA network between 2005 and 2011?

(2) Has there been more forest-cover loss outside in the 10km BAs than inside PAs, during the last seven years?

(3) Have multiple use PAs (VI) or community managed (IRCC) been more effective in preventing deforestation than strict PAs (II to IV)?

2 Theoretical framework – Conceptual background

Intuitively, we perceive that forest cover loss is a process that will be detrimental to biodiversity, landscapes and livelihoods of people living along and beyond PAs borders. To understand the problem of forest-cover loss inside and surrounding PAs, the study approaches an appropriate theoretical framework for the process that results in the effective protection of forest. To achieve this, the measures for the conditions for forest protection and the drivers that influence PAs conservation must be identified. These include GIS, RS NDVI tools related to forest cover measurements, PAs and IR as forest conservation and management strategies, and accessibility (Figure 1).

[1] An eye on habitat change: http://www.terra-i.org/terra-i.html

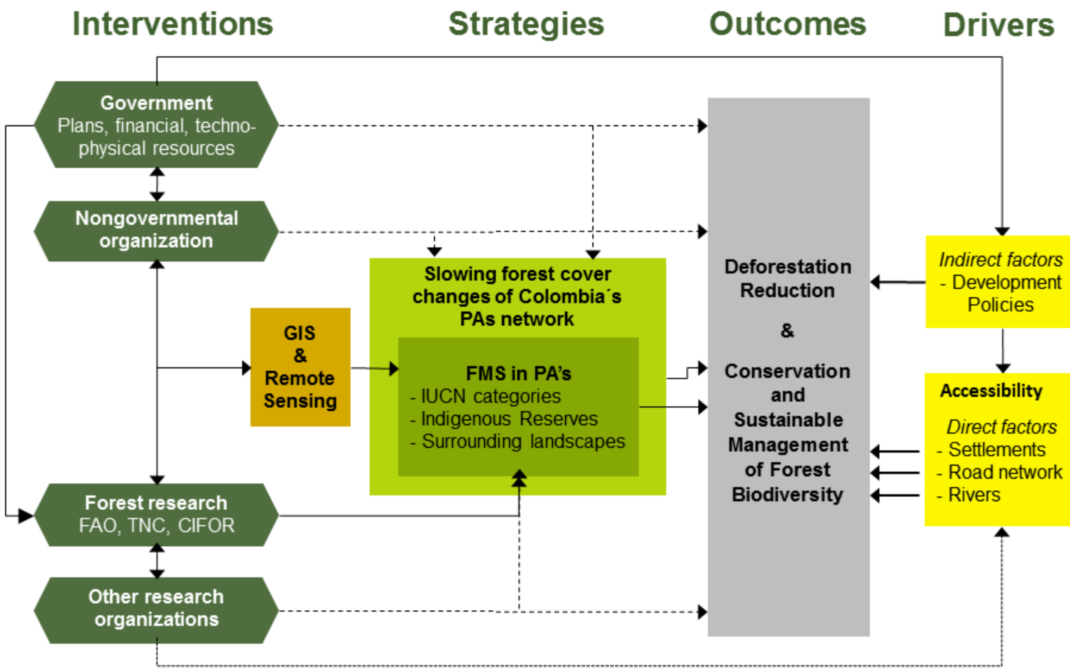


Figure 1 Conceptual framework of monitoring and management of PAs. Forest management research, effectiveness strategies in protection network, driver factors of deforestation and biodiversity conservation target links. FMS: forest management strategies. GIS: Geographical Information Systems.

2.1 PA attributes and the effectiveness outcomes approach

2.1.1 PAs and their historical role

PAs are areas of land or sea dedicated by law or tradition to, and managed for, the protection or other effective means of biodiversity and associated ecosystem services and cultural values (IUCN 1994). They are recognized as the backbone for in situ biodiversity conservation (Chape et al. 2005). Since the 1960s, conservation science and purposes for establishing and managing PAs has developed enormously. To understand the forces driving their global expansion, it is necessary to trace the key during the past 30 years centred on the development of international environmental policy. The campaign to expand PAs began in earnest at the 1982 World Parks Congress in Bali, where delegates recommended that all nations strive to place 10% of their lands under protection (Naughton Treves et al., 2005). A decade later, 167 government leaders signed the Convention on Biological Diversity (CBD) and agree to establish a system of PAs where special measures would need to be taken to conserve biodiversity (Chape et al., 2005). In the same year, representatives at the Fourth World Congress on PAs agreed to allocate a minimum of 10% of each biome under their jurisdiction (oceans, forests, tundra, wetlands, and grasslands) to a national PA networks (Schwartz 1999). In recognition of the fact that not all PAs emphasize biodiversity conservation, in 1994 the IUCN-WCPA developed six different management-based categories (Table 1).

Table 1 The six (I – VI) global categories of PAs coverage network "marines-terrestrial" recognized by World Conservation Union (IUCN)[a].

No sites	**Area Km^2**	**Designations and definitions of the classified PAs management categories**
5,453	998,415	**Category Ia** *Strict nature reserve: PA managed mainly for science* area of land or sea possessing some outstanding or representative ecosystems, geological or physiological features or species, available primarily for scientific research or environmental monitoring
1,357	642,486	**Category Ib** *Wilderness area: PA managed mainly for wilderness protection* large area of unmodified or slightly modified land, and/or sea, retaining its natural character and influence, without permanent or significant habitation, which is protected and managed so as to preserve its natural condition
3,917	4,396,020	**Category II** *National Park: PA managed mainly for ecosystem protection and recreation* natural area of land and/or sea, designated to (i) protect the ecological integrity of one or more ecosystems for present and future generations, (ii) exclude exploitation or occupation inimical to the purposes of designation of the area and (iii) provide a foundation for spiritual, scientific, educational, recreational and visitor opportunities, all of which must be environmentally and culturally compatible
19,690	301,422	**Category III** *Natural Monument: PA managed mainly for conservation of specific natural features* area containing one or more, specific natural or natural/cultural feature which is of outstanding or unique value because of its inherent rarity, representative or aesthetic qualities or cultural significance
26,420	3252074	**Category IV** *Habitat/species management area: PA managed mainly for conservation through management intervention* area of land and/or sea subject to active intervention for management purposes so as to ensure the maintenance of habitats and/or to meet the requirements of specific species

8,575	2,525,635	**Category V** *Protected landscape/seascape: PA managed mainly for landscape/seascape conservation and recreation* area of land, with coast and sea as appropriate, where the interaction of people and nature over time has produced an area of distinct character with significant aesthetic, ecological and/or cultural value, and often with high biological diversity. Safeguarding the integrity of this traditional interaction is vital to the protection, maintenance and evolution of such an area
3,917	4,670,723	**Category VI** *Managed-resource protected area: PA managed mainly for the sustainable use of natural ecosystems* area containing predominantly unmodified natural systems, managed to ensure long-term protection and maintenance of biological diversity, while providing at the same time a sustainable flow of natural products and services to meet community needs

[a] Source: derived from data available at UN Environment Programme's World Conservation Monitoring Centre (2012)

Nevertheless, not all the PAs under these policy commitments reflect the extent to which they achieve their primary management objectives and effectiveness (Southworth et al., 2006). Using a review of concepts and issues on PA effectiveness, I focus on the meanings of conservation strategies to protect forest cover and techniques or methods used to estimate it effectiveness.

2.2 Forest habitat cover: measurement of PAs and RS requirements

2.2.1 Why should forest coverage features of PAs be measured?

Forest cover change involves a process of loss that negatively affects the characteristics of forest habitat (Laestadius et al., 2011). Inside-outside PAs, this process is caused by disturbance which varies in origin, extent, severity and frequency. As earlier mentioned in this work forest habitats face many threats, so we need to know if forests habitat cover inside-outside the PA network is being lost and, if so, to what extend this area has been reduced, so that measures can be taken to avoid further degradation. This information about PA effectiveness is necessary to inform the development of national policies and also represents one of the key indicators of global conservation targets, for example those, adopted in the Aichi targets 11[2] on the Convention of Biological Diversity (CBD). Thus to know if the targets are reached, an effective process for assessing forest cover change is required. However, the main problem of this approach is to cope with the enormous complexity of environmental and human systems, which arise from the various interrelations that the PA network provides. And despite positive results, these forest-cover measurements may only provide a superficial indication of the political commitment to biodiversity conservation nationwide (Chape et al., 2005).

2.2.2 Use of remote sensing to map forest cover extent in PAs

Mapping and assessing global forest cover extent represents the latest developments in RS analysis technology, in particular for remote regions (Achard et al., 2007). Multiple approaches are appropriate and reliable for forest cover mapping at global scales using RS satellite data (Achard et al., 2007). These approaches, such as the wall-to-wall sampling, that use digital analysis of coarse resolution imagery (300 m to– 1 km), have been applied to detect land-cover change and deforestation trends (Fagan and DeFries 2009) or what is referred to as “leakage”. However, coarse resolution (>300m) data lack sufficient spatial detail to provide reliable area estimates of forest extent and change (Hansen et al., 2010).

Forest cover is one category of terrestrial land cover. The Global Land Cover map or GLOBCOVER 2005 as a medium resolution instrument provides a static depiction of forest cover (Archrad et al., 2007). When using GLOBCOVER 2005 forest category, the medium-resolution forest–/non-forest classification has between acceptable and high accuracy (Hansen et al. 2003) but it does not, on its own, indicate change in forest area. According to Archard (2007), the GLOBCOVER 2005 method has some advantages. It serves as a base map against which future change can be assessed. In addition, it helps identify forest areas that need to be monitored for change. Because these assumptions will facilitate the assessment of future change or loss of forest, consistent methodology and spatial resolution are critical for the interpretation of results.

[2] A set of 20 headline targets known as Aichi Biodiversity Targets http://www.cbd.int/sp/targets/rationale/target-11/ Developed to track progress towards the UN Millennium Development Goal 7.

2.2.2.1 Measurement of PA trends in forest cover “area and change”

How can PA forest cover change be measured? Remote sensing provides a particularly effective tool for such a measurement. Satellite image analysis is the most frequently used technique for the mapping of changes in forest cover (Geist and Lambin 2002). The main consideration in measuring forest cover change relate to spatial and temporal scale and trends (Bruner et al., 2001; Naughton-Treves et al., 2005; Figueroa and Sanchez-Cordero 2008; Nagendra 2008; Gaveau et al., 2009). Forest cover change needs to be measured or assessed according to a spatial scale; defined as PA forest map at national level.

Temporal scale is another important aspect in assessment of forest cover change (Chape et al., 2005) of PAs habitat. For example, knowing the time since a forest loss event has occurred, or the length of time a disturbance caused by forest cover change is affecting inside-outside PAs (Hansen et al., 2010). Identification of such conditions requires the establishment of references to a baseline or “ideal state” against which the changed situation can be compared or assessed (Joppa and Pfaff 2010; Laestadius et al., 2011). For instance, forest cover protected effectively can be defined as the state of the situation of natural forest cover, which is spatially intact over a certain time period. In this regard, satellites allow for the measurement of rates of forest-cover change (Jensen 2007) inside-outside PAs, which would indicate the approximate effectiveness of protection conditions and enable to highlight the target areas that need to be included in the PA effectiveness outcomes (Leverington et al., 2010).

A persistent concern for biodiversity loss in developing countries has yielded several studies evaluating extent and conditions in tropical forest PAs. Such studies provide a useful database to evaluate the effectiveness of PA’s across multiple locations. However, they have relied on coarse-scale data sets (DeFries et al., 2005), which are subject to shortcomings of resolution and scale. All these studies have relied primarily on Landsat satellite imagery, supplemented by analyses of aerial photos (Table 2).

Table 2 Comparison of remote sensing data and, rates of forest cover change inside and outside PA´s case by case

Country and Protected areas (PA's)	Ref.	Size of PA in (ha)	Remotely sensed data used for the study*	Time scale	IUCN category	Dif. in rates of change inside vs outside
China						
Wolong	[1]	200.000	MMS; TM	1965-1997	V	Out < In
Costa Rica						
Barra Honda	[2]	2.320	TM	1986–1997	II	In = Out
Cabo Blanco	[2]	1.270	TM	1985–1999	II	In = Out
Braulio Carrillo	[2]	48.158	TM	1986-1997	II	In < Out
Cabo Blanco	[2]	1.172	TM	1986-1997	Ia	In = Out
Cahuita	[2]	1.070	TM	1986-1997	II	In < Out
Carara	[2]	5.312	TM	1986-1997	II	In < Out
Chirripo	[2]	51.641	TM	1986-1997	II	In < Out
Corcovado	[2]	47.563	MMS; TM	1979-1997	II	In < Out
Guanacaste	[2]	38.461	TM	1986-1997	II	In < Out
Manuel Antonio	[2]	682	TM	1986-1997	II	Out < In
Santa Rosa	[2]	37.220	MSS; TM; ETM+	1979-2000	II	Out < In
Tortuguero	[2]	18.746	TM	1986-1997	II	In < Out
Volcan Arenal	[2]	12.010	TM	1986-1997	II	In < Out
Volcan Tenorio	[2]	12.820	TM	1986-1997	II	In < Out
Guatemala						
Dos Lagunas	[3]	30.720	TM	1990–1997	VI	In < Out
El Mirador	[3]	55.150	TM	1990–1997	II	In < Out
El Zotz	[3]	34.930	TM	1990–1997	VI	In < Out
Laguna del Tigre	[3]	288.910	TM	1990-1997	II	In < Out
Laguna del Tigre	[3]	45.170	TM	1990-1997	VI	In < Out
Rio azul	[3]	61.760	TM	1990-1997	II	In < Out
Sierra del Lacandon	[3]	191.870	TM	1990-1997	II	In < Out
Honduras						
Celaque	[4]	27.000	TM	1987-2000	II	In < Out
Indonesia						
Gunung Palung	[5]	30.000	ETM+	1988-2002	II	Out < In
Bukit Barisa Selatan	[6]	365.000	TM; ETM+	1985-1999	II	Out < In
Mexico						
Calakmul	[7]	722.000	TM	1976-2000	UN-MAB	In < Out
Nepal						
Royal Chitwan	[8]	93.200	TM; ETM+	1989–2000	II	In < Out
Sumatra						
Sumatra and Siberut	[9]	44.000.000	TM; ETM+	1990-2000	II	In < Out

[1] Liu et al., 2001; [2] Sanchez-Azofeifa et al., 2003; [3] Sader et al., 2001; [4]Southworth et al., 2004; [5] Curran et al., 2004; [6] Kinnaird et al., 2003; [7] MAS 2005; [8] Nagendra et al., 2004; [9] Gaveau 2009.
* TM = Landsat TM; MSS= Landsat MSS; ETM+ = Landsat ETM+

More recently, a new trend of measuring PA effectiveness in maintaining forest cover centers on regional-scale assessments using lower resolution imagery, such as MODIS (Naughton-Treves et al., 2005) have been used. These studies offer a first-cut analysis of trends in the relative level of protection of PAs in particular regions. A regional example of the application of this simple measure in PAs spatial information was provided by DeFries et al. (2005). They released an analysis of 198 strict PAs (IUCN categories I and II) worldwide, using 500-m MODIS satellite dataset, calibrated with multi-temporal samples of Landsat-derived forest-loss maps over the past two decades. The data from that study revealed that South and Southeast Asia had the highest loss of forest cover of any region because of relatively low surrounding forest habitat in the early 1980s. Dry tropical forests had the subsequent highest deforestation rates. This type of pan-tropical study creates a solid base for launching higher resolution and more focused studies regarding the temporal and spatial trends related to forest cover loss within and outside of PAs.

Another approach of RS imagery mapping forest cover at national level is to implement an incremental buffer analyses to assess forest cover loss, both within and outside of the PAs (Sanchez-Azofeifa et al., 2003), as will be described more completely in Sub-chapter 2.2.3 and Table 2. This mapping shows more detailed patterns of forest loss. For example, the rate of observed forest loss was greater in the BAs closer to the borders of several PAs, rather than beyond borders (Naughton-Treves et al., 2005). Sanchez-Azofeifa et al., (2003) have provided an example of national level PAs deforestation assessment in Costa Rica, using time series from RS to quantify inside-outside forest cover loss (Table 1). They found that inside PAs, deforestation rates were minimal. Areas outside of PAs show that for the 1-km BA surrounding PAs, there was forest increase over a period of 10 years indicating that the boundaries of PAs were respected. Meanwhile, in the 10-km BAs they show significant forest loss for all study periods. This suggests that increasing isolation of protected areas may prevent them from functioning as an effective network.

2.2.3 The meaning and characteristics of ‘PAs’ in effective protection

Evaluating the effectiveness of the PAs network represents a challenge, given the social conditions, their contrasting agendas imposed on PAs and random manner to create it (Naughton-Treves et al., 2005). For example, protection conditions are established through different goals and outcomes including a range of forest management restrictions (Chape et al., 2008) subject to dynamic changes in land-use. As a result, there exists an extensive empirical overlap between PAs and human land-uses across the world (Southworth et al. 2006). Thus the dual character of PA landscapes originates typical patterns of forest cover around them, which in turn varies their effectiveness and jeopardizes outcomes (Southworth et al., 2006). Recent studies on effectiveness assessments point out that PA creation has had mixed results (Naughton-Treves et al., 2005; Southworth et al., 2006). While exclusionary approaches can achieve successful ecological outcomes for protecting forest biodiversity in some instances (Joppa and Pfaff 2010) or keeping land intact (Bruner et al., 2001; DeFries et al., 2005), they do not account for the inclusion of local or indigenous communities for access to forest resources (Southworth et al., 2006). It is also true that other PAs have become even more degraded than in surrounding areas, due to conflicts with local people (Wright et al., 2007). However, Bruner et al., (2001) found that tropical forest cover loss in national parks was far lower than in surrounding parks.

The myopic arguments to rely solely on restrictive approaches to conserve forest biodiversity continues to be fiercely re-evaluated, partly as the potential impacts may be somewhat illusory, because PAs tend to be located in areas that are unattractive for agricultural conversion (Nelson and Chomitz 2011). Thus, the common phrase ´Rock and Ice´ captures the perception that PA locations are biased toward marginal lands where natural forest cover might remain even without a PA (Joppa and Pfaff 2009). Furthermore, the establishment of PAs may cause ‘leakage’ to occur, whereby deforestation pressure is displaced from inside the PA, intensifying forest-loss elsewhere (Gaveau et al., 2009).

To that end, Joppa and Pfaff (2010) provide a re-evaluation with a considerable body of literature for understanding and analyzing various adequate approaches, methods and case studies for effective PA management to avoid deforestation (Table 3). Their compilation describes six methods or analytical designs for forest loss assessment: (i) loss inside PA boundaries, (ii) comparing loss inside PAs with outside regional non-PAs, (iii) differentiating loss inside-outside PAs via buffer areas, (iv) analyzing the loss inside PAs pre and post protection, (v) examining the loss inside-outside PAs via comparing similar features and, (vi) differentiating the loss inside-outside PAs via predictions of regressions over time.

Table 3 Summary of different approaches and case studies used to assess PA effectiveness preventing deforestation.

Approach	**Analytical design**	**Case studies**	**Disadvantages**
Compare forest loss to nowhere	Analyze loss inside PA boundaries	[11, 30, 31]	With no benchmark to compare loss status.
Compare forest loss to everywhere	Contrast loss inside PAs – outside regional non-PAs	[4, 10, 12, 18, 26, 29]	Doesn´t consider location bias.
Compare forest loss to buffer area	Contrast loss inside PAs – outside areas closely surrounding	[4, 8, 14, 15, 16, 19, 20, 22, 27]	Likely susceptible for overestimations to spillovers and even location bias.
Compare forest loss to nearby time	Analyze loss inside PA before and after protection	[12, 14, 21]	Suppose deforestation trend is due to shift in protection status of the area. Cloud cover.

Source: derived and modified from Joppa and Pfaff 2010. (4) Bruner et al., 2001; (8) Curran et al., 2004; (10) DeFries et al., 2005; (11) Fuller et al. (2004); (12) Gaveau et al., 2007; (14) Liu et al., 2001; (15) Linkie et al., 2004; (16) Maiorano et al., 2008; (18) Messina et al., 2006; (19) Nagendra et al., 2004; (20) Nagendra et al., 2006; (21) Nagendra 2008; (22) Nepstad et al., 2006; (26) Sanchez-Azofeifa et al., 2002; (27) Sanchez-Azofeifa et al., 2003; (29) Western et al., 2009; (30) Zeng et al., 2005; (31) Hayes and Schwartz 2002.

2.2.3.1 Deforestation inside PAs approach

This initial approach attempts to examine the status of forest cover only within PAs. But, their results could suggest protection viability without considering the impact of location. As an example of an analytical design proposed by Fuller et al., (2004) in the Kalimantan PA network the study found that this would not be longer feasible. They assessed the viability of a network based on the level of forest loss in the PAs alone. Assuming that Kalimantan’s surrounding non-protected locations showed forest-loss similar to PAs, then the PAs could be described as effective. To assess effectiveness, thus, it is important to compare what happens in PAs to what would have happened in those same locations had the areas not been protected (Joppa & Pfaff 2010).

2.2.3.2 Deforestation inside PAs – outlying regional nonprotected approach

Secondly, outlying regional surroundings approach involves comparing forest loss within PAs to deforestation on all unprotected land outside. It means that if no deforestation occurred inside the PA, for example, one may measure the amount of forest loss that was avoided by understanding the extent of regional deforestation outside (Joppa and Pfaff 2010). This analytical design has been applied in largest-scale assessments of PAs by DeFries et al., (2005) where they examined the isolation of 198 protected moist and dry tropical forests worldwide. They showed that only 25% of PAs presented deforestation, compared to 70% of the regions outside PAs. Another approach, in 2002, Sanchez-Azofeifa et al. examined deforestation rates in the Osa Peninsula of Costa Rica and compared them to deforestation within Corcovado National Park in that same region. They found no deforestation within the PA, but high clearance outside. This approach, however, also carries the potential of non-random location bias in the analysis (Joppa & Pfaff 2010), which gives rise to questions about the impact of social, economic and environmental factors that affect deforestation rates, and affect where PAs are located (Nelson and Chomitz 2011).

2.2.3.3 Deforestation inside-outside PAs "buffer approach"

As a third approach, recent analyses have also implemented an incremental buffer approach to examine forest loss, both within and outside of PAs (MAS 2005; Joppa and Pfaff 2010). This approach reveals more detail about patterns of deforestation but can also create further ambiguity regarding the effectiveness of PAs. For example, lower rates of deforestation inside a PA than outside could lead one to the conclusion that PAs are effective at conserving forest biodiversity (Bruner et al., 2001; Naughton-Treves et al., 2005). Others interpret this trend as evidence of the increasing pressure on the PA and a warning sign of landscape fragmentation and ecological isolation (MAS 2005). Bruner et al., (2001) examined the effectiveness of PAs in the tropics, drawing on survey data of 93 PAs categorized as "partly natural" or "human dominated" across 22 different countries.

Investigators concluded that the conditions within 90% of PAs were better than in their BAs. However, their conclusions remain unclear because these apparent differences have always existed, or could be a side-effect of sampling methodologies (i.e., selection of the parks; design and conduct of the survey; comparing with surrounds larger than the parks in question).

Another case study of Armenteras et al., (2009) using RS data on forest cover changes over time, provides a similar analysis of the buffer approach on PAs and IRs in the Colombian Guyana shield region. The results of the analysis show that while the degree of forest loss in BAs were around four times higher than within PAs, forest loss in BAs was 1.5 times higher than in IRs. Both studies showed that PAs generally are effective at reducing deforestation. In contrast, a 2001 study by Liu et al., applied the same approach, they found that forest loss within the Wolong National Park was equal to or higher than in BAs, which could be considered as imperfect or failed protection.

A cautionary note may be appropriate to warn against the accuracy of this approach. The simple inside–outside comparisons that have also been used in other research (Sanchez-Azofeifa et al., 2003; Nagendra et al., 2006; Nepstad et al., 2006) may have considerably overestimated the protection effect according to one recent study in Costa Rica (Andam et al., 2008). These comparisons ignore the role PAs might play in giving the impression that they are reducing deforestation when in fact they displace losses to other areas through 'neighborhood leakage' or 'spatial spillovers' (Joppa and Pfaff 2010). For example, if people were deforesting within an area that became protected, they may relocate to the buffer zone.

2.2.3.4 Deforestation inside PAs – nearby time approach

This fourth option to analyze protection location is based on the application of RS multi-temporal information to compare forest loss rates inside the same area before and after it was granted legal protection. It has been a critical component in various PA examinations. Liu and his colleagues' (2001) comparison, provided results of forest loss increase after the Wolong Reserve was established. A related study contrasting deforestation rates pre and post protection was done by Gaveau et al. (2007) in Sumatran reserves. Their comparison analyses showed trends of deforestation rates unchanged. Another comparison of levels of forest cover before and after the establishment of protection, based on multi-temporal datasets analysis in 17 PAs worldwide was done by Nagendra (2008). He demonstrated that six PAs, all located in Latin and North America, maintained 100% of their forest after assigned protection status. Of the remaining 11, six PAs had some impact on deforestation rates and the remaining five reported increased rates of clearing after protected-area establishment, appearing to have been ineffective in preventing deforestation.

A principal constraint of this complementary approach arises when deforestation rates are not constant over time in areas without protection status (Joppa and Pfaff 2010). Given that this analysis is based on past deforestation to estimate what would have happened without a protection strategy, if other potential factors can alter deforestation patterns over time then this approach can inaccurately include their effects in evaluating the impacts of protection (Joppa and Pfaff 2010). Other disadvantages of this analysis include its relatively high cost and the process to clean the presence of clouds from the images, especially in the tropical regions.

3 Study area – Colombia's PAs system

Colombia is the fourth largest country in South America and covers an area of 1.14 million km^2 (Figure 2). It has about 45.4 million people and an average population density of 40.1 people per km^2 (see http://www.dane.gov.co). Differences in elevation and latitude produce large climatic variation across the country. For example, there are dramatic differences in annual precipitation, ranging from 350 mm (Guajira peninsula) to 12,000 mm (Pacific lowlands). Consequently, the combination of different climates, elevation ranges, and geographic location have allowed the development of a high diversity of habitats and species richness. For instance, it accounts the highest of known bird species, and is second for known plants and amphibians (IUCN 2009). However, it also has been undergoing rapid process of land-use/cover changes and habitat conversions (Etter et al., 2006). Colombia can be divided into five continental regions: Andean, Caribbean, Pacific, Orinoco, and Amazon, each with varied bio-geographical characteristics, socio-cultural, economic, and demographic differences. Consequently, land-use/cover change across the country has undergone distinct land transitions in each region.

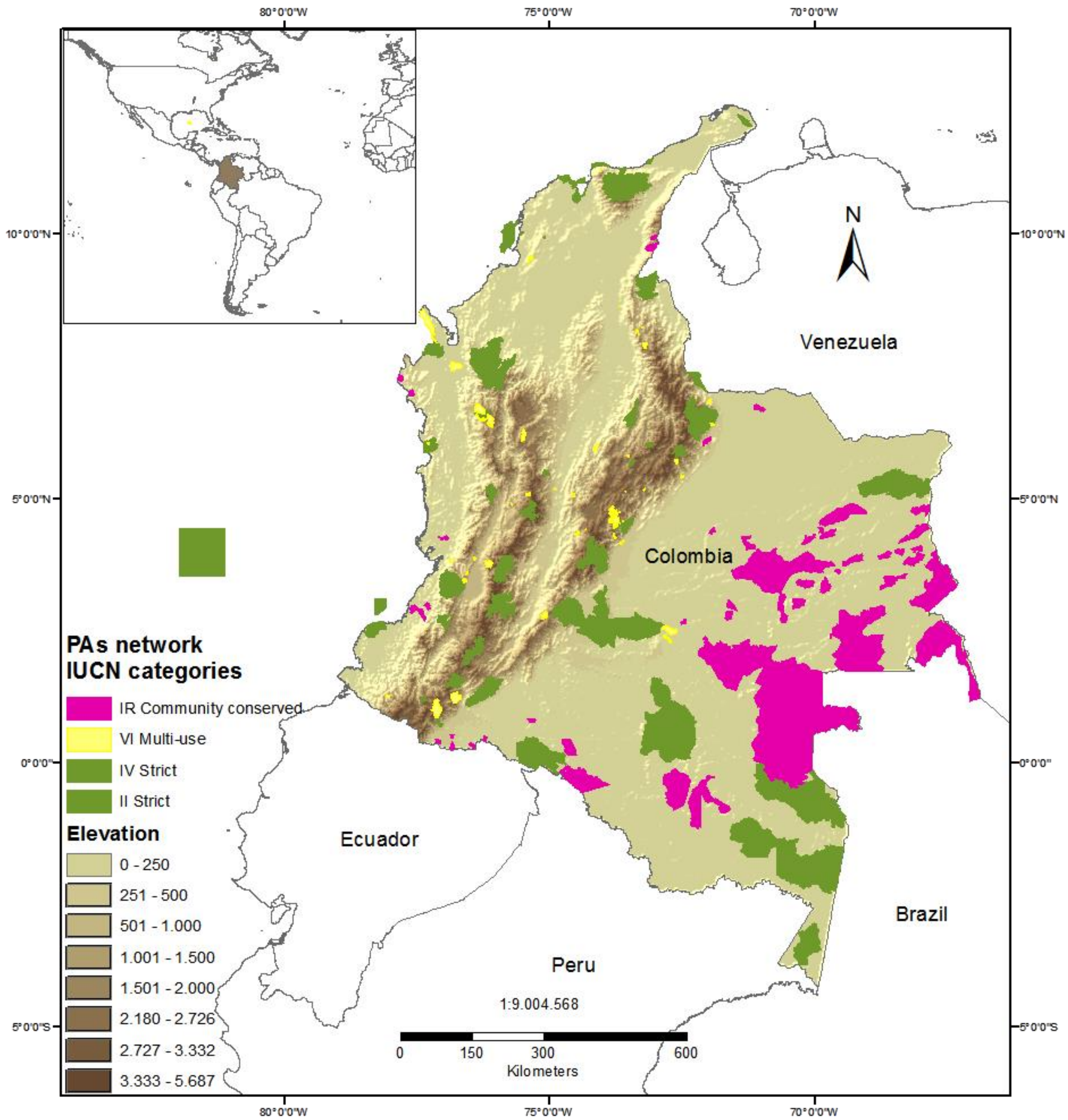


Figure 2 My case study area, Colombia country showing the location and distribution of the whole PA network, including marines. Shaded areas in brown dark and light correspond to altitude.

Historically, the majority of the population (65%) has been concentrated in the Andean region (Colmenares 1999). The average rural population density in Colombia is approximately 30 people per km^2, but for example, depending on the region can be lower than 5 in the "Amazon" or as high as 74 people per km^2 in the "Andean" (Armenteras et al., 2011). In addition, deforestation rate in the Andean region is high (0.67% per year), with annual deforestation rates lower in montane forests than in lowland forests (Armenteras et al., 2011). This situation of deforestation have been related to population density and economic activity represented by intensive productive activities such as coffee and potatoes, pasture establishment and, recently, the presence of illicit crops and mining (Etter et al., 2006; Davalos et al., 2011; Armenteras et al., 2011). According to national estimates of forest habitat loss by the Instituto de Hidrologia, Meteorologia y Estudios Ambientales (IDEAM) indicates that average rate of deforestation until 2004 was of 100.000 ha per year (Cabrera et al., 2011). However, there is no consistent multi-temporal dataset of forest cover change for Colombia. Nevertheless, implementing systematic forest assessments at the national scale using higher resolution is difficult because of the limitations in technical infrastructure, expertise, and regular availability (DeFries et al., 2005). The Moderate Resolution Imaging Spectroradiometer (MODIS) satellite data products are reliable and useful tools for monitoring forest cover changes at national scales. These characteristics allowed the last development in near real-time of land-cover changes detection, using Terra-i algorithms. Recently, Terra-i models have detected a more updated average annual deforestation rate of 152.000 ha per year, until 2009 (Reymondin 2012).

From around 1960s, Colombia began actively to identify lands to build a network of PAs in order to repel these forest cover changes. Nowadays, its National Natural Park System has 56 PAs, covering more than 11% of the country territory (DNP 2010). In order to explicate this approach, forest loss was analyzed at national scale, with the most current spatial information (2009) on Colombia's PAs. They were separated into three categories on the basis of IUCN level of protection they afford to the natural habitats (IUCN 1994), excluding marine PAs. Category II – IV PAs, which cover about 9.4 million ha of the country, consist of 48 Natural National Parks, category VI that cover 462 mil ha comprised 51 National Protective Forests Reserves and 161 Indigenous Reserves (IRs) that account for over 15.3 million ha (Figure 2 and Annex 1).

4 Material and Methods

Drawing on RS imagery and GIS datasets, this analysis undertaken sought to scope the extent of forest cover loss and effectiveness preventing deforestation (Figure 3). Extent (percentage and rates) of forest cover clearing within can be compared outside 10-km buffer to nearby time, to see if establishment of the PAs has prevented rates of forest cover change over time. Thus, a combination of both approaches 3 & 4 (*subchapter 2.2.3*), becomes useful in this analysis. However, it is also subject to the limitation that in general the fairly long time span over which many PAs have existed and the recent dates for which most RS images are available (Nagendra 2008).

4.1 Data sources

For the comprehensive analysis of PAs effectiveness, I combined datasets from various sources. I used four physical and environmental variables: PA's, BA's, GlobCover and Terra-i (Table 4).

Table 4 Summary of the characteristics and origins of the datasets used in this study.

Data type	Variable description	Spatial resolution	Data source
Protected areas	Polygon with the areas of the PA network	Linear Feature	WDPA[1]
Buffer areas	Polygon with surrounding area 10-km outside	Linear Feature	Author himself
Global Land Cover	Area and percentage of remaining forest cover in 2005	300m–Grid	ESA/DUE[2]
Terra-i MODIS NDVI	Forest covers change area and percentage 2005-2011	250m–Grid	Terra-i[3]

1 World Database on Protected Areas; 2 European Space Agency Data User Element; 3 Terra-i near real time monitoring; an eye on habitat change.

4.1.1 Selection of PAs polygons

I selected 80 PAs remotely distributed across Colombia's geographic landscape. Specifically, I used the following criteria to determine which PAs to include in the analysis: (1) those with park and reserve boundaries delineated in the World Database on Protected Areas (WDPA) developed by the United Nations Environment Program (UNEP) World Conservation Monitoring Centre (WCMC) in collaboration with the IUCN World Commission on Protected Areas; (2) I excluded those PAs with small areas (less than 5000 ha), as this is not the optimal area to maintain ecosystem-level processes (Rodriguez et al., 2004; Naughton-Treves et al., 2005), and for the scale to cover at least a significant number of pixels in the resolution MODIS NDVI data; (3) I did not include marine PAs because of the limitations of the dataset scale; and (4) portions of PAs that extended into marine environments were clipped out. Overlapping PAs were combined to avoid double-counting errors (Annex 2).

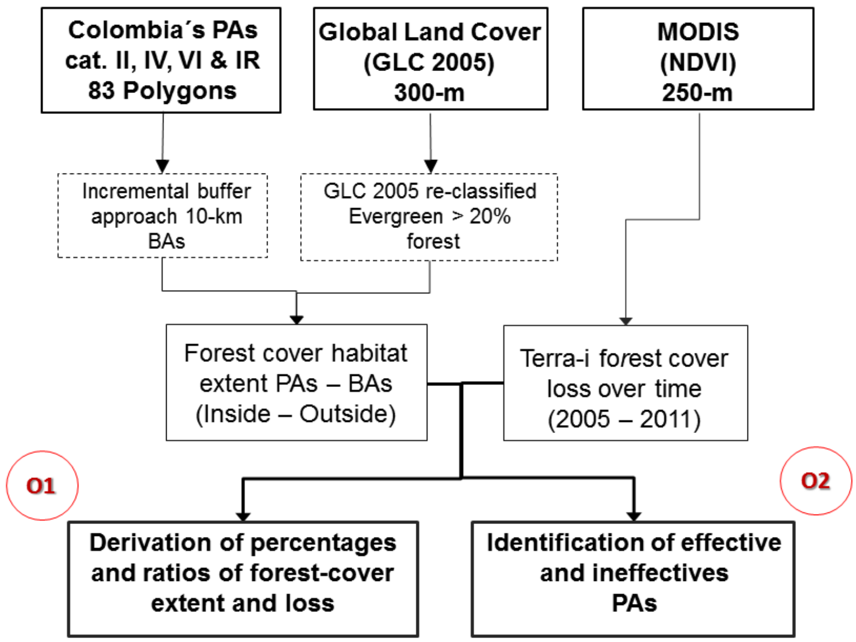


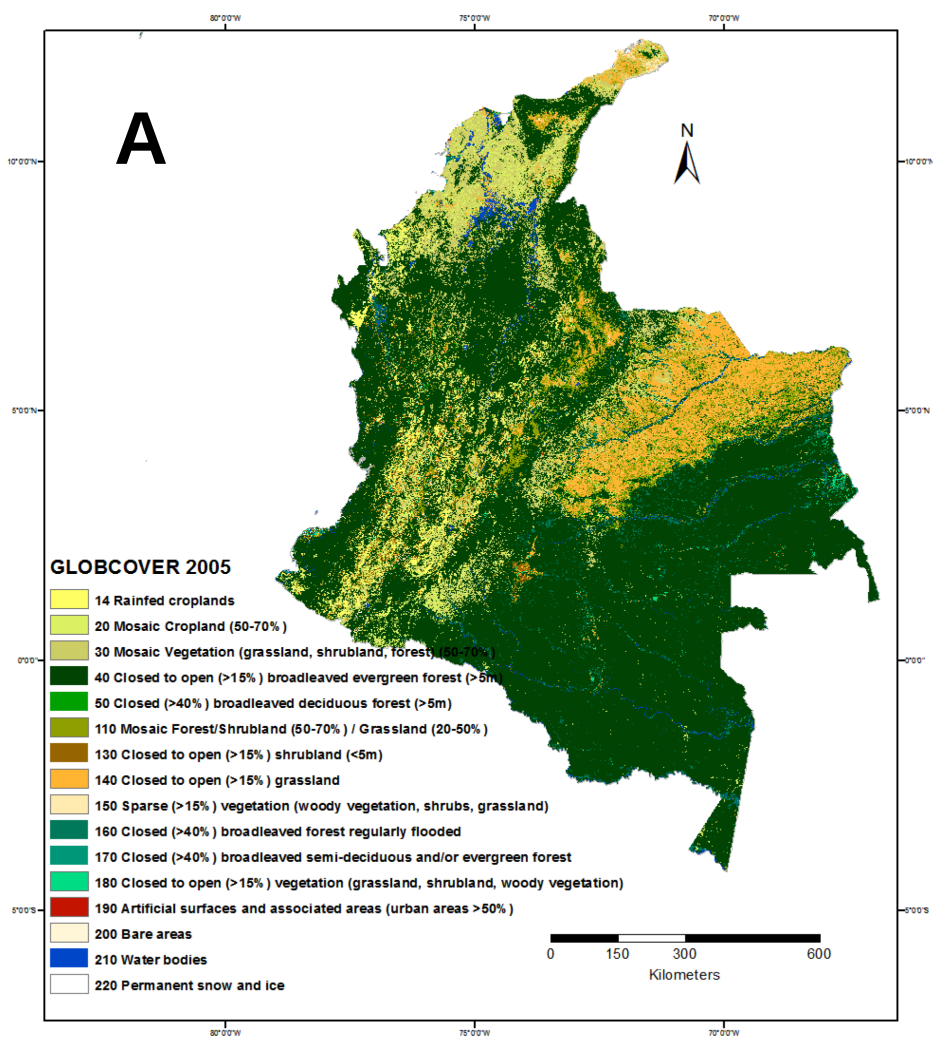
Figure 3 Schematic representation of methodological framework approach used in this study. O1 and O2 indicate the objectives of this study.

4.1.2 Buffer areas (BAs) polygons and process of refining overlay data

To compare forest loss inside-outside PAs, we derived a data set consisting of 10-km wide buffer belts (delineated zones around their polygon perimeter) using a GIS package (ArcGIS ESRI v. 10). The 10-km BAs were selected based upon the appropriate distance from polygon PAs border, which constitutes BAs that represent the same area proportion or equivalent size of the PAs. In addition, this particular distance allows comparison with other effectiveness studies (Bruner et al., 2001; Sanchez-Azofeifa et al., 2003). Due to the high levels of spatial overlaps between PAs (reserves lying within the boundaries of national parks) and superimposed BAs for those territories, a limitation of the accuracy with overestimation of double counting were produced. Thus, I reduced and limited this overlapping error using a GIS-based approach. After the cleaning and filtering process within these polygons, the extent of evergreen forest in 2005 was extracted from land cover data sources.

4.1.3 Forest coverage dataset

The Global Land Cover map (GLOBCOVER 2005) dataset (Arino et al., 2007) was taken as a starting point of forest habitat extent, which provides classification of land cover at 300m spatial resolution. The GLOBCOVER 2005 provides a thematic legend of 23 classes of land cover. It uses a globally compatible legend with the FAO-UNEP Land Cover Classification System (LCCS), with an overall accuracy about 68% (Bontemps et al., 2009). An alteration was made in this base-map, re-classifying the GLOBCOVER 2005 map in two categories: forests and non-forests (Figure 4 A and B). The forest cover extraction process is explained in more detail in sub-chapter 4.2.1.



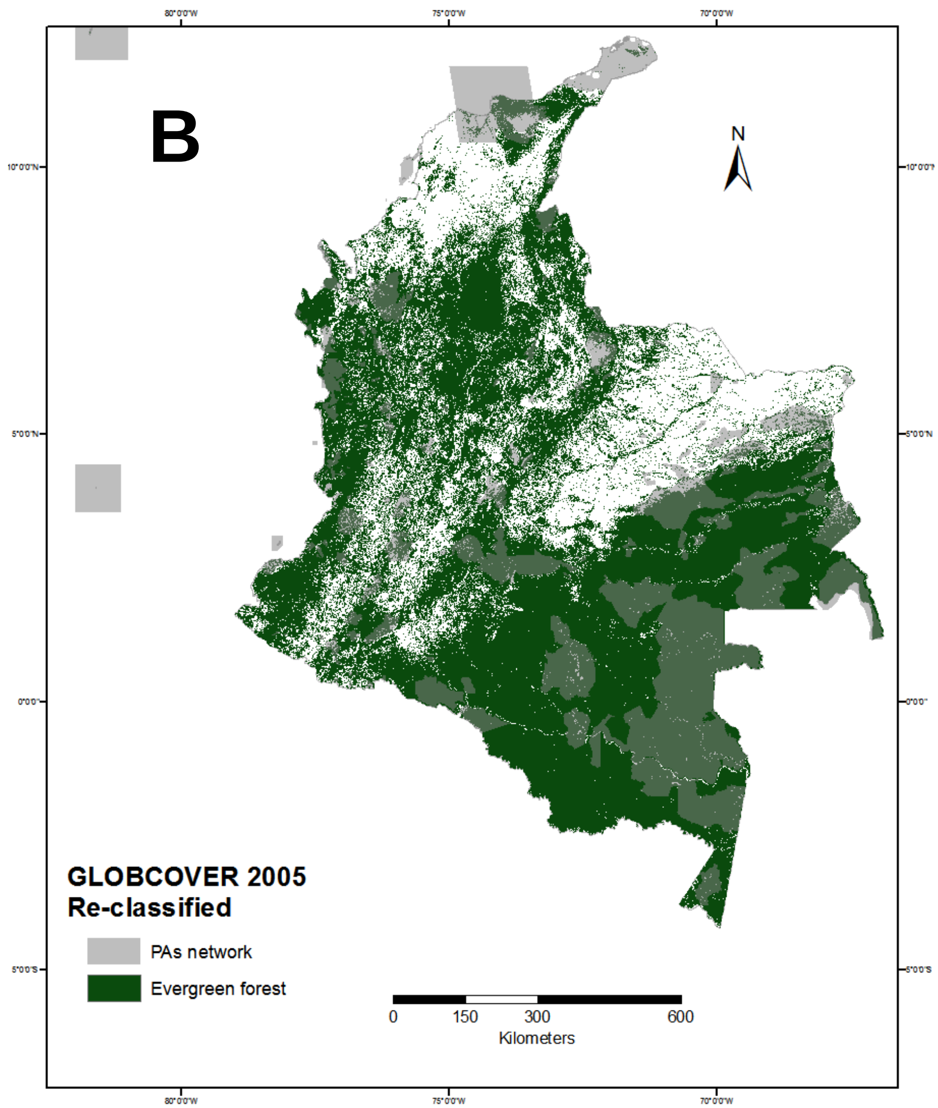


Figure 4 (A) Land cover map GLOBCOVER 2005. (B) Forest cover "evergreen forests" re-classified from the GLOBCOVER 2005 dataset overlapped with distribution of PA network across Colombia (as of November 2012). Raw data layer compiled from WCPA and IUCN.

4.1.4 Forest cover changes satellite dataset (Terra-i real-time system)

Forest cover change was estimated from Terra-i near real-time monitoring system using the Moderate Resolution Imaging Spectroradiometer (MODIS 13Q1) Normalized Difference Vegetation Index (NDVI)[3]. NDVI enables consistent spatial and temporal comparisons of

[3] **MODIS** sensor acquires data in 36 spectral bands with 16-day temporal resolution. Of the 36 bands, bands 1 and 2 (with 250-m spatial resolution) centered on the red (620–670 nm) and infrared (841–876 nm) portions of the spectrum; they are designed to service the global NDVI products.

vegetation conditions, providing a measure of the spectral response of forest cover surface. If vegetation is degraded, it will reflect the blue and even more the red (R) visible spectrum. On the other hand, if the vegetation is healthy, it will reflect the near-infrared spectrum (NIR). According to Jensen (2007), mathematically NDVI was calculated for each date of MODIS normalized reflectance bands, as follows:

Equation

$$\mathbf{NDVI} = \frac{\mathbf{NIR} - \mathbf{R}}{\mathbf{NIR} + \mathbf{R}}$$

Human activities create disturbances that alter the usual cycle of vegetation greenness in an area. Disturbances can be detected when the Normalized Difference Vegetation Index (NDVI) of the landscape changes from its baseline values (Reymondin et al., 2012).

Hence, Terra-i approach on build a forecasting model capable of predicting the evolution of vegetation greenness for a site, based on the relationship between previous greenness measurements and simultaneous climatic measurements at that site. Such a model is then used to predict future NDVI values (16 days ahead, given the current climatic conditions) and to identify anomalies or abrupt changes in vegetation where NDVI observations from MODIS differ from the model predictions (Raymondin et al., 2012). The model calculates an anomaly probability based on the difference between predicted and observed values. It is assumed that vegetation evolution (NDVI evolution at a site) is influenced by recent and seasonal rainfall trends. When major changes in the vegetation index are detected (outside of the usual pattern of seasonal evolution), it is assumed that they are due to human intervention. These events are, therefore, flagged in near-real time as events that land managers, conservationists, and policy makers should be aware of.

Prior to developing these change analysis maps, MODIS time-series are corrected of noise introduced by atmospheric, view angle variations and cloud contamination (Beck et al., 2007). Thus, Terra-i uses machine learning algorithms to test and validate maps of forest cover change every 16 days from 2004 to present. To this end, a pre-processing sequences started applying a compositing method “Fourier transform” (Roerink et al., 2000) for correct cloud contamination, atmospheric variability, bi-directional reflectance. It provides a smooth NDVI time series and more stable imagery. Terra-i also requires two inputs to produce confident datasets: (i) previous rainfall from Tropical Rainfall Measuring Mission (TRMM) and (ii) Temperature from WorldClim (Reymondin et al., 2012). These data are run to analyze, identify and validate drivers of change (floods and droughts) in the time-series NDVI intervals. In doing so, each anomaly detected and the pixel identified, are corrected using The Land Surface Water Index (LSWI) for floods and TRMM data for drought anomalies (Reymondin et al., 2012).

Because MODIS sensor resolution is relatively low (250-m), small-scale events are more difficult to detect. Thus, auxiliary high resolution Landsat scenes (30 x 30-m) combined with a definition of forest as > 80% tree canopy cover (either undisturbed or partially degraded by selective logging)- were used to calculate the proportion of events in a given size or sub-pixel events (Reymondin et al., 2012). Finally, high-confidence and validated forest cover pixel changes of MODIS NDVI dataset were produced to 23 values per year. Approximately two images per month, for a total of 184 original images, were processed from 2005 to 2011. A representation of the Terra-i product is given in only one map (figure 5).

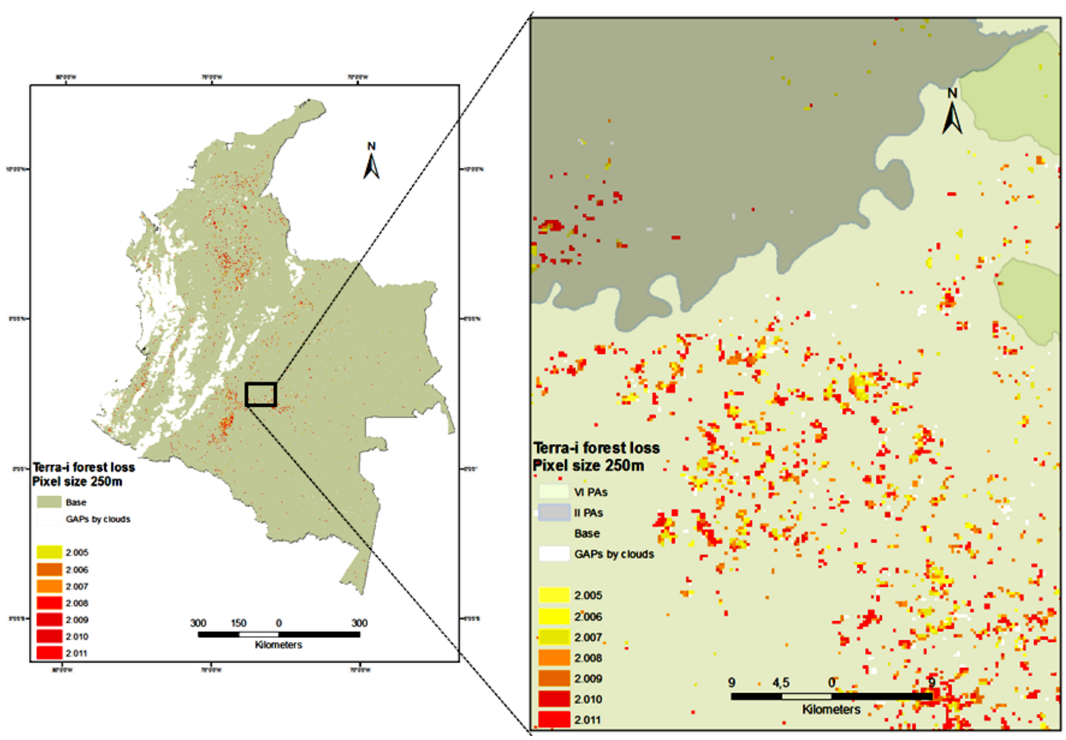


Figure 5 Terra-i forest cover loss detection 250-m spatial resolution. From yellow to red color indicate forest cover loss from 2005 to 2011.

It is important to highlight that this study does not develop the Terra-i algorithm detection described by Reymondin et al. (2012). CIAT processed this data to provide habitat change map.

4.2 Image processing and analyzing (methodology)

4.2.1 Extracting forest covers extent data

It should be noted that in this analysis, I evaluated forest cover areas "evergreen forest" (classified as broad-leaved evergreen tropical forest; ESA classification). Thus, all the 5 forest cover classes for Colombia that contain forest or forest mosaics were extracted from GLOBCOVER, where the average amount of forest cover was > 20 percent. More than 20 percent was chosen to minimize the risk of including tropical savannas and other land that was already largely cleared of forest that was predominantly used for agriculture. Its statistics definition may also include different forest cover types that can potentially support intact forest in which canopy cover threshold has been reduced to below 40 percent. This threshold- allows balancing for small patches of evergreen forest remaining inside-outside PAs. The five forest classes from GLOBCOVER 2005 include: [Class 40] Closed to open (>15%) broadleaved evergreen and/or semi-deciduous forest (>5m); [Class 50] Closed (>40%) broadleaved deciduous forest (>5m); [Class 130] Closed to open (>15%) shrubland (<5m); [Class 160] Closed (>40%) broadleaved forest regularly flooded and; [Class 170] Closed (>40%) broadleaved semi-deciduous and/or evergreen forest regularly flooded (Figures 4A and B). Using this definition of forest and zonal statistics as table tool in ESRI ArcMap v.10, I calculated the areas in hectares and percentages of forest cover 300-m pixel over three IUCN category. These hectares and percentages provide the pixel areas in each 300-m pixel containing forest cover extent inside and outside each polygon categories (Figure 6).

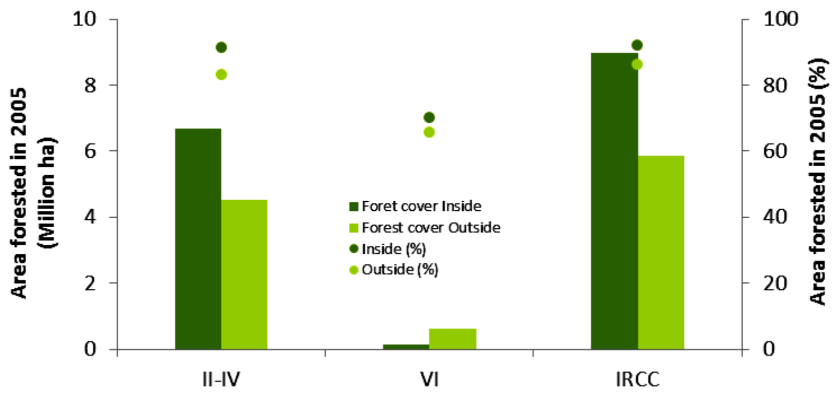


Figure 6 Estimated areas in hectares and percentage of forest cover in the year 2005 for each PAs IUCN categories. Within PAs (dark green) and outside 10-km buffer (light green), shows cover areas in hectares. The green points are estimates of their percentages.

4.2.2 Determining and analyzing forest cover extent and loss inside-outside PAs over time

To determine how forest cover changed into PA network categories, I analyzed the forest maps in two ways. First, using the modified-reclassified GLOBCOVER grid (processed and geographically projected as Magna Colombia Bogota), I calculated areas of forest existing in 2005 for each PA and BA polygons as a benchmark and- I summarized them as forest in hectares (Table 4). Then percentage area was calculated as the per-centage of forest cover area within the boundaries of the PA's and within the BA's. I assumed that historically the percentage area loss in each PA and BA was zero.

Secondly, I applied forest loss rates to determine actual 2011 forest cover area loss. Then, using ArcGIS based on a pixel re-sample analysis and overlapping technique, I combined GLOBCOVER and Terra-i grid covers at the same pixel size (250 m) to obtain an accurate measure of forest-area change across the PA network annually. Thus, for each PA and BA processed, I estimate forest cover rate of change (Puyravaud 2003) as the annual percentage of loss of forest areas relative to the total evaluated GLOBCOVER area, as follows:

Equation $$FCRL \quad \frac{1}{T_2 - T_1} * Ln \frac{A_2}{A_1}$$

Where FCRL = Forest Cover Rate of Loss, A1 = Initial modified forest PA (GLOBCOVER 2005), A2 = Final modified forest PA (GLOBCOVER 2011), T1 = Start time of period (2005), T2 = Final time of period.

Moreover, changes in forest cover inside PAs and BAs were quantified and analyzed by following quantitative characteristics: The extent of the forest covers in 2005 and 2011, in terms of hectares and percentage (Table 5).

4.2.3 Determining effectiveness index (EI)

I evaluated the effectiveness for PA's according to the method described in Figueroa and Sanchez (2008), but here- as the sum of four parameters, with data standardized form 0 to 1. The EI used by Figueroa and Sanchez (2008), was selected for one reason: most of the PA's included in this study were parks falling within the same IUCN categories and the methodology for determining EI levels and trends was simple, straight forward to use, and easily replicable. The following four parameters were calculated from the raw data and included in measuring the effectiveness index: (1) percentage of forest cover area loss inside PA (2005-2011); (2) comparison between the percentage of forest cover loss inside and outside PA; (3) rate of forest cover area loss inside PA (2005-2011); (4) comparison between rate of loss of forest cover inside and outside PA (Table 5).

I chose two groups of effectiveness parameters. The first involving the total extent and annual rate of loss of forest cover in the PA's (parameters 1 and 3) as a reference value for comparison, as each PA has a particular trend in protection over time, contributing to the measure progress toward the quantitative and qualitative element of Aichi Biodiversity Target 11.[4] The second (parameters 2 and 4) involves comparison or proportion estimates based on the ratio inside divided outside PA's for the total extent and annual rate of loss. It is usually assumed that PA size might affect the impact of PA's has to prevent forest loss.

[4] Convection on Biological diversity (CBD): http://www.cbd.int/decision/cop/. Accessed 20 May 2013

For example, two PA's have the same values in forest loss, but vary widely in their size. Hence, these ratios were calculated to avoid the PA size effect.

On the basis of these parameters, the first set of score values was then normalized. All the parameters were scaled or normalized from 0 to 1, as follows:

Equation
$$PN = \frac{PV - PV_{min}}{PV_{max} - PV_{min}}$$

Where PN = parameter normalized, PV = parameter value, PV_{min} = parameter value minimum, PV_{max} = parameter value maximum.

For the status of each PA comparison, it was arbitrarily assigned a score value of zero for PA's showing lower percentage and rate of loss inside than observed in the corresponding buffer areas, and value of one, for PA's showing higher percentages values of loss than the buffer areas. Lastly, the effectiveness index of each PA was then calculated as the sum of the four normalized parameter values.

Effectiveness index was derived with the following equation:

Equation
$$EI = PN_1 + PN_2 + PN_3 + PN_4$$

Where EI = Effectiveness index, PN = Parameter normalized from 1 to 4.

Table 5 Estimated forest cover loss percentages and rates (2005-2011) inside/outside 10-km buffer for 80 Colombia´s PA(s) included in the study.

Protected area PA(s)	IUCN Category	Size PA (ha)	Forest cover In-PA 2005 (ha)	Forest Loss In-PA 2011 (%)	Forest loss Out- 10km buffer 2011 (%)	Forest loss extent In-PA 2011 (ha)	Forest loss extent BA 2011 (ha)	Forest loss rate In- PA (%)	Forest loss rate Out- BA (%)
Aduche	IRCC	202.993	200.250	0,11	0,09	225,0	218,8	0,000	0,000
Afilador	IRCC	9.779	6.494	0,19	0,44	18,8	193,8	-0,001	-0,001
Amacayacu	II-IV	274.858	267.469	0,24	0,19	662,5	493,8	0,000	0,000
Atana Pirariami	IRCC	50.839	41.600	0,12	0,13	62,5	150,0	0,000	0,000
Bachaco Buena Vista	IRCC	68.475	67.294	0,05	0,08	37,5	150,0	0,000	0,000
Bajo Rio Guainia y Rio Negro	IRCC	842.422	635.869	0,15	0,06	1.237,5	118,8	0,000	0,000
Barranco Ceiba y Laguna Araguato	IRCC	20.083	18.538	0,22	0,83	43,8	462,5	-0,001	-0,001
Buenavista	IRCC	6.734	6.581	0,65	0,91	43,8	412,5	-0,002	-0,001
Cahuinarí	II-IV	560.162	543.400	0,13	0,07	718,8	281,3	0,000	0,000
Calle Santa Rosa	IRCC	18.271	16.731	0,21	0,80	37,5	500,0	-0,002	-0,001
Caño Cavasi	IRCC	26.157	21.650	0,12	0,06	31,3	68,8	0,000	0,000
Caños Cuna Tsepajibo Warracana	IRCC	48.041	39.488	0,13	0,04	62,5	50,0	0,000	0,000
Carpintero Palomas	IRCC	41.008	32.681	0,05	0,20	18,8	231,3	0,000	0,000
Catatumbo - Bari	II-IV	161.326	154.375	0,72	0,77	1.156,3	1.300,0	-0,001	0,000
Chaparral-Barronegro	IRCC	14.987	12.406	0,29	0,39	43,8	356,3	-0,001	0,000
Ciénaga Grande De Santa Marta	II-IV	27.939	15.119	0,00	0,13	0,0	143,8	-0,001	-0,001
Cordillera De Los Picachos	II-IV	288.266	261.169	1,92	1,40	5.537,5	2.993,8	-0,003	0,001
Corocito Yopalito Gualabo	IRCC	8.239	2.163	0,00	0,02	0,0	12,5	0,000	0,000
Corocoro	IRCC	22.248	21.725	0,08	0,22	18,8	156,3	0,000	0,000
Cuchilla El Minero	VI	9.986	9.394	2,82	4,82	281,3	3.868,8	-0,010	-0,005
Cuenca Alta del Río Algodonal.	VI	8.008	6.806	0,00	0,08	0,0	56,3	0,000	0,000
Cuencas Río Blanco y Negro	VI	12.684	9.144	0,00	0,00	0,0	0,0	0,000	0,000

Table 5 (*Continued*)

Cumaral Brazo Amanaven	IRCC	22.877	22.444	0,08	0,24	18,8	206,3	0,000	0,000
Darién Frontera Col. Panameña	VI	62.163	30.756	0,25	0,89	156,3	656,3	-0,002	-0,001
El Unuma	IRCC	928.968	807.144	0,30	0,26	2.812,5	1.287,5	-0,001	0,000
Guaco Bajo y Guaco Alto	IRCC	47.006	45.044	0,33	0,27	156,3	325,0	0,000	0,000
Guangui	IRCC	19.342	18.231	5,17	5,78	1.000,0	4.000,0	-0,011	-0,001
Huila	IRCC	10.901	10.775	8,31	7,48	906,3	4.437,5	-0,014	0,001
Inga de Nineras	IRCC	10.593	9.794	0,89	1,06	93,8	806,3	-0,002	-0,001
Iroka	IRCC	8.634	5.856	0,00	0,13	0,0	50,0	0,000	0,000
Isla De Salamanca	II-IV	57.608	9.338	0,00	0,00	0,0	0,0	0,000	0,000
Jurado	IRCC	14.599	11.350	0,13	0,36	18,8	143,8	-0,001	0,000
La Fuga	IRCC	7.621	6.819	0,90	0,91	68,8	637,5	-0,002	0,000
La Paya	II-IV	429.447	420.869	0,63	1,00	2.706,3	2.637,5	-0,002	-0,001
Laguna Anguilla-La Macarena	IRCC	16.620	15.688	0,19	0,12	31,3	106,3	0,000	0,000
Laguna Negra y Cacao	IRCC	17.291	16.938	0,25	0,14	43,8	118,8	0,000	0,000
Los Farallones De Cali	II-IV	207.026	153.800	0,46	1,91	950,0	4.593,8	-0,004	-0,003
Los Katios	II-IV	81.136	61.994	0,15	0,10	125,0	112,5	0,000	0,000
Macuare	IRCC	21.870	21.625	1,26	0,60	275,0	593,8	-0,001	0,001
Macuira	II-IV	26.776	10.844	0,00	0,00	0,0	0,0	0,000	0,000
Mataven Fruta	IRCC	86.105	80.088	0,19	0,14	162,5	231,3	0,000	0,000
Ministas Miralindo	IRCC	44.053	43.775	0,38	0,13	168,8	162,5	0,000	0,000
Monochoa	IRCC	322.328	303.306	0,07	0,06	212,5	150,0	0,000	0,000
Morocoto Buenavista	IRCC	50.265	49.438	0,06	0,05	31,3	68,8	0,000	0,000
Munchique	II-IV	47.070	37.819	0,72	1,17	337,5	1.768,8	-0,003	-0,001
Murcielago-Altamira	IRCC	5.373	4.856	0,12	0,09	6,3	56,3	0,000	0,000
Nukak	IRCC	890.357	877.150	0,32	0,59	2.818,8	3.012,5	-0,001	0,000
Nunuya de Villazul	IRCC	94.809	93.056	0,03	0,04	25,0	62,5	0,000	0,000
Paramillo	II-IV	532.963	476.119	0,44	0,31	2.368,8	1.362,5	-0,001	0,000
Páramo Urrao	VI	29.900	22.488	0,25	0,19	75,0	306,3	0,000	0,000
Parte Oriental del Vaupes	IRCC	3.411.199	3.352.590	0,21	0,19	7.256,3	775,0	0,000	0,000

Table 5 (*Continued*)

Paujii	IRCC	58.086	56.775	0,22	0,63	125,0	631,3	-0,001	-0,001
Pisba	II-IV	36.777	21.644	0,00	0,00	0,0	6,3	0,000	0,000
Predio Putumayo	IRCC	273.717	259.769	0,61	0,16	1.681,3	312,5	0,000	0,001
Puinawai	IRCC	1.055.315	1.036.850	0,09	0,12	925,0	675,0	0,000	0,000
Rio Atabapo	IRCC	516.337	442.463	0,08	0,15	431,3	375,0	0,000	0,000
Rio Curiche	IRCC	10.259	10.050	0,61	0,51	62,5	306,3	-0,001	0,000
Río Escalarete y San Cipriano	VI	5.568	4.781	2,81	1,14	156,3	637,5	-0,002	0,003
Río León	VI	34.243	17.850	0,29	0,72	100,0	787,5	-0,002	-0,002
Rio Nare	VI	15.045	13.494	0,37	0,26	56,3	250,0	-0,001	0,000
Río Puré	II-IV	1.002.515	988.125	0,15	0,16	1.543,8	550,0	0,000	0,000
Rio Siare o Barranco Lindo	IRCC	47.768	47.275	0,18	0,25	87,5	268,8	0,000	0,000
San Jose de Lipa	IRCC	19.092	12.494	0,33	0,23	62,5	225,0	-0,001	0,000
San Rafael	IRCC	38.745	2.956	0,00	0,05	0,0	62,5	-0,001	-0,001
Santa Maria de Pangala	IRCC	8.849	8.719	1,98	0,99	175,0	818,8	-0,002	0,002
Santa Rosa de Sucumbios	IRCC	6.668	5.463	0,84	0,49	56,3	268,8	-0,001	0,000
Santa Rosa del Guamuez	IRCC	14.575	7.300	0,00	0,08	0,0	75,0	0,000	0,000
Santa Teresita del Tuparro	IRCC	204.008	94.394	0,01	0,39	18,8	831,3	-0,002	-0,002
Selva De Florencia	II-IV	10.016	9.025	0,06	0,31	6,3	231,3	-0,001	-0,001
Serranía De Chiribiquete	II-IV	1.202.760	1.152.280	0,11	0,26	1.281,3	1.662,5	0,000	0,000
Serrania de Coraza y Montes de M.	VI	6.652	6.181	0,00	0,02	0,0	18,8	0,000	0,000
Serranía De Los Yariguies	II-IV	59.698	48.600	0,29	0,35	175,0	681,3	-0,001	0,000
Serranía del Capricho, Mirol y Cer.	VI	40.568	36.275	0,42	1,61	168,8	1.806,3	-0,003	-0,003
Sierra De La Macarena	II-IV	607.618	582.925	0,79	1,88	4.793,8	9.175,0	-0,004	-0,002
Sierra Nevada De Santa Marta	II-IV	402.546	218.019	0,00	0,03	0,0	93,8	0,000	0,000
Sokorpa	IRCC	26.497	19.819	0,21	0,19	56,3	100,0	0,000	0,000
Tayrona	II-IV	19.341	11.006	0,00	0,00	0,0	0,0	0,000	0,000
Tinigua	II-IV	215.287	209.238	4,92	9,75	10.587,5	12.718,8	-0,018	-0,010
Witora	IRCC	69.303	68.900	0,09	0,29	62,5	337,5	0,000	0,000
Yaigoje Apaporis	II-IV	1.060.539	1.032.170	0,12	0,12	1.268,8	562,5	0,000	0,000

5 Results

5.1 Extent of forest covers loss – inside and outside the PAs

The total forest cover area loss between 2005 and 2011 comprised 1.1% nationwide and 0.3% of 80 selected PAs, equivalent to a 57.000 ha with lowly variable values, ranging from 0% (e.g., in 13 PA) to 8.3% (Huila). In terms of number of PAs with forest loss, 67 (about 84%) occurred inside PA's and 76 (about 95%) occurred outside PA's (Table 6). As might be expected, there is considerable variance in both within and surrounding PA(s). In the 10-km buffers outside the 80 PAs forest cover loss extent was strongest with a decrease of 75.356 ha (0.57%) over the seven year period. These values were slightly variable, ranging from 0% to 9.7%. Most BAs (95%) showed percentages of forest loss rate.

5.2 Forest cover loss among IUCN protection categories

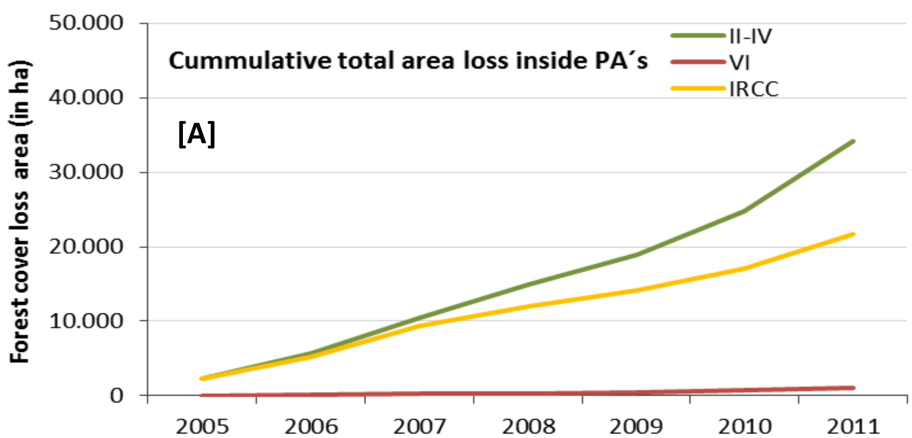
Table 5 provides a summary of PAs forest cover area loss based on the categories as defined by IUCN. From this, it can be seen that inside PAs, loss of forest covers occurred in 72% of those located in the category II–IV, 70% in the category VI and 91% in the category IRCC, although there were a very small number of PAs in the category VI. The total forest area loss accumulated inside the three PA categories were (34.221ha) II-IV, (21.738ha) IRCC and VI (993ha) between 2005 and 2011 (Table 5 and Figure 7A).

This forest area loss translates into mean deforestation rates of 0.54%, 0.56% and 0.72%, respectively. In terms of an absolute forest cover loss, within PAs the categories (II-IV) were 1.6 times higher than inside (IRCC). Moreover, the overall observed mean deforestation rate among the three categories have lost less than 1.0% inside and outside PAs, indicating that they lost comparatively little of their forest cover area between 2005 and 2011 (Table 5).

Table 6 Estimated forest area, losses in forest cover area and deforestation rates as an average percentage among IUCN categories inside PAs and in the 10-km buffer from 2005 to 2011.

Areas of the PAs categories		**Inside PAs**	**Outside PAs 10-km buffer**	**Total # and area**
II-IV	PAs number with forest loss (#)	16	19	22
	Forest cover 2005 (ha)	6.685.347	4.484.774	11.170.121
	Forest cover 2011 (ha)	6.651.126	4.443.402	11.094.528
	Forest cover loss (ha)	34.221	41.372	75.593
	Mean deforestation rate (%)	0.54	0.91	0.72
	Annual average deforestation rate (% per year)	0.09	0.18	0.14
VI	PAs number with forest loss (#)	7	9	10
	Forest cover 2005 (ha)	157.169	629.495	786.664
	Forest cover 2011 (ha)	156.176	621.107	777.283
	Forest cover loss (ha)	993	8.388	9.381
	Mean deforestation rate (%)	0.72	0.98	0.85
	Annual average deforestation rate (% per year)	0.14	0.22	0.18
IRCC	PAs number with forest loss (#)	44	48	48
	Forest cover 2005 (ha)	8.992.664	5.860.799	14.853.463
	Forest cover 2011 (ha)	8.970.926	5.835.193	14.806.119
	Forest cover loss (ha)	21.738	25.606	47.344
	Mean deforestation rate (%)	0.56	0.57	0.57
	Annual average deforestation rate (% per year)	0.10	0.11	0.11

When examining the loss of forest cover area inside and outside PAs, the category II-IV had the highest lost, 34.221ha and 41.372ha, respectively (Table 5 and Figure 7B). This difference translated into a mean deforestation rate outside PAs (0.91%) of nearly 1.6 times higher than inside PAs (0.54%). This could mean that PAs in the category II-IV reduced deforestation rates by 0.37 percentage points between 2005 and 2011. However, this measure is unbiased only if there is no differentiated between landscape characteristics inside and outside PAs.



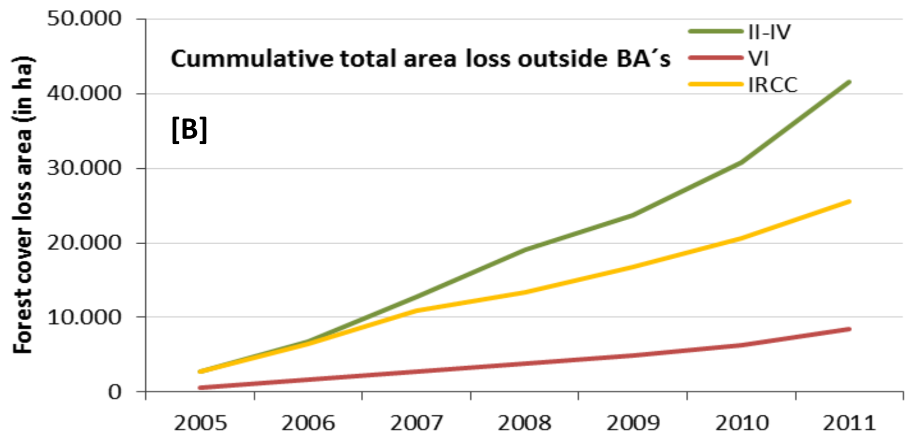


Figure 7 Annual area of forest covers loss inside PA (A) and in the 10-km buffer area (B) between 2005 and 2011 among the three categories of protection and management based on IUCN.

5.3 Effectiveness of PA network

In order to assess quantitatively the effectiveness of PAs decreasing forest cover loss, an effectiveness index (EI) was developed. Four different PAs effectiveness levels were determined: (1) PAs that received an EI score between 0 and 0.01 (14 PAs; 17.5%) were considered very satisfactorily protected; (2) PAs that received EI scored between 0.11 and 0.52 (27 PAs; 33.7%) were described satisfactory; (3) PAs that received EI scored between 0.54 and 1.0 (26 PAs; 32.5%) were considered dissatisfactory protected; and, PAs that received an EI scored between 1.01 and 2.58 (13 PAs; 16.3%) were described as very dissatisfactory (Table 7).

Table 7 Trends in effectiveness parameters, index values and levels for 80 Colombian protected areas.

Protected area	**Effectiveness parameters**[a]				**Effectiveness Index EI**	**Effectivenes Level EL**
	1	**2**	**3**	**4**		
Sierra Nevada De Santa Marta [b]	0,00	0,00	0,00	0,00	0,00	Very satisfactory
Pisba	0,00	0,00	0,00	0,00	0,00	Very satisfactory
Macuira	0,00	0,00	0,00	0,00	0,00	Very satisfactory
Isla De Salamanca	0,00	0,00	0,00	0,00	0,00	Very satisfactory
Tayrona	0,00	0,00	0,00	0,00	0,00	Very satisfactory
Ciénaga Grande De Santa Mart. [b]	0,00	0,00	0,00	0,00	0,00	Very satisfactory
Cuenca Alta del Río Alg, Rios O-F. [b]	0,00	0,00	0,00	0,00	0,00	Very satisfactory

Table 7 (*Continued*)

Serrania de Coraza y Montes de M. [b]	0,00	0,00	0,00	0,00	0,00	Very satisfactory
Cuencas Río Blanco y Negro	0,00	0,00	0,00	0,00	0,00	Very satisfactory
Iroka [b]	0,00	0,00	0,00	0,00	0,00	Very satisfactory
Corocito Yopalito Gualabo [b]	0,00	0,00	0,00	0,00	0,00	Very satisfactory
San Rafael [b]	0,00	0,00	0,00	0,00	0,00	Very satisfactory
Santa Rosa del Guamuez [b]	0,00	0,00	0,00	0,00	0,00	Very satisfactory
Santa Teresita del Tuparro	0,00	0,01	0,00	0,00	0,01	Very satisfactory
Selva De Florencia	0,01	0,05	0,01	0,04	0,11	Satisfactory
Carpintero Palomas	0,01	0,06	0,01	0,07	0,14	Satisfactory
Witora	0,01	0,08	0,01	0,08	0,19	Satisfactory
Calle Santa Rosa	0,02	0,07	0,03	0,07	0,19	Satisfactory
Barranco Ceiba y Laguna Araguato	0,03	0,07	0,03	0,07	0,20	Satisfactory
Cumaral Brazo Amanaven	0,01	0,09	0,01	0,09	0,20	Satisfactory
Corocoro	0,01	0,10	0,01	0,10	0,23	Satisfactory
Paujii	0,03	0,09	0,03	0,09	0,23	Satisfactory
Serranía del Capricho, Mirol. y Cerr.	0,05	0,07	0,06	0,06	0,24	Satisfactory
Serranía De Chiribiquete	0,01	0,11	0,01	0,11	0,25	Satisfactory
Jurado	0,02	0,09	0,02	0,12	0,25	Satisfactory
Afilador	0,02	0,11	0,03	0,12	0,29	Satisfactory
Darién Frontera Colombo Panameña	0,03	0,07	0,10	0,10	0,31	Satisfactory
Rio Atabapo	0,01	0,15	0,01	0,15	0,32	Satisfactory
Río León	0,04	0,11	0,08	0,10	0,32	Satisfactory
Nunuya de Villazul	0,00	0,18	0,00	0,17	0,36	Satisfactory
Nukak	0,04	0,14	0,04	0,15	0,36	Satisfactory
Los Farallones De Cali	0,06	0,06	0,19	0,06	0,37	Satisfactory
Bachaco Buena Vista	0,01	0,18	0,01	0,19	0,39	Satisfactory
Puinawai	0,01	0,19	0,01	0,19	0,40	Satisfactory
Sierra De La Macarena	0,09	0,11	0,10	0,10	0,41	Satisfactory
Rio Siare o Barranco Lindo	0,02	0,19	0,02	0,19	0,42	Satisfactory
Chaparral-Barronegro	0,04	0,19	0,04	0,19	0,47	Satisfactory
La Paya	0,08	0,16	0,08	0,15	0,47	Satisfactory
Serranía De Los Yariguies	0,04	0,22	0,07	0,19	0,51	Satisfactory
Buenavista	0,08	0,19	0,08	0,18	0,52	Satisfactory
Munchique	0,09	0,16	0,13	0,15	0,52	Satisfactory
Yaigoje Apaporis	0,01	0,25	0,01	0,26	0,54	Dissatisfactory
Río Puré	0,02	0,25	0,02	0,26	0,55	Dissatisfactory
Atana Pirariami	0,01	0,25	0,02	0,28	0,56	Dissatisfactory
Inga de Nineras	0,11	0,22	0,12	0,20	0,64	Dissatisfactory
Morocoto Buenavista	0,01	0,31	0,01	0,31	0,64	Dissatisfactory
Monochoa	0,01	0,30	0,01	0,32	0,64	Dissatisfactory
Parte Oriental del Vaupes	0,03	0,29	0,03	0,30	0,64	Dissatisfactory
El Unuma	0,04	0,30	0,04	0,27	0,64	Dissatisfactory
Aduche	0,01	0,31	0,01	0,32	0,65	Dissatisfactory

Table 7 (*Continued*)

Catatumbo - Bari	0,09	0,24	0,09	0,24	0,66	Dissatisfactory
Sokorpa	0,03	0,29	0,04	0,29	0,64	Dissatisfactory
Amacayacu	0,03	0,34	0,03	0,34	0,73	Dissatisfactory
Guaco Bajo y Guaco Alto	0,04	0,32	0,04	0,34	0,74	Dissatisfactory
La Fuga	0,11	0,26	0,12	0,25	0,74	Dissatisfactory
San Jose de Lipa	0,04	0,37	0,06	0,28	0,75	Dissatisfactory
Rio Nare	0,04	0,37	0,05	0,28	0,75	Dissatisfactory
Murcielago-Altamira	0,01	0,35	0,02	0,37	0,75	Dissatisfactory
Mataven Fruta	0,02	0,36	0,02	0,36	0,76	Dissatisfactory
Rio Curiche	0,07	0,31	0,08	0,31	0,77	Dissatisfactory
Los Katios	0,02	0,39	0,02	0,36	0,79	Dissatisfactory
Páramo Urrao	0,03	0,34	0,05	0,38	0,80	Dissatisfactory
Paramillo	0,05	0,38	0,11	0,32	0,86	Dissatisfactory
Laguna Anguilla-La Macarena	0,02	0,40	0,02	0,42	0,86	Dissatisfactory
Laguna Negra y Cacao	0,03	0,46	0,03	0,44	0,96	Dissatisfactory
Cahuinarí	0,02	0,47	0,02	0,48	0,98	Dissatisfactory
Caño Cavasi	0,01	0,54	0,02	0,44	1,00	Dissatisfactory
Santa Rosa de Sucumbios	0,10	0,45	0,12	0,34	1,01	Very dissatisfactory
Cuchilla El Minero	0,34	0,15	0,41	0,13	1,04	Very dissatisfactory
Cordillera De Los Picachos	0,23	0,36	0,39	0,37	1,35	Very dissatisfactory
Macuare	0,15	0,55	0,15	0,55	1,41	Very dissatisfactory
Tinigua	0,59	0,13	0,64	0,13	1,49	Very dissatisfactory
Bajo Rio Guainia y Rio Negro	0,02	0,64	0,02	0,84	1,52	Very dissatisfactory
Santa Maria de Pangala	0,24	0,52	0,25	0,53	1,53	Very dissatisfactory
Ministas Miralindo	0,05	0,75	0,05	0,75	1,59	Very dissatisfactory
Caños Cuna Tsepajibo Warracana	0,02	0,86	0,02	0,80	1,70	Very dissatisfactory
Guangui	0,62	0,23	0,65	0,24	1,75	Very dissatisfactory
Río Escalarete y San Cipriano	0,34	0,64	0,34	0,63	1,95	Very dissatisfactory
Predio Putumayo	0,07	1,00	0,08	1,00	2,15	Very dissatisfactory
Huila	1,00	0,29	1,00	0,29	2,58	Very dissatisfactory

[a] Effectiveness parameters: 1. Percentage of forest cover area loss inside PA´s (2005-2011), 2. Comparison between the percentage of forest cover loss inside and outside PA´s, 3. Rate of forest cover area loss inside PA´s (2005-2011), 4. Comparison between rate of loss of forest cover inside and outside PA´s. [b] Ten PAs were reallocated from satisfactory to very-satisfactory status of effectiveness. EI: the sum of 1, 2, 3, and 4.

When I assigned the status to each PA, I decided that forest cover loss of zero inside the PAs indicates a level of very effective protection. When the PAs were analyzed comparing their forest covers status inside and outside, ten PAs inside had zero score, but their buffer areas demonstrated a small score decrease. Thus, their status was reallocated from satisfactory to very satisfactory (Table 6).

PAs that received protection level of very satisfactory and satisfactory were considered effective at preventing forest cover area loss. When they were analyzed using percentages and rates, the effectiveness in very satisfactory level differed, showing zero values inside and outside. Except for the Santa Teresita Del Tuparro Indigenous Reserve, where it showed a small increase outside (Table 6).

PAs in satisfactory protection level, were less effective, i.e. relatively low percentage of forest cover loss inside, but sharply tended to increase outside PAs. However, of this level 5 PAs (Sierra De La Macarena, La Paya, Serrania De Chiribiquete, Farallones De Cali and Munchique Natural National Parks), had higher percentages and rates of forest loss within and outside. In the cases of the Sierra De La Macarena and La Paya National Parks, forest cover loss was highest, where the absolute extent of loss inside reached 4.794ha and 2.706ha and- outside 9.175ha and 2.638ha, respectively (Table 4). There was, however, an indication of “neighborhood leakage” in the PA Serrania De Los Yariguies Natural National Park. It had the same lower absolute loss of forest before establishment of protection, and after 2007 it was not able to maintain this state and showed increased forest loss outside following establishment of protection (Annex 3). Thus, while these PAs have been satisfactory in limiting forest cover loss, the buffer areas have experienced a trend toward increasing loss.

A different pattern prevails in the ineffective protection level. These PAs were described as dissatisfactory and very-dissatisfactory at preventing forest cover area loss. Overall, both levels showed an opposite trend among the proportions of forest loss within and outside. This discrepancy is due to the higher percentages and rates of forest cover loss inside as compared to outside. In the dissatisfactory level, differences in the rate and percentages of loss within PAs and outside were low and small. Except in three PAs, ‘Inga de Nineras’ and ‘La Fuga’ Indigenous Reserves and- ‘Catatumbo Bari’ Natural National Park, where they showed high percentage and rate of loss inside and only a percentage outside, but tended to be lower than outside. However, the differences did not have an effect on the value of their effectiveness index.

On the very dissatisfactory level, PAs showed higher values in percentage and rate of forest cover loss inside than outside. Although in three PAs the values of loss were higher outside: ‘Tinigua’ Natural National Park, ‘Cuchilla el Minero’ Forest Reserve, and ‘Guangi’ Indigenous Reserve. In one of these, ‘Tinigua’ National Park, the loss of forest within and outside was the highest in this study. The observed patterns of these PAs can suggest a general tendency for protection efforts to decrease, partially attributed to high local pressure (for whatever reason including uncontrolled extraction, settlements or the construction of roads inside and close to PA borders).

Effectiveness level for forest protection differed within IUCN protection categories: 40% of National Protective Forest Reserves (VI), 41% of Natural National Parks (II-IV) and 54% of Indigenous Reserves Community Conservation (IRCC) were dissatisfactory and very dissatisfactory, some of them losing more than 2% of their forest cover. Moreover, satisfactory and very satisfactory protection levels showed the highest proportion of effective areas (60%) in National Protective Forest Reserve areas (Table 8).

Table 8 Forest cover trends in effectiveness levels of 80 Colombian PAs (n. %) across protection categories defined by (IUCN 1994) between 2005 and 2011.

PAs in effectiveness levels	**IUCN management categories (n, %)**						**Total**	
	II – IV		**VI**		**IRCC**		**(n, %)**	
Very satisfactory	6	(27,2)	3	(30)	5	(10,4)	14	(17,5)
Satisfactory	7	(31,8)	3	(30)	17	(35,4)	27	(33,7)
Dissatisfactory	7	(31,8)	2	(20)	17	(35,4)	26	(32,5)
Very dissatisfactory	2	(9,0)	2	(20)	9	(18,7)	13	(16,2)
Total	22	(100)	10	(100)	48	(100)	-	-

6 Discussion

How much forest cover loss (deforestation rate) has there been in the PA network between 2005 and 2011?

This analysis comprised more than half of the current decreed area of the whole PA network in Colombia. The results indicate that strategies for preventing deforestation have been a proactive, re-affirming that Colombian PA network has a substantially low level of deforestation rate as compared with PA studies in other tropical regions (1.47 %; Porter-

Bolland et al., 2011). However, contrasting interactions between conventional policy institutional structure and land cover and land use schemas reflex the problem of regional PA occupation and deforestation (Rodriguez et al., 2012).

Has there been more forest cover loss outside PAs in the 10-km BAs than inside PAs, during the last seven years?

The hypothesis that there has been more forest cover loss outside in the 10 km BAs than inside PAs proves to be true. Similar to the findings of previous research comparing the extent of forest cover loss within and surrounding PAs for developing countries (Naughton-Treves et al., 2005; DeFries et al., 2005; Vuohelaunen et al., 2012) and the Colombian Andes (Rodriguez et al., 2012), this study identified that inside PAs, loss of forest cover occurred in 84% and 95% outside the PAs. However, within these losses occurring, just 4% of PA's lost more than 5% of forest inside and 5% lost by more than 5% outside. These results indicate that a considerable percentage of PAs lost their forest covers inside and outside. There was, however, a subtle loss of forest covers for the majority of them, suggesting that the PAs system has somewhat slowed forest cover loss inside the borders during the seven years.

When looking at forest cover loss through the IUCN management categories, the analysis suggests that there were considerable results. The levels of absolute forest cover loss in Colombian Guyana PAs has been explored previously by Armenteras et al. (2009), who found that deforestation levels in the buffer areas of the categories II-IV and IRCCs were highest than inside the PAs. Similarly, they found that deforestation inside IRCCs was greater than within the PAs category (II-IV). The same pattern of major deforestation outside rather than inside PAs in those categories was identified in this study, although to a much lesser extent. Conversely, deforestation within the PAs in the category (II-IV) was greater than outside (IRCCs). The considerable differences of the results could be explained by the time period of the analysis used on both studies (Armenteras et al. over 17 years while 7 years in this study). This is because the mean rate values between categories mask substantial differences among individual PAs and, also because the relatively large size of the PAs (II-IV) compared to the category (IRCC Figure 7).

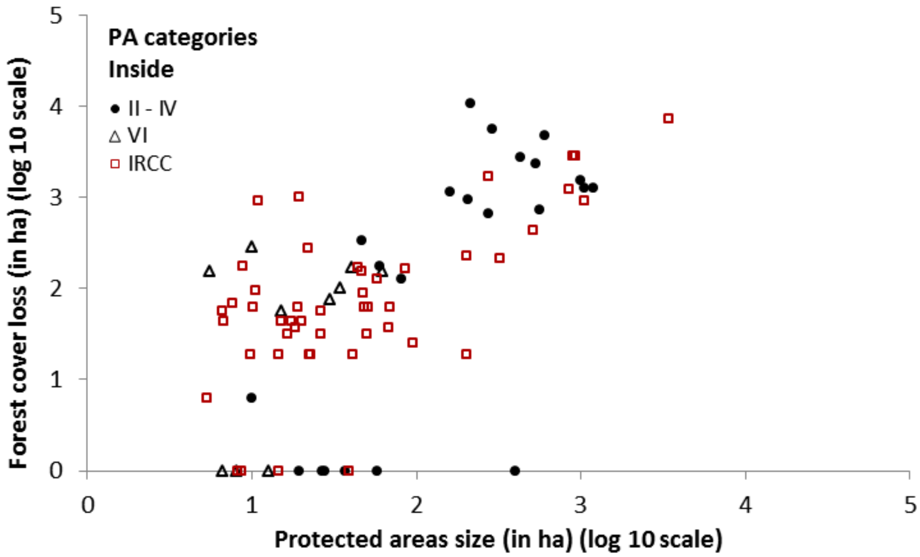


Figure 8 Forest loss trends within individual PAs of three different protection categories between 2005 and 2011 as function of protected area size (log 10 scale).

Have multiple-use PAs (VI and IR) been more effective in preventing deforestation than strict PAs (II to IV)?

Here, PA effectiveness was defined as a measure of prevented forest cover loss. However, where PAs have different management objectives and effectiveness (Southworth et al., 2006) this can lead to the performance of PAs being measured using indicators that do not reflect their objectives (IUCN 2009). In this analysis >50% of the PAs were effective in preventing forest cover loss between 2005 and 2011. But, a sizeable proportion of PAs were ineffective, suggesting that conservation objectives may have to address greater challenges than previously faced.

Of the 80 studied PAs, the 14 with the highest effectiveness score (very-satisfactory) included 6 strict protection (IUCN/II-IV), 3 multi-use management (VI/IUCN) and 5 Indigenous reserves. Three very satisfactory strict protection PAs (Macuira, Isla de Salamanca and Tayrona) revealed no overall forest cover area loss within or outside the 10 km buffer. In such cases, the absence of forest cover loss may be the consequence of very low evergreen forest cover area inside and outside the PAs, explained by the difference in habitat types (Figure 9A-B-C). For example, most of the area of Macuira is Paramo vegetation, while the two others are Marine areas. It is also important to recognize that the management category – particularly biosphere reserve (UNESCO-MAB) – could also have influenced the findings obtained. Such results, especially in two PAs, reflect findings from effectiveness of PAs based in Mexico, which found highest scores of effectiveness in many PAs described as biosphere reserves (Figueroa and Cordero 2008). In addition, these findings suggest the significance of financial support received for an efficient conservation strategy. For the remainder, very satisfactory PAs into the mixed-use management VI and IRCC, the nonexistence of deforestation inside may be the consequence of geographical location or by cooperative arrangement with local communities for sustainable use of PAs, suggested by the combination of absence of loss inside and minimal forest loss outside such PAs.

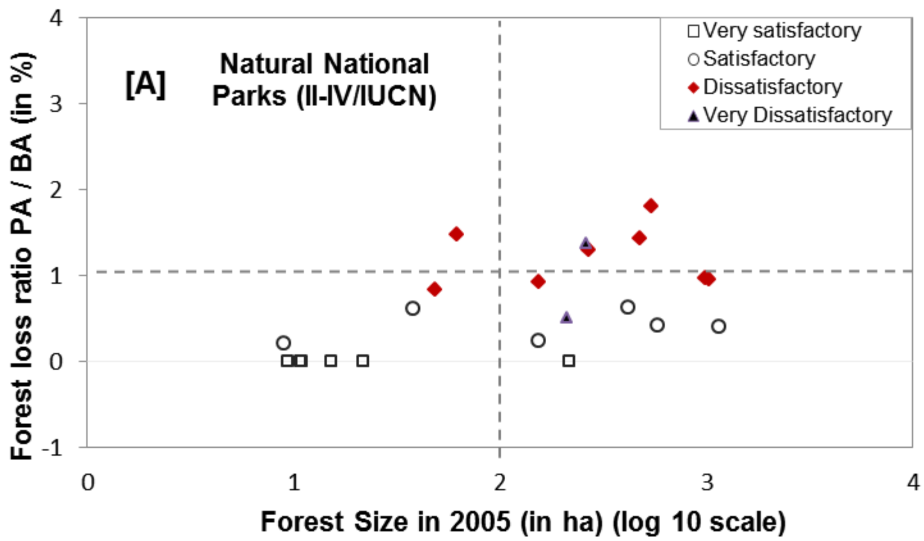
In the other 27 satisfactory level PAs most of them presented a moderately higher proportion of deforestation outside compared to inside PAs, which may be partially explained by the major forest cover loss in the surrounding peripheries. This has been observed in previous Colombian studies on effectiveness performance of some specific strict protection PAs II-IV and IRCC, but not entirely consistent with the patterns found here. This further reveals the complexity involved in evaluating deforestation in both Colombia's PAs and IRCCs. For example, patterns of low deforestation or high effectiveness of PAs in the Central, Eastern Mountain and Amazon Foothill range by Rodriguez et al. (2012) agree with the patterns found here, where II-IV PAs were satisfactory effective for preventing forest loss. Meanwhile, ineffective or high deforestation rates in PAs II-IV on the Western Mountain range (e.g. Farallones and Munchique National Parks) differs from the good performance of PAs in this study. Perhaps, some of these differences could be attributed to the fact that the time frame applied in Rodriguez et al. (2012) analysis was long-term – 1985 to 2005 –, but neither was a synthetic index for effectiveness performance used. Because of this, it is not surprising that, in general, the analysis of performance indices shows a nonconformity image (Naughton-Treves et al., 2005), and emphasizes that evaluations of PAs effectiveness ought to be standardized over a set time period.

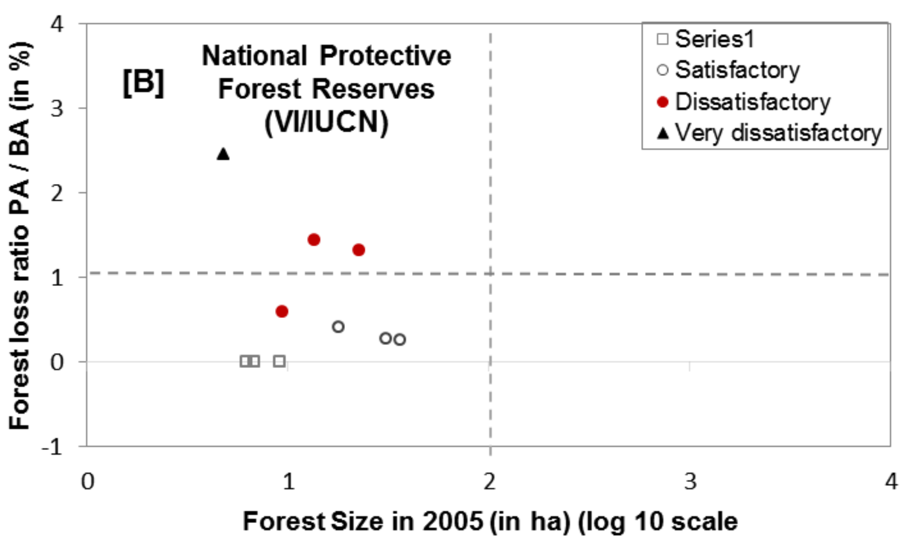
The other analysis conducted by Armenteras et al. (2009) in the Colombian-Guyana shield, also reported trends of a slow rate of deforestation or higher effectiveness of PAs (II-

IV/IUCN) than IRCCs, most likely explained by differential colonization of non-indigenous populations across localities. This study provides no substantial support for previous assertions of the colonization influences, but the overall trends could appear to re-affirm these results. For instances, I noted that La Macarena PA in this study maintained the same trend as one of the most deforested inside and outside, but more moderately here. Besides this, the indication for leakage around Serrania De Los Yariguies Natural National Park needs to be analyzed in more detail with improved spatial resolution satellite images going back to the 1990s, linked with specified fieldwork for the PA established after 2005. Nevertheless, higher pressures outside than inside PAs boundaries may signal conservation failures in the long run, as has been shown in other regional studies (Naugthon-Treves., 2005; DeFries et al., 2005).

Dissatisfactory and very dissatisfactory PAs (II-IV/IUCN) and IRCCs covered 49 PAs where forest cover losses were higher than in their buffer area (Table 4 and 6). Although both descriptions indicate ineffectiveness at different levels, most of the IRCCs showed more areas with dissatisfactory effectiveness (Table 7). This result is unsurprising because it is likely the people living within and around the IRCC legally use these areas for agricultural conversion and timber extraction (Armenteras et al., 2009), whereas the activities performed inside strict PAs (II-IV/IUCN) are considerably contributing to ineffectiveness were forest extraction is not allowed. This exemplifies, on one hand, how the conservation of forest cover in IRCCs can occur even with the presence of deforestation pressure, and on the other, of attention required of strict PAs, because they appear to be incapable of preventing forest loss inside.

I originally hypothesized that multiple-use PAs are more effective than strict PA’s at preventing forest cover loss. Importantly, I found that multiple-use PA’s have been somewhat ineffective in preventing forest loss within their borders than strict PA’s, and this result are agree with previous research results on PA’s effectiveness (Nepstad et al., 2006) but contrast with the results found in other tropical forest (Nelson and Chomitz 2011; Porter-Bolland et al., 2011). These findings may well be attributable to the location of the PA’s rather than its protected status per se. Thus, they merit further exploration of counterfactual data (e.g., altitude, remote locations and slope) which likely influence the use of forest resources. From a policy point of view, these situations highlight the need to review the design and management of ineffective IRCCs and PAs to ensure effective conservation actions.





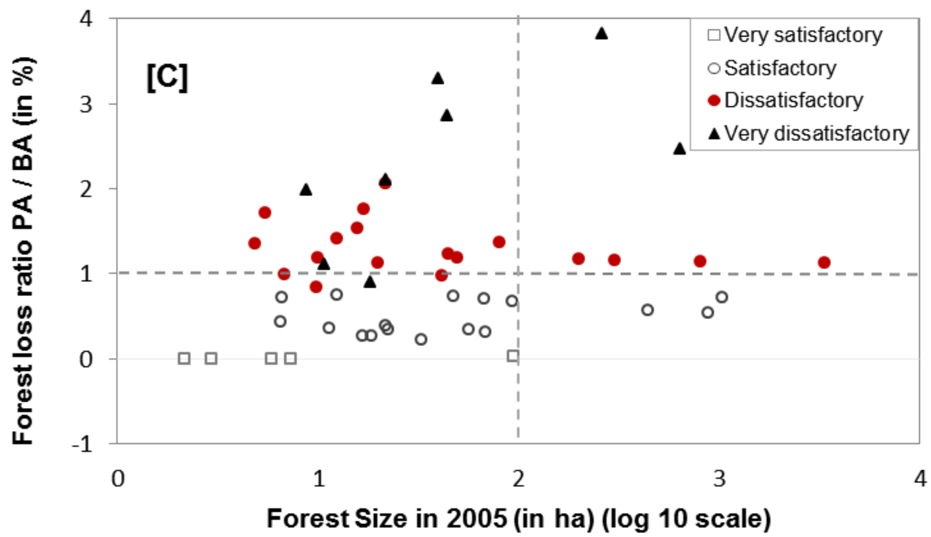


Figure 9 Forest loss ratio inside/outside trends within effectiveness protection levels of three IUCN categories; [A] strict protection (II-IV), [B] multiple-use (VI) and [C] Indigenous reserves community management (IRCC) between 2005 and 2011 as a function of initial forest cover size in 2005 (log 10-scale).

6.1 Research limitations

Methodological limitations: I recognize this effectiveness study has some shortcomings. This study resulted in a partial evaluation in the sense that it does not include the analysis of why the performance of individual PA's differs. The identification of environmental and socio-economic factors associated with forest cover loss inside and outside PA's, which have contributed to its success or failure would require the extension of this study and the use of methods such as matching techniques controlling for bias developed by Joppa and Pfaff (2010). In Colombia forest cover loss (deforestation) inside and outside PAs is highly influenced by the expansion of roads and illicit crops (Armenteras *et al.*, 2009). Therefore, future analysis should be conducted in order to determine the drivers of deforestation using Terra-i near real-time detection land cover change.

Data availability limitations: In data availability, the low number of PAs polygons distributed among protection categories, mostly in the category VI, was a limitation to this study. These limitations involved, on one hand, the spatial overlaps between Terra-i grid gaps (obscured by clouds) and PA layers, although this seems to provide a good example of forest maintenance. On the other hand, the accurate overlap between Terra-i deforestation pixels and GlobCover grid. The low number of certain PAs could be seen overall in the Andes region and IRCC in the pacific region. Thus, future advances in radar detection of forest cover will perhaps make it possible to include in studies those areas and polygons with constant cloud cover using high resolution images. Also, the overlapping between low cover of the GlobCover grid and the Terra-i grid could cause zero values of forest loss inside some PAs, overall in the very satisfactory level.

Spatial spillovers or leakages were not taken into account for this study. However, given the important impact of leakage as discussed on the background, this study noted an indication for spillover surrounding the Natural National Park ´Serrania de los Yariguies´. Hence, it is extremely important future monitoring and detailed analysis of these PA’s using higher spatial resolution satellite combining current fieldwork information and land use database before they were created.

7 Conclusions and recommendations

The results of this research, as well as the above studies, demonstrated the positive outlook that the role of PA network management strategies can play towards preventing forest cover loss, having a substantial effect on forest protection in Colombia. However, human pressure is also known to lead to forest cover loss inside PAs, especially among the little effective PAs between IUCN categories.

Most noteworthy evidence of this outlook is that in Colombia >50% (41 PA’s) were effective preventing forest cover loss. Moreover, to some extent the level of protection itself explained its differences in effectiveness, where strict PA’s (categories II-IV) were found more effective than multiple-use PA’s (categories VI-IRCC). Nevertheless, many effective PA’s are located in areas with low and high forest conversion risk (Forero-Medina and Joppa 2010). Thus, to optimize the positive impact of conservation efforts, the Colombian PA network should target PA’s with low level of protection and substantial rates of forest cover loss inside-outside PA’s.

With regards to very ineffective (~16%) 13 PA's, particular attention should be paid to them, regarded as highest rates of forest loss inside than outside their boundaries. These trends of non-effective connection between the PA's and the surroundings have severe implications to conserve species richness and maintain ecological process, which depends on this interaction. For instance, Cordillera de Los Picachos and Tinigua parks under strict protection have had very high loss of forest cover inside than outside from 2005 to 2011. Thus, it needs to be conscientiously analyzed.

I suggest promoting alternatives for increased management of PA's as regional landscape arrangements. Creating connected PA's to corridors and buffer zones (DeFries et al., 2005) could be useful for maintaining critical elements of the landscape surrounding PAs. At the same time, it is crucial to implement pricing and compensation mechanisms to value the ecosystem services provided by land surrounding PAs to locate conservation activities within the appropriate economic, political, social and cultural contexts.

Finally, the Colombian government needs to continue its efforts with regard to more contribution on management conservation of the PA network to the 2020 target of the Convention on Biological Diversity, whereby 17% of the world's terrestrial surface must be conserved through area-based measures. Consequently, forest cover trends and indicators of scientific studies (like this one) are a base-line to prioritize and make effective decisions to improve the management of PA's as well as the non-protected forest biodiversity.

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Annexes

Annex 1. List of Colombian PA network (260). Excluding marine PA.

IUCN Management Category	Natural protected área (NPA)	Official designation according to management category	Date of decree	Size area (Ha)
II	El Tuparro	Natural National Park	1980	561.758
II	Sierra De La Macarena	Natural National Park	1989	607.619
II	Paramillo	Natural National Park	1977	532.963
II	Sierra Nevada De Santa Marta	Natural National Park	1977	402.547
II	El Cocuy	Natural National Park	1977	307.662
II	Cordillera De Los Picachos	Natural National Park	1988	288.266
II	Amacayacu	Natural National Park	1988	274.859
II	Nevado Del Huila	Natural National Park	1977	166.088
II	Sumapaz	Natural National Park	1977	223.179
II	Los Farallones De Cali	Natural National Park	1978	207.027
II	Las Hermosas	Natural National Park	1977	125.005
II	Sanquianga	Natural National Park	1977	86.990
II	Purace	Natural National Park	1977	90.076
II	Los Katios	Natural National Park	1982	81.136
II	Chingaza	Natural National Park	1998	78.290
II	Tame	Natural National Park	1977	51.537
II	Pisba	Natural National Park	1977	36.778
II	Munchique	Natural National Park	1977	47.071
II	Los Nevados	Natural National Park	1974	62.144
II	Las Orquideas	Natural National Park	1974	29.118
II	Macuira	Natural National Park	1977	26.776
II	Isla De Salamanca	Natural National Park	1985	57.609
II	Tayrona	Natural National Park	1975	19.341
II	Cueva De Los Guacharos	Natural National Park	1995	7.435
II	La Paya	Natural National Park	1984	429.447
II	Tatame	Natural National Park	1987	43.020
II	Ensenada de Utria	Natural National Park	1987	10.771

II	Serrania De Chiribiquete	Natural National Park	1989	1.202.761
II	Catatumbo - Bari	Natural National Park	1989	161.327
II	Tinigua	Natural National Park	1989	215.287
II	Cahuinari	Natural National Park	1987	560.163
II	Alto Fragua - Indiwasi	Natural National Park	2002	76.049
II	Rio Pure	Natural National Park	2002	1.002.516
II	Utria	Natural National Park	1987	63.787
II	Yaigoje Apaporis	Natural National Park	2009	1.060.540
II	Selva De Florencia	Natural National Park	2005	10.016
II	Serrania De Los Yariguies	Natural National Park	2008	59.699
II	Complejo Volcanico Doña Juana- Cascabel	Natural National Park	2007	65.650
II	Serrania De Los Churumbelos	Natural National Park	2007	97.321
IV	Cienaga Grande De Santa Marta	Fauna And Flora Sanctuary	1977	27.939
IV	Los Colorados	Fauna And Flora Sanctuary	1977	1.044
IV	Isla De La Corota	Fauna And Flora Sanctuary	1977	16
IV	Galeras	Fauna And Flora Sanctuary	1985	8.268
IV	Guanenta-alto Rio Fonce	Fauna And Flora Sanctuary	1993	10.256
IV	Iguaque	Fauna And Flora Sanctuary	1977	6.922
IV	El Corchal "el Mono Hernandez"	Fauna And Flora Sanctuary	2002	4.215
IV	Otun Quimbaya	Fauna And Flora Sanctuary	1996	458
IV	Plantas Medicinales Orito Ingi Ande	Flora Sanctuary	2008	10.233
VI	Cuenca de los caños La Esperanza, Agua Bonita, Negro, La Maria y La Lindosa	National Protective Forests Reserves	1977	7.127
VI	Cuenca Alta del Rio Mocoa	National Protective Forests Reserves	1984	32.767
VI	Zona Musinga - Carauta	National Protective Forests Reserves	1975	30.171
VI	Rio Nare	National Protective Forests Reserves	1971	15.045
VI	Paramo Urrao	National Protective Forests Reserves	1975	29.900
VI	Cuenca Alta del Rio Cravo Sur	National Protective Forests Reserves	1986	4.759
VI	Cuchilla de Sucuncuca	National Protective Forests Reserves	1989	1.778
VI	Sierra el Peligro	National Protective Forests Reserves	1988	1.590
VI	El Malmo	National Protective Forests Reserves	1976	51
VI	Cuencas Hidrograficas Rio Blanco y Quebrada Olivares	National Protective Forests Reserves	1990	4.992
VI	Paramo de Chingaza	National Protective Forests Reserves	1971	21.511
VI	Predio Rio Rucio	National Protective Forests Reserves	1987	601
VI	Cuenca Hidrografica del Rio San Francisco	National Protective Forests Reserves	1985	2.872

VI	La Bolsa	National Protective Forests Reserves	1990	2.710
VI	Cuencas Altas de los Rios Chorreras y Concepcion	National Protective Forests Reserves	1991	4.428
VI	El Hortigal	National Protective Forests Reserves	1988	216
VI	Paramo el Atravesado	National Protective Forests Reserves	1972	3.186
VI	La Mistela	National Protective Forests Reserves	1992	94
VI	Cerro Quinini	National Protective Forests Reserves	1987	1.932
VI	Cuchillas Peñas Blancas	National Protective Forests Reserves	1983	1.627
VI	Cuenca Alta Rio Las Ceibas	National Protective Forests Reserves	1983	13.485
VI	Laguna la Cocha - Cerro Patascoy	National Protective Forests Reserves	1973	50.057
VI	Rio Tejo	National Protective Forests Reserves	1985	2.424
VI	Cuenca Alta del Rio Algodonal, Rios Orocue y Frio	National Protective Forests Reserves	1985	8.008
VI	Cuenca Alta de las Quebradas La Nona, El Zurrumbo y El Mani	National Protective Forests Reserves	1980	628
VI	Cuenca Alta Quebrada Teneria	National Protective Forests Reserves	1984	791
VI	Parque el Higueron	National Protective Forests Reserves	1991	21
VI	Cuchilla El Minero	National Protective Forests Reserves	1993	9.987
VI	Cuenca Hidrografica de la Quebrada El Peñon y San Juan	National Protective Forests Reserves	1960	637
VI	Cuenca Alta de Caño Alonso	National Protective Forests Reserves	1987	467
VI	Serrania de Coraza y Montes de Maria	National Protective Forests Reserves	1983	6.652
VI	Jirocasaca	National Protective Forests Reserves	1981	292
VI	Cuenca Alta del Rio Satoca	National Protective Forests Reserves	1992	4.157
VI	Cuenca del Rio Tame	National Protective Forests Reserves	1986	1.649
VI	Quebrada la Tablona	National Protective Forests Reserves	1981	2.679
VI	Cuenca Alta del Caño Vanguardia (Aguas Claras) y Qubrada Vanguardiuno	National Protective Forests Reserves	1988	534
VI	Darien Frontera Colombo Panameña	National Protective Forests Reserves	1977	62.163
VI	Rio Escalarete y San Cipriano	National Protective Forests Reserves	1983	5.568
VI	Cerro Vanguardia	National Protective Forests Reserves	1984	197
VI	Cuenca Alta del Rio Cali	National Protective Forests Reserves	1938	3.234
VI	Cuenca Alta del Rio Nembi	National Protective Forests Reserves	1984	2.484
VI	Cuenca del Rio Guabas Municipio de Guacari y Ginebra	National Protective Forests Reserves	1938	16.148
VI	Cuenca Quebrada Mutata	National Protective Forests Reserves	1985	991
VI	Cuencas Rio Blanco y Negro	National Protective Forests Reserves	1982	12.684
VI	El Cerro de Dapa - Carisucio	National Protective Forests Reserves	1938	1.413
VI	Paramo Grande	National Protective Forests Reserves	1975	7.117
VI	Quebrada Guadualito y el Negrito Adicion a RF YOTOCO	National Protective Forests Reserves	1975	1.224

VI	Quebrada Honda y Caños Parrado y Duque	National Protective Forests Reserves	1945	1.452
VI	Rio Leon	National Protective Forests Reserves	1975	34.243
VI	Rio MelÚndez, Cañaveralejo, Lili y Pance	National Protective Forests Reserves	1941	2.450
VI	Serrania del Capricho, Mirolindo y Cerritos	National Protective Forests Reserves	1984	40.568
Declared	Puinawai	Natural National Reserve	-	1.055.315
Declared	Nukak	Natural National Reserve	-	890.358
Not Reported	Monochoa	Indigenous Reserve	-	322.328
Not Reported	Aduche	Indigenous Reserve	-	202.993
Not Reported	Miriti-Parana	Indigenous Reserve	-	1.387.968
Not Reported	Caiman Nuevo	Indigenous Reserve	-	7.317
Not Reported	San Jose de Lipa	Indigenous Reserve	-	19.093
Not Reported	Cobaria	Indigenous Reserve	-	58.391
Not Reported	Tauretes Agua Blanca	Indigenous Reserve	-	7.252
Not Reported	Agua Negra	Indigenous Reserve	-	1.176
Not Reported	Guangui	Indigenous Reserve	-	19.343
Not Reported	Infi	Indigenous Reserve	-	3.714
Not Reported	Huila	Indigenous Reserve	-	10.902
Not Reported	San Antonio del Fragua	Indigenous Reserve	-	2.360
Not Reported	Witora	Indigenous Reserve	-	69.304
Not Reported	Consejo	Indigenous Reserve	-	4.736
Not Reported	El Duya, San Juanito y Paravare	Indigenous Reserve	-	11.691
Not Reported	Caño Mochuelo - Hato Corozal	Indigenous Reserve	-	86.719
Not Reported	Arhuaco de la Sierra Nevada	Indigenous Reserve	-	137.086
Not Reported	Iroka	Indigenous Reserve	-	8.634
Not Reported	Sokorpa	Indigenous Reserve	-	26.497
Not Reported	Tanela	Indigenous Reserve	-	884
Not Reported	Jurado	Indigenous Reserve	-	14.599
Not Reported	Tahami del Andagueda	Indigenous Reserve	-	43.313
Not Reported	Rios Uva y Pogue	Indigenous Reserve	-	38.523
Not Reported	Rios Lanas o Capa	Indigenous Reserve	-	6.059
Not Reported	Rios Valle y Boroboro	Indigenous Reserve	-	20.589
Not Reported	Jagual-Rio Chintado	Indigenous Reserve	-	35.736
Not Reported	Docordo-Balsalito	Indigenous Reserve	-	3.137
Not Reported	Rio Nuqui	Indigenous Reserve	-	6.832

Not Reported	Rios Catru y Dubasa	Indigenous Reserve	-	42.008
Not Reported	Rios Jurubida, Chori y Alto Baudo	Indigenous Reserve	-	102.633
Not Reported	El Doce o Quebrada Borbollon	Indigenous Reserve	-	1.162
Not Reported	Rio Pangui	Indigenous Reserve	-	7.518
Not Reported	El Veinte, Playalta y El Noventa	Indigenous Reserve	-	3.061
Not Reported	Caño Negro	Indigenous Reserve	-	1.850
Not Reported	Barranco Ceiba y Laguna Araguato	Indigenous Reserve	-	20.084
Not Reported	Caño Jabon	Indigenous Reserve	-	9.068
Not Reported	Caño Ovejas o Betania-Corocito	Indigenous Reserve	-	1.637
Not Reported	Macuare	Indigenous Reserve	-	21.871
Not Reported	Cuambi-Yaslambi	Indigenous Reserve	-	4.903
Not Reported	Gabarra Catalaura	Indigenous Reserve	-	12.675
Not Reported	La Samaritana	Indigenous Reserve	-	4.032
Not Reported	Buenavista	Indigenous Reserve	-	6.734
Not Reported	Sibundoy Parte Alta	Indigenous Reserve	-	4.214
Not Reported	Chami Rio San Juan Margen Derecha	Indigenous Reserve	-	14.795
Not Reported	Chami Rio Garrapatas	Indigenous Reserve	-	19.644
Not Reported	Chachajo	Indigenous Reserve	-	816
Not Reported	Parte Oriental del Vaupes	Indigenous Reserve	-	3.411.199
Not Reported	Rio Siare o Barranco Lindo	Indigenous Reserve	-	47.768
Not Reported	Saracure y Rio Cada	Indigenous Reserve	-	191.081
Not Reported	Caño Cavasi	Indigenous Reserve	-	26.157
Not Reported	Caños Cuna Tsepajibo Warracana	Indigenous Reserve	-	48.041
Not Reported	Santa Teresita del Tuparro	Indigenous Reserve	-	204.008
Not Reported	Rios Tomo Weberi	Indigenous Reserve	-	62.380
Not Reported	San Luis del Tomo	Indigenous Reserve	-	25.632
Not Reported	Santa Rosalia	Indigenous Reserve	-	1.732
Not Reported	La Pascua	Indigenous Reserve	-	18.578
Not Reported	La Llanura	Indigenous Reserve	-	97.888
Not Reported	Bete, Auro Bete y Auro del Buey	Indigenous Reserve	-	10.674
Not Reported	Tiosilidio	Indigenous Reserve	-	2.596
Not Reported	Calle Santa Rosa	Indigenous Reserve	-	18.272
Not Reported	Rio Domingodo	Indigenous Reserve	-	20.431
Not Reported	Mocagua, Macedonia, El Vergel y Zaragoza	Indigenous Reserve	-	4.515

Not Reported	Alta y Media Guajira	Indigenous Reserve	-	932.760
Not Reported	El Suspiro o Rincon del Socorro	Indigenous Reserve	-	385
Not Reported	El Saladillo	Indigenous Reserve	-	5.008
Not Reported	Union Choco-San Cristobal	Indigenous Reserve	-	23.586
Not Reported	Atana Pirariami	Indigenous Reserve	-	50.840
Not Reported	Mataven Fruta	Indigenous Reserve	-	86.105
Not Reported	Rio Icho y Quebrada Baratudo	Indigenous Reserve	-	3.908
Not Reported	Rio Negua	Indigenous Reserve	-	3.969
Not Reported	Comeyafu	Indigenous Reserve	-	18.872
Not Reported	Puerto Cordoba	Indigenous Reserve	-	39.270
Not Reported	Rio Taparai	Indigenous Reserve	-	15.759
Not Reported	Rio Pichima	Indigenous Reserve	-	6.033
Not Reported	Caño Guaripa	Indigenous Reserve	-	7.735
Not Reported	Caño La Hormiga	Indigenous Reserve	-	7.221
Not Reported	Caño Bachaco	Indigenous Reserve	-	5.293
Not Reported	Alto Rio Tagachi	Indigenous Reserve	-	21.877
Not Reported	Alto Rio Buey	Indigenous Reserve	-	13.934
Not Reported	Coayare-El Coco	Indigenous Reserve	-	11.112
Not Reported	El Venado	Indigenous Reserve	-	33.395
Not Reported	Caranacoa-Yuri-Laguna Morocoto	Indigenous Reserve	-	39.061
Not Reported	Almidon-La Ceiba	Indigenous Reserve	-	42.640
Not Reported	Bachaco Buena Vista	Indigenous Reserve	-	68.476
Not Reported	Laguna Negra y Cacao	Indigenous Reserve	-	17.291
Not Reported	Chami Margen Izquierda Rio San Juan	Indigenous Reserve	-	7.128
Not Reported	Puado, Matare, La Lerma Y Terdo	Indigenous Reserve	-	3.333
Not Reported	Merey La Veraita	Indigenous Reserve	-	2.299
Not Reported	Guacamayas-Mamiyare	Indigenous Reserve	-	34.243
Not Reported	Alto Rio Bojaya	Indigenous Reserve	-	39.984
Not Reported	Alto Rio Cuta	Indigenous Reserve	-	20.182
Not Reported	Napipi	Indigenous Reserve	-	21.033
Not Reported	Opogado	Indigenous Reserve	-	29.305
Not Reported	Laguna Anguilla-La Macarena	Indigenous Reserve	-	16.620
Not Reported	Caño Bocon Brazo Amanaven	Indigenous Reserve	-	9.135
Not Reported	Yuri Brazo Amanaven	Indigenous Reserve	-	16.568

Not Reported	Giro Brazo Amanaven	Indigenous Reserve	-	18.687
Not Reported	Morocoto Buenavista	Indigenous Reserve	-	50.266
Not Reported	Cumaral Brazo Amanaven	Indigenous Reserve	-	22.877
Not Reported	Arrecifal	Indigenous Reserve	-	3.623
Not Reported	Barranquito Laguna Colorado	Indigenous Reserve	-	16.445
Not Reported	Carrizal	Indigenous Reserve	-	10.119
Not Reported	Chaparral-Barronegro	Indigenous Reserve	-	14.987
Not Reported	Ministas Miralindo	Indigenous Reserve	-	44.053
Not Reported	Pueblo Nuevo Laguna Colorada	Indigenous Reserve	-	43.687
Not Reported	Guaco Bajo y Guaco Alto	Indigenous Reserve	-	47.007
Not Reported	Carpintero Palomas	Indigenous Reserve	-	41.008
Not Reported	Rio Murindo	Indigenous Reserve	-	19.025
Not Reported	Santa Maria de Pangala	Indigenous Reserve	-	8.850
Not Reported	Campoalegre y Ripialito	Indigenous Reserve	-	7.712
Not Reported	Rio Curiche	Indigenous Reserve	-	10.259
Not Reported	Rio Orpua	Indigenous Reserve	-	17.766
Not Reported	Caimanero de Jampapa	Indigenous Reserve	-	1.508
Not Reported	Murcielago-Altamira	Indigenous Reserve	-	5.373
Not Reported	Sejalito-San Benito	Indigenous Reserve	-	3.017
Not Reported	Guayabal de Partado	Indigenous Reserve	-	4.804
Not Reported	Polines	Indigenous Reserve	-	2.493
Not Reported	El Tablero	Indigenous Reserve	-	4.193
Not Reported	El Hacha	Indigenous Reserve	-	12.113
Not Reported	Predio Putumayo	Indigenous Reserve	-	273.718
Not Reported	Nunuya de Villazul	Indigenous Reserve	-	94.810
Not Reported	Yaigoje-Rio Apaporis	Indigenous Reserve	-	690.934
Not Reported	Chuscal y Tuguriducito	Indigenous Reserve	-	5.154
Not Reported	Puerto Alegre y la Divisa	Indigenous Reserve	-	21.828
Not Reported	Rio Bebarama	Indigenous Reserve	-	9.808
Not Reported	Tarena	Indigenous Reserve	-	5.341
Not Reported	Inga de Nineras	Indigenous Reserve	-	10.594
Not Reported	Chimurro y Nedo	Indigenous Reserve	-	14.237
Not Reported	Coropoya	Indigenous Reserve	-	1.828
Not Reported	Corocoro	Indigenous Reserve	-	22.249

Not Reported	Chololobo-Matatu	Indigenous Reserve	-	5.895
Not Reported	Agua Clara y Bella Luz del Rio Ampora	Indigenous Reserve	-	9.686
Not Reported	Kananeruba	Indigenous Reserve	-	4.778
Not Reported	Calenturas	Indigenous Reserve	-	2.511
Not Reported	Guaguando	Indigenous Reserve	-	12.331
Not Reported	Rio Naya	Indigenous Reserve	-	592
Not Reported	Macucuana	Indigenous Reserve	-	6.416
Not Reported	Rio Verde	Indigenous Reserve	-	7.631
Not Reported	Carraipia	Indigenous Reserve	-	5.439
Not Reported	Venezuela	Indigenous Reserve	-	695
Not Reported	Barrancon	Indigenous Reserve	-	1.041
Not Reported	La Fuga	Indigenous Reserve	-	7.622
Not Reported	Corocito Yopalito Gualabo	Indigenous Reserve	-	8.239
Not Reported	San Rafael, Abariba, Ibibi	Indigenous Reserve	-	38.745
Not Reported	La Sal	Indigenous Reserve	-	3.155
Not Reported	Yarina	Indigenous Reserve	-	6.883
Not Reported	Luzon	Indigenous Reserve	-	2.346
Not Reported	Santa Rosa de Sucumbios	Indigenous Reserve	-	6.668
Not Reported	Santa Rosa del Guamuez	Indigenous Reserve	-	14.576
Not Reported	El Unuma	Indigenous Reserve	-	928.968
Not Reported	Rios Muco y Guarrojo	Indigenous Reserve	-	87.814
Not Reported	Afilador	Indigenous Reserve	-	9.779
Not Reported	Guayacan-Santa Rosa	Indigenous Reserve	-	340
Not Reported	Bajo Rio Guainia y Rio Negro	Indigenous Reserve	-	842.423
Not Reported	Alto Rio Guainia	Indigenous Reserve	-	125.376
Not Reported	Rio Atabapo	Indigenous Reserve	-	516.338
Not Reported	Paujii	Indigenous Reserve	-	58.087
Not Reported	Cuiari-Isana	Indigenous Reserve	-	432.055
Not Reported	Purace	Indigenous Reserve	-	6.172

Annex 2. Process of refining and accuracy PAs polygons.

IUCN categories	NPAs official management categories	Total		No Marines		>5000 ha		Analyzed	
		No	**Area (ha)**	**No**	**Area (ha)**	**No**	**Area (ha)**	**No**	**Area (ha)**
Ia	Fauna And Flora Sanctuary	1	6.707	1	6.707	1	6.707	-	-
II	Natural National Park	42	9.620.676	39	9.429.627	39	9.429.627	21	7.347.533
III	Natural Area	1	635	1	635	-	-	-	-
IV	Fauna And Flora Sanctuary	11	1.050.497	9	69.351	5	63.618	1	27.939
VI	National Protective Forests Reserves	52	465.406	51	461.765	18	390.520	10	231.948
IRCC Not Reported	Indigenous Reserves Community for Conservaiton	170	21.545.561	167	15.342.202	124	15.242.498	48	10.204.496
Total		289		280		199		**80**	**17.811.916**

Annex 3. Protected area indicating leakage effect. Ineffective protection (dissatisfactory level PA).