BUILDING A DECISION – SUPPORT METHODOLOGY

TO DEFINE ECOSYSTEM SERVICES BUNDLES AND TO ANALYZE TRADE-OFFS IN DIVERSE LANDSCAPES. APPLICATION TO ECUADORIAN ECOSYSTEMS.

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Building a decision – support methodology to define ecosystem services bundles and to analyze trade-offs in diverse landscapes. Application to Ecuadorian ecosystems.

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So many times, I have photographed stories that show the degradation of the planet. I had one idea to go and photograph the factories that were polluting, and to see all the deposits of garbage. But, in the end, I thought the only way to give us an incentive, to bring hope, is to show the pictures of the pristine planet – to see the innocence.

To think that these three-month-old trees will reach their apex in 400 years. Perhaps from there, we could try to grasp the concept of eternity. Maybe eternity is measurable.

Sebastião Salgado[1]
(1944 -)

1 Sebastião Ribeiro Salgado Júnior is an awarded Brazilian social documentary photographer and photojournalist. He has worked since the 1990's on the restoration of a small part of the Atlantic Forest in Brazil. In 1998, He succeeded in turning this land into a nature reserve and created the *Instituto Terra*. The *Instituto* is dedicated to a mission of reforestation, conservation and environmental education.

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With the publication of this thesis, an important stage of my life ends and another one full of illusions and projects begins where I will be able to contribute with my knowledge to the fight against climate change at the local level and in my own environment.

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Abstract

A key challenge of ecosystem management is determining how to manage multiple ecosystem services across landscapes. Enhancing provisioning ecosystem services (i.e., food, timber, etc.) might lead to tradeoffs between regulating and cultural ecosystem services (i.e., nutrient cycling, flood protection, tourism, etc.). Ecosystem service-bundle analysis can help to identify areas on a landscape where ecosystem (mis)management has produced (un)desirable sets of ecosystem services. Ecuador is now suffering the effects of intensive land-use (LU) change, a fact that is reconfiguring landscapes at all spatial levels. This process generates (a) land fragmentation resulted from the gradual clearing of native forests, (b) the introduction of patches of plantations in open grasslands and sensible ecosystems, and finally (c) an impact on ecosystem services (ES). It is thus primordial to develop a decision support methodology able to assess ES at different scales and to help decision-makers to articulate objectives more clearly and evaluate the consequences of alternative management actions. In this research we aim at setting the stage for developing this kind of decision support methodology, taking into account: the many constraints regarding data availability in terms of types (i.e., numerical, spatial, imagery, etc.) and acquisition (i.e., remote sensing, open official information, on-site, etc.), the temporal evolution and dynamic change of ES and ES-bundles, and the influence of fragmentation (stage of criticality) in this change. We consider two case studies at different spatial scales: Guayas ecosystem and Abras de Mantequilla (AdM) wetland. These have been chosen for their ecosystemic and environmental importance for the whole country, in terms both of regulating and provisioning ES, and for being important ecological sites now much under human pressure and land-use change dynamics. The main contribution of this thesis is to have been highly capable to design and obtain a protocol of action in the decision-making processes built from real and accurate data acquired through modern technologies -not necessarily implying that the data is of high quality-, socio-economic knowledge of the environment and recent complexity theories implementation.

Resumen

Un desafío clave en la gestión de los ecosistemas es determinar cómo administrar múltiples servicios ecosistémicos en paisajes de gran diversidad. Mejorar la sostenibilidad de los servicios de los ecosistemas de tipo aprovisionamiento podría llevar a compensaciones entre los servicios ecosistémicos reguladores y culturales (es decir, el ciclo de los nutrientes, la protección contra inundaciones, el turismo, etc.). Por otro lado, el análisis del conjunto de servicios ecosistémicos, puede contribuir a identificar áreas de criticalidad en un determinado paisaje sobre todo en contextos donde el ecosistema ha sufrido un alto stress en cuanto a la disponibilidad y calidad de sus servicios. Dentro de este contexto actual, Ecuador tiene el gran reto de gestionar y actuar antes los efectos del cambio intensivo en el uso de la tierra, un hecho que está reconfigurando sus paisajes en todos los niveles espaciales. Este proceso de cambio intensivo en el paisaje del país Sudamericano, está generando (a) la fragmentación de la tierra como resultado de la tala gradual de los bosques nativos, (b) la introducción de plantaciones en campos abiertos y ecosistemas sensibles, y finalmente (c) un impacto en los servicios del ecosistema. Por lo tanto, es primordial desarrollar una metodología que permita evaluar los servicios ecosistémicos a diferentes escalas y ayudar a los responsables de la toma de decisiones a articular objetivos de manera más clara y eficiente en a la evaluación de los servicios y su afección en el sistema ecológico, socio-económico y agrícola. En esta investigación, nuestro objetivo es establecer el escenario para desarrollar este tipo de metodología de apoyo a la toma de decisiones, teniendo en cuenta: las muchas restricciones con respecto a la disponibilidad de datos (ej. numéricos, espaciales, imágenes, etc.) su adquisición, la evolución temporal y el cambio dinámico de los servicios ecosistémicos, los *clusters* que puedan conformarse en el territorio, y la influencia de la fragmentación (etapa de criticidad). Consideramos dos casos de estudio a diferentes escalas espaciales: el ecosistema de Guayas y el humedal Abras de Mantequilla (AdM). Estos han sido elegidos por su importancia ecosistémica y ambiental para todo el país, tanto en términos de regulación como de aprovisionamiento de servicios ecosistémicos, y por ser sitios ecológicos importantes que ahora están bajo la presión humana y la continua dinámica de cambio en cuanto al uso de la tierra. La principal contribución de esta tesis es haber sido altamente capaz de diseñar y obtener un protocolo de acción en los procesos de toma de decisiones construidos a partir de datos reales y precisos adquiridos a través de tecnologías de las ciencias de datos y espaciales, conocimiento económico del medio ambiente y la implementación reciente de teorías de complejidad.

Contents

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Ecosystem services in Ecuadorian landscapes. An on-going process towards sustainability

Ecosystem services (ES) are the goods and services that ecosystems provide to society and may be categorized as provisioning, regulating, cultural, and supporting services (Reid *et al.*, 2005). Wherever humans live, complex socio-ecological interactions are formed with the surrounding landscape, affecting the availability, usage and particularly, the sustainability of ES. With regard to sustainability, the usage of its concept in the ES framework, we ponder Costanza & Patten (1995) definition when it is applied to ecosystems: "Since ecosystems experience succession as a result of changing climatic conditions and internal developmental changes, they too have a limited life span. The key is differentiating between changes due to normal life span limits and changes that cut short the life span of the system. Under this definition, anything that reduces a system's natural longevity also reduces its sustainability." (p.195). Following Costanza & Patten sustainability definition approach, the major detriments in ES sustainability, are social drivers such as urbanization, agriculture, and associated deforestation influence the distribution of ecosystems and their services (Alberti, 2005; Geist and Lambin, 2006; Power, 2010).

As a result of the growing interest in the science of ecosystem and landscape functions and services and especially since the release of the Millennium Ecosystem Assessment (Reid *et al.*, 2005) there have been many researches and remarkable results in this field which, nevertheless, is in deep need of continuing investigation related to the integration of ES framework into landscape planning, management and decision-making.

In our field of interest, it is noticed that the main challenge of research exists at the landscape level, where there is not a clear optimal land management option in terms of many different land use (LU) options. Landscape functions (and services) have become an important concept in policymaking, as decision-makers have to deal with an explicit demand for landscape services from a broad range of stakeholders (Hollander, 2004; Wilson, 2004; Bills and Gross, 2005; Hein *et al.*, 2006). However, landscape services are still lacking in most policy support tools (Pinto-

Correia, Gustavsson and Pirnat, 2006), and current landscape models mostly deal with either land cover (LC) patterns (Verburg and Chen, 2000; Geertman and Stillwell, 2004) or are strongly sector-oriented (Meyer and Grabaum, 2008).

In the case of Latin America, changes in the LU scale continuously occur and they have important implications for the future of freshwater and coastal marine ecosystems and their management. However, there is a lack of information about the potential of LU and biophysical alteration in the large-scale impact of tropical ecosystems. In the case of Ecuador in particular, rapid population growth and increasing international demand for tropical products have resulted in the conversion of vast areas of land for intensive agricultural production, as is typical of many other tropical developing regions of the world (Ojima, Galvin and Turner, 1994; Hollander *et al.*, 2013). The economic benefit of exporting these products to meet international demands has driven deforestation and LU changes in many tropical forests located in the Ecuadorian coast and linked to the basin of the Guayas River. In this sense, the geographic dimension of this research involves the characterization of the remaining ecosystems of mainland Ecuador. Our case study will be located in those Ecuadorian ecosystems where landscapes are experiencing serious environmental consequences and changes in their environmental services associated with the destination of LU and the various anthropogenic activities that have placed in the ecosystem boundaries, such as agricultural, livestock, industrial forestry, and other agricultural-productive activities. There is evidence of ecosystem degradation (e.g. “Abras de Mantequilla” (AdM) wetland) which belongs to the Guayas River Basin (the largest tropical agricultural system on the Pacific coast of South America). This ecosystem has suffered the loss of its native forests, due to the introduction of tree species like teak, African palm, and banana cultivations. On the other hand, the estuary basin and coastal zone that are part of the same basin are also experiencing major problems such as eutrophication, sedimentation, and pollution driven by urbanization, agriculture, aquaculture, and deforestation.

For terrestrial ecosystems, the most important direct drivers of change in ES in the past 50 years have been LU and land cover (LC) changes. Landscape-scale approaches to reducing the loss of ES and biodiversity have therefore become increasingly important (Tengberg *et al.*, 2012). On the other hand, the provision of ES depends not just on landscape composition but also on the landscape spatial configuration (i.e., the composition and organization of LC patches within the landscape). Therefore, this research is the basis for explaining the state of Ecuadorian ecosystem related to LU patterns in the last years to make better decisions regarding tradeoffs involved in LC and LU change, and a systematic account of the relationships between ecosystem management and the ES and values that it generates. In this study, the potential to support native biodiversity will be assessed using available landscape shape metrics to analyze landscape fragmentation and its potential impact on landscape capacity and ES.

LC mapping at multiple points in time provides a spatially explicit time series of biophysical characteristics of landscapes that are relevant for ES. Also, the indirect information obtained from LC data can be used as a proxy for ecosystem service assessments. This is particularly important in remote mountainous regions that encompass ecosystems that are highly vulnerable to socio-economic and climatic changes, and where land management is critical to the sustainability of communities living in and outside these regions (Reid *et al.*, 2005; Grêt-Regamey, Brunner and Kienast, 2012). This is the case of Ecuador where its vegetation cover exhibits a clear demarcation between ecological units according to elevation, the latter being the source of variations in temperature, precipitation, atmospheric pressure, humidity, and solar radiation.

However, the quantitative measurement of the relationship that exists between LU, ecosystem management and the provision of ES at national and more local scale in Ecuador is rare in terms of a widespread landscape functions analysis that will help to assess the quantifications and quality of ES in general and ES bundles in particular in order to identify their tradeoffs and synergies. Here we use the term ES bundles as a set of ES that repeatedly appear together across a landscape in terms of space or time (tradeoffs and synergies) (Raudsepp-Hearne, Peterson and Bennett, 2010). Therefore, it is important to determine the scale of the analysis, because it is the main factor in linking patterns and processes in the diverse landscape functions that construct Ecuadorian ecosystems.

On the other hand, The Millennium Ecosystem Assessment, the Convention on Biological Diversity and UNEP agree on the importance of ES for the support of life systems. This management is only feasible through the ongoing review of ES especially those at greatest risk of ecological fragility (Secretariat of the Convention on Biological Diversity, 2004). Due to the socio-economic and environmental relevance of our case study, this research has also the objective of quantifying the provision of interactions between multiple ES of our interest. Thus, it will be necessary to identify the exchanges/tradeoffs among environmental services and their synergies. The importance of identifying both exchanges and synergies of a fragile ecosystem as the case study is to enable sustainable ecosystem management of the most important forest and lands in Ecuador and to enhance the ecosystem's multi-functionality and real human being.

Scaling and adequate characterization of tree and LC distributions must span scales ranging from that of the individual to that of the landscape. Large-scale patch studies have proven to be extremely valuable for defining vegetation characteristics such as canopy gap distribution and species-specific clustering (Scanlon *et al.*, 2007). Consequently, policymakers can use this information to design spatial policies and evaluate the effect of their LU strategies on the capacity of the landscape to provide goods and services.

1.1 Landscape patterns and ES

The study of vegetation and LU patterns has been an important approach in much of the ecological research in terms of landscape. Nevertheless, there is a lack of a correct determination of the factors that generate and maintain patterns in a specific landscape. The reason for this is the existence of multiple mechanisms that can give rise to commonly observed spatial measures. This diversified pattern analyzes options have led to distinguishing several types of landscape pattern evaluations.

For example, random patterns can be indicative of the absence of spatial interactions, but random patterns are also known to emerge from strong competitive interactions. Aggregated patterns, such as those routinely observed for woody tree species in natural communities, have been attributed to the disparate mechanisms of dispersal limitation and habitat differentiation. It has been suggested that the identification of dominant processes that lead to emergent vegetation pattern could benefit from a more thorough statistical measure of the vegetation spatial structure that implicitly considers the broad range of spatial scales over which aggregation occurs, rather than simply characterizes the average aggregation tendency of individuals. We adopt such an approach in applying cluster size analysis to tree canopy distributions and evaluate the consistency of the patterns over a range of environmental conditions (Scanlon *et al.*, 2007).

When landscape pattern discussion is extrapolated in the Ecuadorian ecosystems, it is evident the major changes in LC are related to their composition. This issue is observable in the entire country and in each of the Ecuadorian regions: Andean, Amazon, and Coast; where the introduction of tree exotic species has arisen to forest and LC fragmentation.

The change in LC composition goes along with a change in LC configuration. The increase in landscape fragmentation resulted from the gradual clearing of native forests and the introduction of patches of pine plantations in high Andean open grasslands of the Ecuadorian Andean region.

That is the case of “Pangor” watershed (Fig. 1.1), which is in the Western Andean Range of the country and it has an altitude between 1434 and 4333m. This watershed is a good example of rapid forest and land cover fragmentation due to an increase in landscape changes, particularly since the second half of the 20th century. Changes in and cover patterns between 1963 and 2009 were characterized by an increase in the number of LC patches and a decrease in their mean size, by an order of magnitude in each case (Table 1.1). Forest fragmentation is particularly striking from 1991 onwards with a 5-fold increase in the number of LC patches (Balthazar *et al.*, 2015)

The mentioned study made an analysis of landscape capacities between 1963 and 2009, considering a catchment-based approach to mapping the impact of forest cover change on ES in the Ecuadorian Andean region.

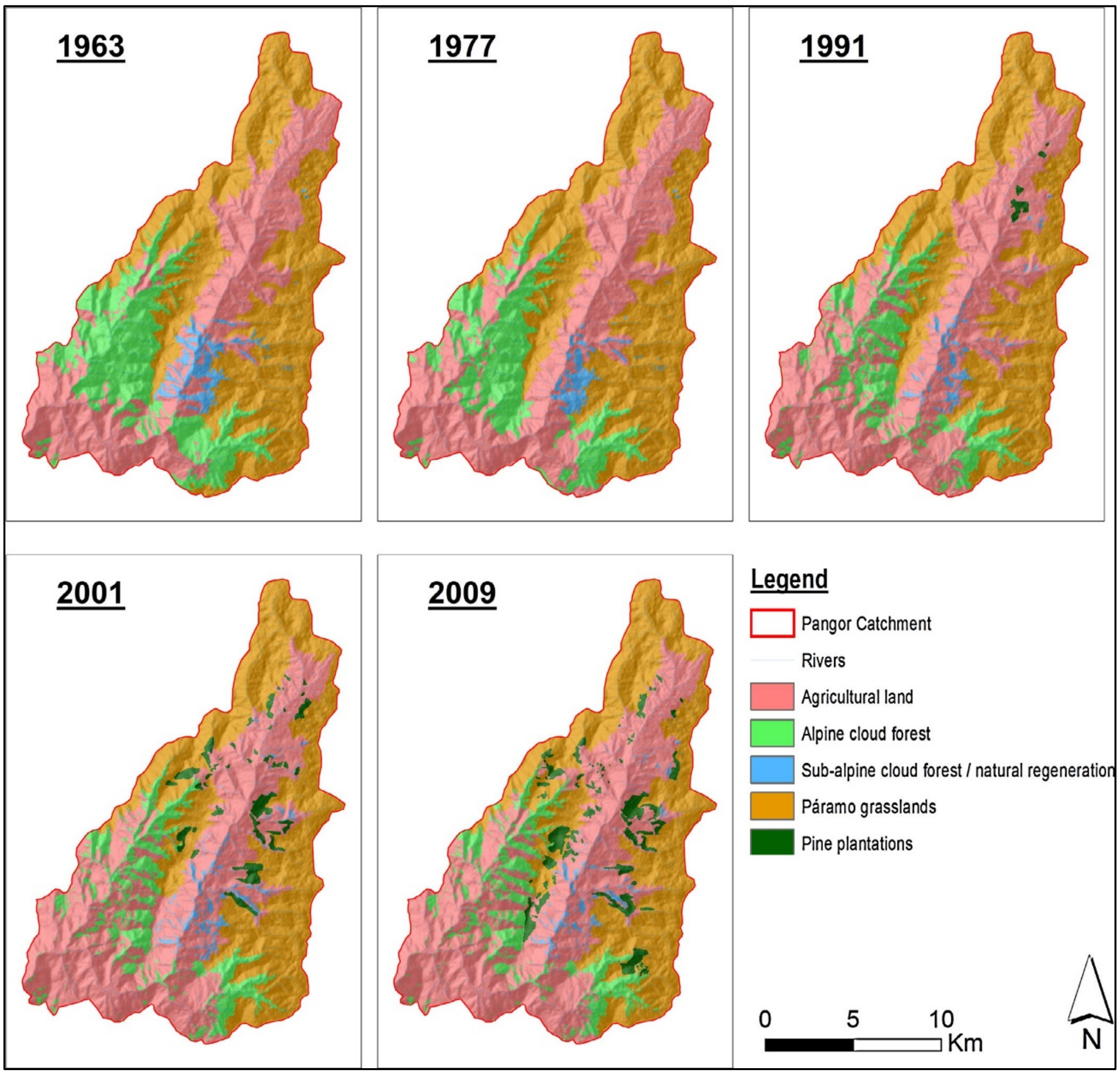


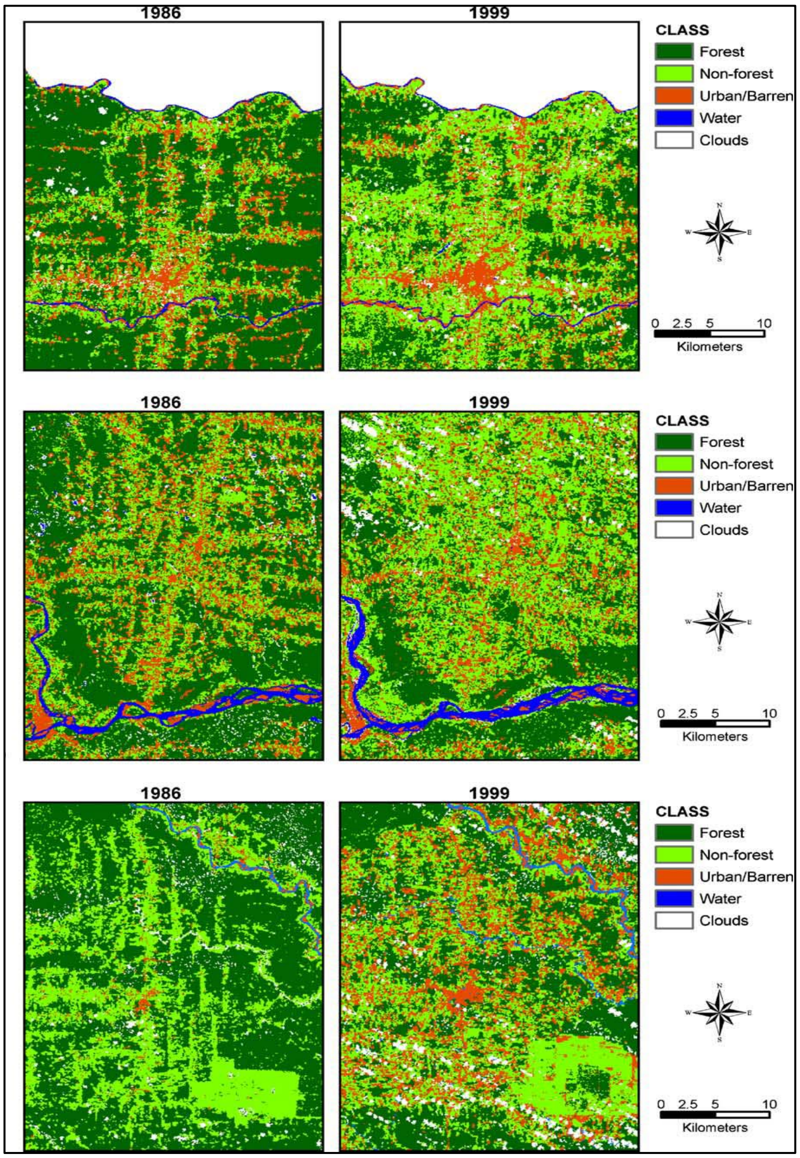
Fig. 1.1 Time-series of land cover maps composed of 5 dates that are created based on multi-source data, i.e. aerial photographs (1963–1977) and satellite imagery. (1991–2001–2009). (Balthazar *et al.*, 2015)

Year	Number of patches	Mean area of patches (ha)
1963	56	505
1977	63	449
1991	289	98
2001	544	52
2009	659	43

Table 1.1 Change in LC configuration between 1963 and 2009, as measured by two landscape metrics: the number of LC patches, and the mean area of the patches. (Balthazar *et al.*, 2015)

The first exotic tree plantations were observed in 1977, but their expansion started from the 1990s onwards, with an increase in the area of 8.15km2 between 1991 and 2001. The first large pine plantations in 1991 were in the upper part of the catchment. The increase in pine plantations continued during the 2000s, with an increase of 5.97% per year leading to a total surface covered by pines of about 15km2 in 2009. This trend continues until now as field observations in 2011 revealed large young pine tree plantations in *moorland* grasslands. From the 2000s onwards, patches of pines were located throughout the upper part of the catchment and, to a lesser extent, in the central and lower parts of the study area. Among the consequences of the native forest conversion to a forest with an important population of exotic tree plantations like the pine trees, the Ecuadorian catchment case is a good example of the negative impacts of this forest pattern alteration on native biodiversity. The on-site effects are deterioration of the aesthetic quality of the landscape caused by the rapid turnover time between pine tree plantation and the waste resulting from harvesting it and the retard of natural regeneration of vegetation on-site. On the other hand: The off-site effects of the conversion of moorland grasslands to pine plantations are changes in the water balance and flow discharge. This means a strong decrease in the total water yield, a decrease in the water flow regulation capacity and a negative impact on slope stability (Balthazar *et al.*, 2015)

When it comes to analyzing LC configuration in the Ecuadorian Amazon, there are other drivers influencing its landscape fragmentation. In the case of the northern Ecuadorian Amazon, the rapid migration since the 1970s linked to the settlement of petroleum companies has changed the landscape mosaic in a region with an extraordinarily biologically diversity and considered one of the 11 ecological “hot spots” in the world. In-migration also introduced new agricultural systems than including annual crops such as corn and rice; semi-perennials such as plantains, bananas, and yucca; and perennial tree cash crops, mainly coffee (on over 80% of all farms) with a modest production of cacao. In this case, the radical fragmentation of the land due to the farm subdivisions are evident. In 1990, 11% of *fincas* (small farms of approximately 50ha.) were sub-segmented compared to 54% in 1999. This increase in landscape fragmentation is a result of high population growth—the population density increased by 55% from 1.62 persons per ha in 1990 to 2.51 in 1999. Here, the importance of spatial patterns is also associated with land-composition (at the farm-level) and how socio-economic, demographic, biophysical, and geographical variables explain the observed variation in LULC patterns in the year period of 1986-1999 in three intensive study areas (ISA) with the area of the northern Ecuadorian Amazon (Fig. 1.2) (Pan *et al.*, 2004).



(a)

(b)

(c)

Fig. 1.2 (a) Classified Landsat TM image for 1986 and 1999 for the Northern ISA. (b) Classified Landsat TM image for 1986 and 1999 for the Southern ISA. (c) Classified Landsat TM image for 1986 and 1999 for the Eastern ISA. (Pan *et al.*, 2004)

When it comes to bringing the same analysis in the Ecuadorian coast region, we will examine it in two different case studies located in the Coast region of the South-American country, throughout this research.

What is evident is the actual effects in landscape pattern changes in the esthetic and recreational services of this type of forest/ecosystem, because of a decline in native forests, an increase in exotic tree plantations and extra pressure on LU from agricultural activities. The three drivers have led to diminished forests´ resilience and capability to facilitate its vegetation recovery (Schröder and Seppelt, 2006).

1.2 Agricultural landscapes

Pattern landscapes interact not only with LU or forest coverage changes caused by the introduction of exotic tree species like the "Pangor" catchment case. They are also linked to one of the most common land conversions, which is agricultural landscapes in the case of the northern Ecuadorian Amazon.

As the Ecuadorian catchment case shows its respective evidence, a rapid conversion in LU is driven mainly by agricultural landscape introduction in the LU classifications (e.g. the northern Ecuadorian Amazon). The agricultural landscape has an important influence on land conversion, which is attributable to its characterizations that are ruled by regular growth and harvest phases, reflected by related changes in their ecosystem service supply.

Of course, additional agricultural strategies and crops with various growing and harvesting rhythms exist. Better information on these variations is highly relevant for site-specific landscape management, i.e. to optimize additional inputs. Respective seasonal patterns can be found for regulating (e.g. during a storm or rain seasons) and cultural ecosystem service (e.g. tourist season) supply (and demand) as well. Another provisioning ES, such as timber, shows much longer rotation periods taking several decades to grow before being harvested rather suddenly. Therefore, the selection and definition of appropriate temporal assessment scales have to be carried out very carefully (Burkhard *et al.*, 2014).

1.3 Temporal and spatial scales

The issue of the scale is a decisive feature to consider when landscape functions and ES are analyzed in terms of determining the positive or negative feedback of LU patterns that can occur in diverse regional and local scales. Therefore, is extremely important to define scales of our research, associated with time and space.

Scales can be defined by the extent and resolution: extent refers to the size of a dimension, for example, the size of the study area or the duration of time under consideration, whereas resolution refers to the precision used in the measurement. There is increasing awareness of the importance of spatial and temporal scales for the analysis and valuation of ES (de Groot, Wilson, and Boumans, 2002)

The importance of scales has been widely recognized in both economics and ecology. However, to date, few ecosystem valuations studies have explicitly considered the implications of scales for the analysis and valuation of ES. There are two key scales (economic and ecological scales) proposed by (de Groot *et al.*, 2010) that need to take into account in ecosystem management issues field:

- **Economic scales**. Some examples are described such as (1) Distances to urban centers have been widely used as an explanatory variable for economic activity; (2) Spatial dimensions have been included in economic optimization models for resource harvesting.

- **Ecological scales**. A specific ecological scale can be identified at which an ecosystem service is generated depending on its scale, dimensions and regulation services (Table 1.2).

Ecological scale	Dimensions	Regulation services
Global	>1,000,000 km^2	Carbon sequestration Climate regulation through regulation of albedo, temperature and rainfall patterns
Biome—landscape	10,000–1000,000 km^2	Regulation of the timing and volume of river and groundwater flows Protection against floods by coastal or riparian ecosystems Regulation of erosion and sedimentation Regulation of species reproduction (nursery service)
Ecosystem	1–10,000 km^2	Breakdown of excess nutrients and pollution Pollination (for most plants) Regulation of pests and pathogens Protection against storms
Plot plant	<1km^2	Protection against noise and dust Control of run-off Biological nitrogen fixation (BNF)

Table 1.2 Most relevant ecological scales for the regulation services (de Groot et al.*, 2010).*

For instance, a local forest patch may provide pollination service to nearby cropland. The supply of the hydrological service depends on a range of ecological processes that operate at the scale of the watershed. On a global scale, ecosystems may provide a carbon sink or support the conservation of biodiversity. Analyses of the dynamics of ES supply requires consideration of drivers and processes at scales relevant for the ES at stake (de Groot *et al.*, 2010).

1.4 LU/LC in Ecuador

The importance of the agricultural sector in the country is mainly due to three aspects; first, to its participation in the GDP, which according to official data of the Central Bank during the last decade has been of 8% is the one that contributes the most after Manufacturing, Oil, and Mines, Construction, Trade and Education of Social Services and Health; second, because it is a source of foreign currency through the agricultural-food export sector with products such as bananas, coffee and cocoa; and new products such as mango, passion fruit, broccoli, asparagus, naranjilla, and flowers. This is a sector that has grown gradually in the decade of 2000s, from US$2.9 billion Free on Board (FOB) in 2007 to US$7.2 billion FOB in 2016 (Salazar *et al.*, 2017).

Finally, for constituting the basis of the food sovereignty policy promoted by the current Constitution in Art. 281.- "Food Sovereignty constitutes a strategic objective and an obligation of the State to guarantee that individuals, communities, peoples, and nationalities achieve the self-sufficiency of healthy food and culturally appropriate permanently "; besides being a fundamental base of information for the national strategy of change of productive matrix.

Considering these backgrounds and due to the fundamental role of the agricultural sector in Ecuador, the National Agricultural Statistical System (SEAN) updated the sampling frame, allowing to improve the levels of estimation of the results generated by the survey, with the main objective of obtaining and produce data that permanently measure the dynamics of the agricultural sector in a scientific, modern, efficient and with technological innovation.

Land use refers to its category in the rural sector. Thus, we find the following categories provided by the SEAN: permanent crops, temporary/transitory crops, and fallow land, break crop, cultivated pastures, natural pastures, woodlands and forests, moors and other uses.

The total national land-use area is 12’355.146 ha in 2017. It must be emphasized that the main land-categories are permanent and temporary crops. The total national LU has shown a decrease rate of 25% compared to the total surface in 2016. From the total land use, the segmentation of LU/LC participation is the following (Fig. 1.3):

- Permanent crops, 11.58%.
- Transitory/temporary crops, 7.32%.
- Cultivated pastures 19.81%
- Natural pastures 5.49%
- Moorland 2.69%.
- Woodland and forests, 45.94%.
- Other land uses, 6.13%.

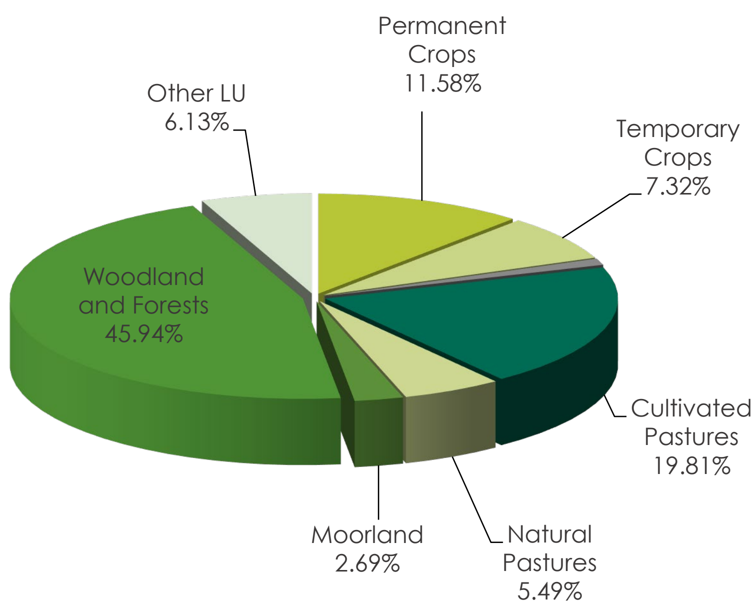


Fig. 1.3 Land use national percentage according to LU/LC segmentation. The year 2017. Compiled by the author based on data from the SEAN.[1]

An analysis of the most important areas concerning land use in the country (Table 1.3, Fig. 1.4, Fig. 1.5), permanent crops represents a decrease of 0.60% in the area of the year 2016. In 2017

[1] Sistema Estadístico Agropecuario Nacional from the Instituto Nacional de Estadística y Censos (INEC) of Ecuador (https://www.ecuadorencifras.gob.ec/institucional/home)

the national land-use area destined to permanent crops occupies 1.43 million hectares, and at a regional level the Coast has a 72.04% participation, followed by the Andes with 17.11%, finally the Amazon/Rainforest Region and the Non-Delimited Zones with 10, 18% and 0.67% respectively. Transitory crops present a growth rate of 6.42% in the national area in 2017, compared to the previous year, registering a total of 0.90 million hectares. The Coast region has 65.72% of the national transitory crops area´s share, the Andes has 30.42%, and the Rainforest has 3.85%. Besides, the Coastal region is highlighted by the production participation of permanent and temporary crops, such as oil palm, banana, coffee, cocoa, and rice; just to mention some of them. These crops dominate the LU scene in the region because of the favorable climate and soil conditions.

Land-use category	Characteristics	Year		
		2015	2016	2017
Permanent crops	Area (ha)	1.483.366	1.439.117	1.430.497
	Annual growth rate (r)	4,68%	-2,98%	-0,60%
	National LU share	11,79%	11,62%	11,58%
Temporary/transitory crops	Area (ha)	950.649	849.685	904.224
	Annual growth rate (r)	8,46%	-10,62%	6,42%
	National LU share	7,55%	6,86%	7,32%
Cultivated pastures	Area e (ha)	2.531.442	2.300.539	2.447.634
	Annual growth rate (r)	12,04%	-9,12%	6,39%
	National LU share	20,11%	18,57%	19,81%
Natural pastures	Area (ha)	706.777	800.496	677.911
	Annual growth rate (r)	-14,67%	13,26%	-15,31%
	National LU share	5,62%	6,46%	5,49%
Moorland	Area (ha)	454.347	377.791	332.418
	Annual growth rate (r)	-9,00%	-16,85%	-12,01%
	National LU share	3,61%	3,05%	2,69%
Woodland and forests	Area (ha)	5.729.799	5.773.290	5.675.402
	Annual growth rate (r)	-1,13%	0,76%	-1,70%
	National LU share	45,53%	46,61%	45,94%
Other land uses	Area (ha)	612.090	719.109	757.791
	Annual growth rate (r)	9,54%	17,48%	5,38%
	National LU share	4,86%	5,81%	6,13%
	Total National Area	**12.585.860**	**12.385.973**	**12.355.146**

Table 1.3 Agricultural growth rate. The Years 2015-2017. Compiled by the author based on data from the SEAN and (Salazar et al., 2017).

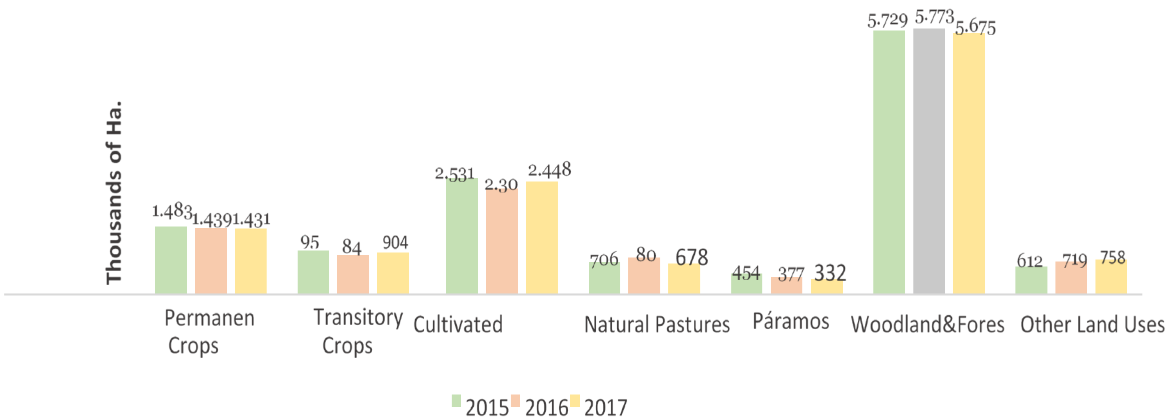


Fig. 1.4 National land-use trends. The Year 2017. Compiled by the author based on data from the SEAN.

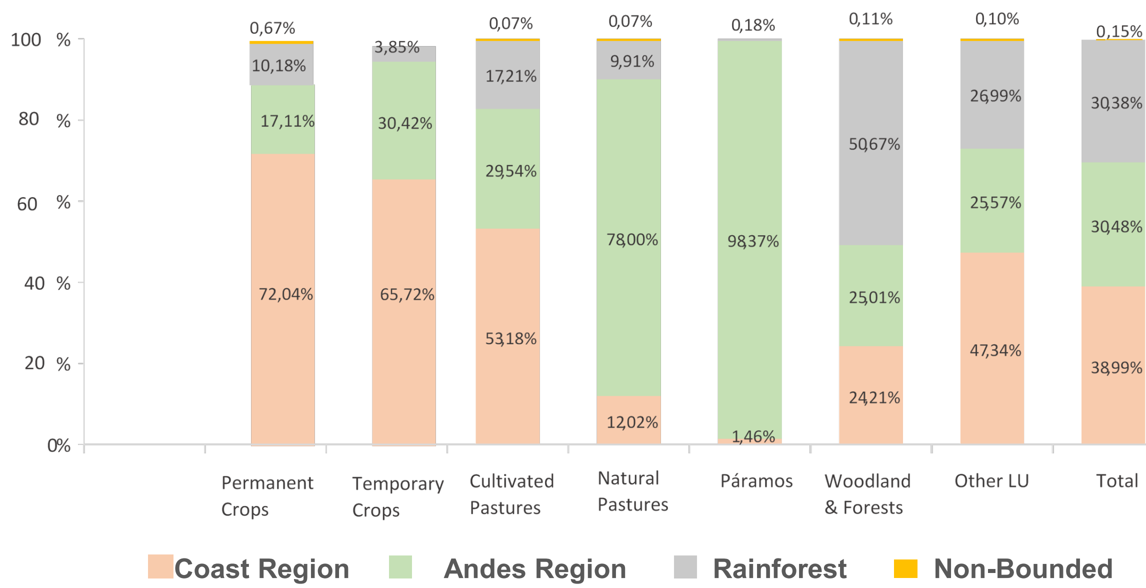


Fig. 1.5 Participation by categories of land use. The year 2017. Compiled by the author based on data from the SEAN.

When we analyze the land use category of cultivated pastures, it presents a growth of 6.39%, occupying a national area of 2.45 million hectares in 2017; by region it is distributed as follows: The Coast region 53.18%, Andes 29.54%, Amazon/Rainforest Region 17.21%, and Non-Delimited Zones 0.07%. The area designated to natural pastures presented a decrease of 15.31%, occupying

0.68 million hectares. the Coast region represents 12.02%, the Andes 78.00%, the Rainforest 9.91%, and the Non-Bounded Zones 0.07%. Although farmers in the Andes region are dedicated to the cultivation of a variety of short-cycle crops, the vast terrain occupied by natural and cultivated pastures shows livestock activity is highly predominant in the area.

The area occupied by woodland and forests registered an annual decrease of 1.70% occupying 5.68 million hectares nationwide. This land use category in the Rainforest region is the one that occupies the greater area with 50.67% of the national share, followed by the Andes Region with 25.01%, then the Coast Region with 24.21%, and a small area of 0.11% for the Non-Bounded Areas.

Last but not least, moorland (paramo landscape) area showed a significant annual decrease of 12.01 at national level in 2017, occupying a total of 332,418 hectares, which by regions is segmented as follows: The Andes region is the one that concentrates the majority of this LU category with 98.37% of participation, the Coast region with a 1.46%, and then the Rainforest region with 0.18%.

For all the categories of land use that are predominant in Ecuador, one of the most exposed to climate change is the moorland landscape. This type of vegetation, misty and marshy at the same time, is the ecological basis that ensures access to clean water resources to northern South America. Moorlands´ importance is also related to their vegetation cover functions and climate conditions. Most of the plant's species are adapted to the extreme climate conditions in the high-altitude tropics (Carrington, 2019). The moorlands have a cold and humid climate, with sudden changes in the atmospheric state and, although the fluctuation of annual temperature is small (2 to 10 ° C) the daily temperature changes vary from the freezing point to 30 ° C, these fluctuations produce a daily cycle of freezing, increased temperature and strong exposure to solar radiation.

In the region, moorlands have been part of the protected area's inventory, nevertheless, the Ecuadorian moorland landscapes are facing several threats: vegetation destruction by farming and mining, rapidly rising temperatures and a triple plague attacking the exotic plants that are inherent to this land (e.g. frailejones plants).

1.4.1 Land use analysis according to the most important national agri-products

- **Banana (Fig. 1.6, Fig. 1.7).** During the year 2017, the harvested area of banana plantations showed a decrease of 12.35%, which means 22,280 hectares were reduced from the total amount of ha. The banana production directed to export markets is located mainly in the Coast Region. The provinces of Los Ríos, Guayas, and El Oro add 82.39% of the total area harvested from this product. It is substantial to notice the main producers in terms of the national administrative units are these three provinces, which represent an important percentage of the total Guayas ecosystem. This is a zone that is interlinked, at ecological and hydrological levels, with the Guayas river basin. It is observed that the province of Los Ríos, is the one that dedicates the most to the cultivation of bananas, with a participation of 31.81% of its surface, and production of 37.05% nationwide. The following provinces in importance are El Oro and Guayas with 26.76% and 23.82% of the harvested area respectively. These, in turn, concentrate 23.62% and 26.22% of the total metric tons of bananas produced.

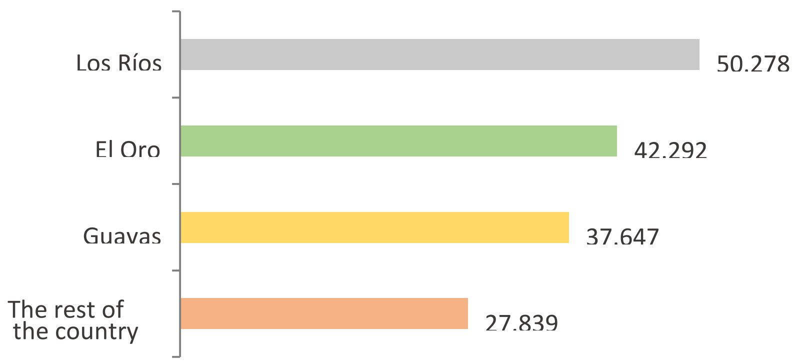


Fig. 1.6 National harvested area of banana (ha) 2017. Compiled by the author based on data from the SEAN.

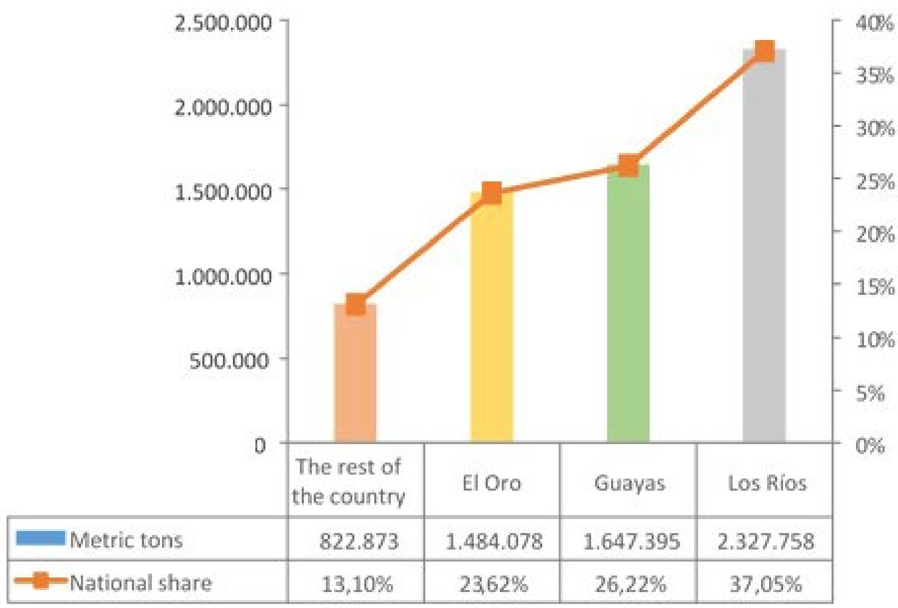


Fig. 1.7 National production of banana (Mt) 2017. Compiled by the author based on data from the SEAN.

- **Sugar cane (Fig. 1.8, Fig. 1.9).** The sugar cane harvested area has maintained a growing trend, with a national rate of 5.68% between 2016 and 2017. Sugarcane is located mainly in the Coast Region, which is the zone where our case study has a major territorial presence. In 2017, the province of Guayas reached 82.83% of the total harvested area from this product. In the Andes region, the remarkable provinces are Cañar with 8.74% and Loja with 5.09% of the harvested area. Similarly, in terms of production, it is found that 82.95% of the total tons of sugarcane are produced in Guayas, followed by Loja with 7.52% and Cañar with 5.12%.

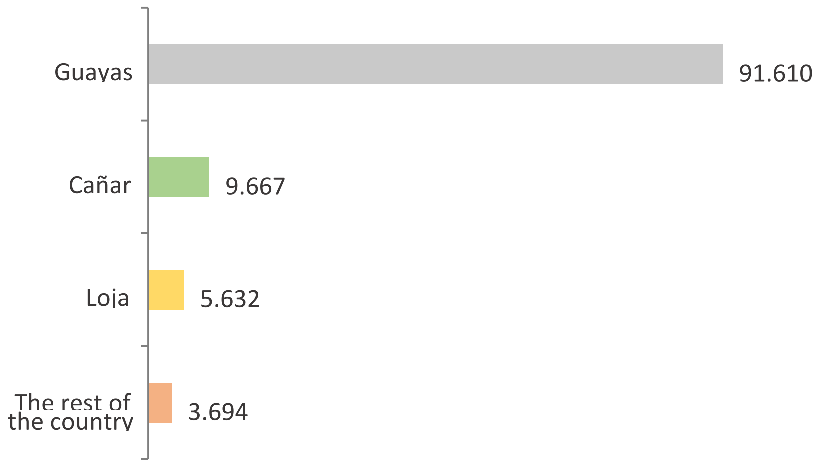
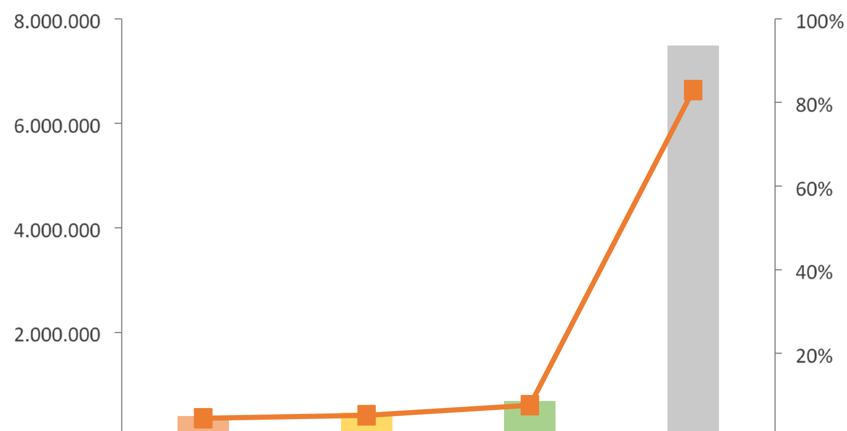


Fig. 1.8 National harvested area of sugarcane (ha). 2017. Compiled by the author based on data from the SEAN.



	The rest of the country	Cañar	Loja	Guayas
Metric tons	398.457	462.573	678.873	7.490.170
National share	4,41%	5,12%	7,52%	82,95%

Fig. 1.9 National production of sugarcane (Mt) 2017. Compiled by the author based on data from the SEAN.

- **African palm-oil (Fig. 1.10, Fig. 1.11).** At the national level, the harvested area of African palm for the year 2017 registered a decrease of 1.34%. The production of palm, however, shows a growth of 4.86% compared to the previous year, which indicates a higher yield per hectare, in 2017 there were 152 thousand additional metric tons than in 2016. The African palm crops are located mainly in the Coast Region. The provinces that mainly concentrated on its production are Esmeraldas with 47.84% of national production, Los Ríos 13.37%, and Sucumbíos 11.54%. From these three provincial regions, Los Rios integrates the "Guayas Ecosystem" with 13.37% of the share. This is a fact that is important to analyze further considering the African palm is a type of crop that is cultivated in large size fields and its derivate products, like palm oil, are worldwide demanded.

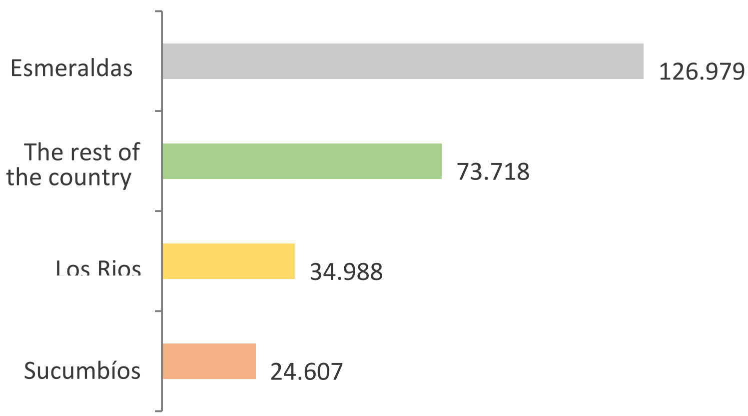


Fig. 1.10 National harvested area of African palm oil plantations (ha) 2017. Compiled by the author based on data from the SEAN.

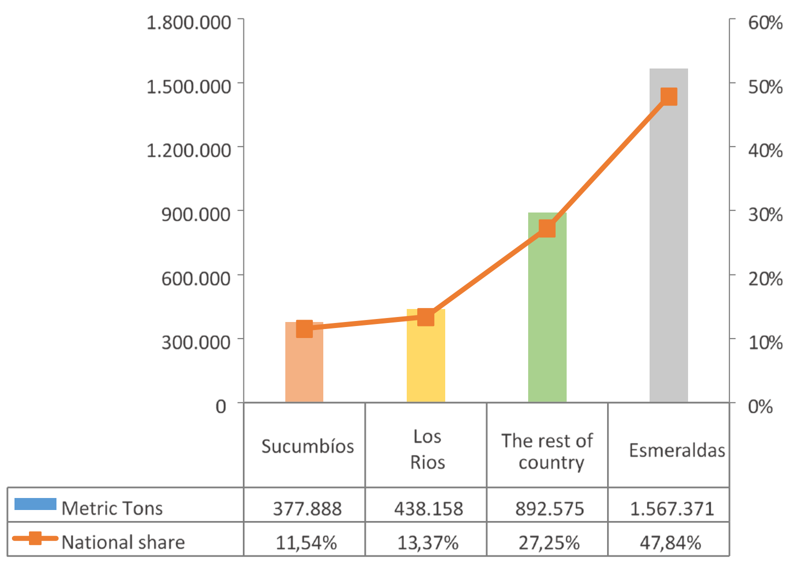


Fig. 1.11 National production of African palm (Tm) 2017. Compiled by the author based on data from the SEAN.

This increase in demand for palm oil and other African palm derivatives has had a large impact on the escalation of land use to produce it. This type of crop requires land conditions that are linked only to humid tropics. The intense growth in this agricultural frontier has come at the expense of species-rich and carbon-rich tropical forests. Some of the global facts about the expansion of African palm oil plantations show a land cover conversion from forest to palm crops of an average of 270,000 ha annually in main palm oil-exporting countries (2000-2011) (Henders, Persson and Kastner, 2015). One example, shows the two most important palm oil exporters in the world, Indonesia and Malaysia, had a conversion >50% of forest territory in 1990, into oil palm plantations in 2005 (Koh and Wilcove, 2008). Another recent study reveals regional trends in deforestation (Fig. 1.12, Table 1.4) associated with oil palm agriculture. In the case of South America, the percentage was 31% (1989- 2013) as a region unit. But when we direct the analysis to Ecuador, the percent increase in FAO total oil palm planted area from 1989-2013 is 74.7% and the estimated percent of oil palm planted area coming from deforestation since 1989 is 60.8%. This data alludes to a rapid transition from forest to plantations, resulting in higher levels of deforestation during the study period (Vijay *et al.*, 2016).

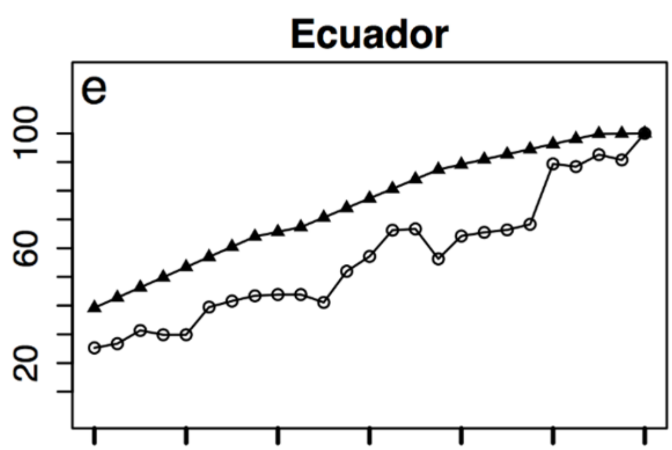


Fig. 1.12 Trends of deforestation and oil palm planted area. Trends of deforestation inside sampled oil palm plantations (solid triangle) and total FAO oil palm planted area for eight countries (open circle). Both trends are relative to 2013 values, thus both reach 100% in 2013. (Vijay et al., 2016)

Producer country	Percent increase in planted area	Percent of the area from deforestation
Indonesia	91.7	53.8
Malaysia	63.3	39.6
Nigeria	24.7	6.6
Thailand	85.5	0.0
Ghana	63.9	0.4
Ivory Coast	62.0	4.1
Colombia	69.5	0.0
Ecuador	74.7	60.8
Dem. Rep. of Congo	16.0	0.7
Papua New Guinea	72.3	25.3
Cameroon	59.3	16.9
Honduras	81.0	0.4
Brazil	77.0	39.4
Costa Rica	73.2	0.0
Guatemala	95.4	10.4
Philippines	72.1	0.0
Peru	87.0	53.1
Mexico	97.8	1.6
Venezuela	90.0	0.0
Dominican Republic	94.1	0.0

Table 1.4 Percent increase in FAO total oil palm planted area from 1989–2013 by country and estimated percent of oil palm planted area coming from deforestation since 1989. (Vijay et al., 2016)

- **Rice (Fig. 1.13, Fig. 1.14)**. Rice fields are mostly located in the Coast Region because of the climatic and soil conditions of the area. The provinces of Guayas and Los Ríos share 95% of the total harvested area for this product at a national level. It is observed that the province of Guayas is dedicating more agricultural land to the cultivation of rice, with a total of 247.101 ha harvested. Correspondingly its production is superior compared to the other producers, representing 71, 4% of the total production of the rice. Furthermore, the province of Los Ríos concentrates 93000 ha of the harvested area and 22.7% of the cereal grain national production share. At the regional level, we must bear in mind that short-cycle crops like rice, corn, and soybean, occupy 64% of the soil of the AdM wetland, this activity being fundamental and needed for people to make their lands producible. With an expansionist projection, these crops are destroying riparian vegetation and promoting the development of other species that become aggressive by having optimal conditions for their development, such as "*lechuguin*" (Alberti, 2005). In general, the uniformity of monocultures destroys the regeneration capacity of the ecosystems and generates desiccation and washing of soils in areas where the jungle - or forest - cushioned the fall of rainwater (Gudynas, 2009).

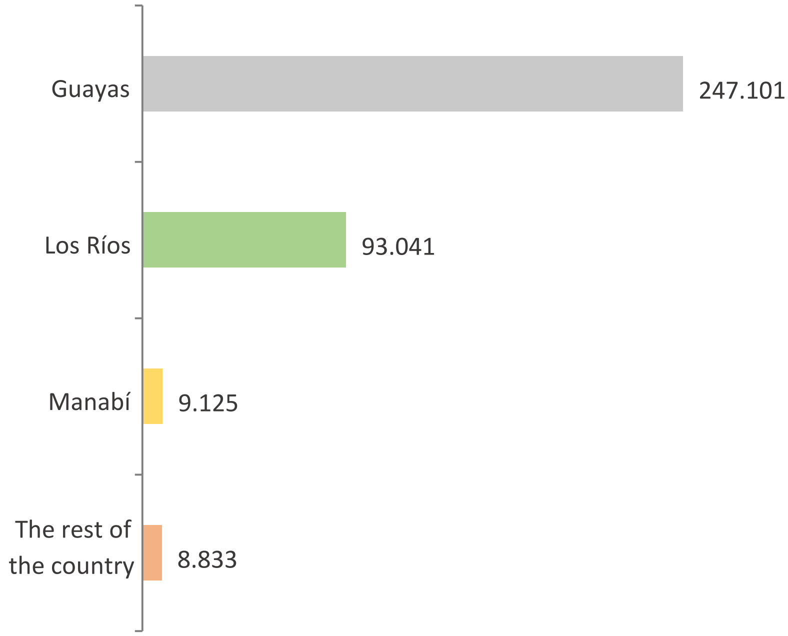
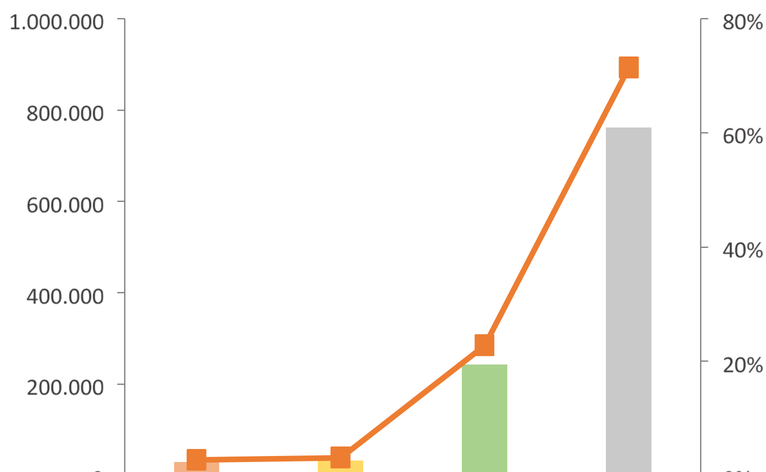


Fig. 1.13 National harvested area of rice fields (ha). The year 2017. Compiled by the author based on data from the SEAN.



	The rest of the country	Manabí	Los Ríos	Guayas
Metric tons	28.828	32.953	242.879	761.954
National share	2,70%	3,09%	22,77%	71,44%

Fig. 1.14 National production of paddy rice (Tm). The year 2017. Compiled by the author based on data from the SEAN.

Dried corn (Fig. 1.15, Fig. 1.16). Dry corn plantations are located mainly in the Coast Region. The provinces of Los Ríos, Manabí and Guayas added 79,98% of the national harvested area of this primary product. The province of Los Ríos has the most extended area of dried corn plantations, with a concentration of 35.96% at the domestic level; similarly, its production is the highest contribution to national grain production with 39.42%. Manabí and Guayas concentrate 24.74% and 21.96% of the national production, respectively.

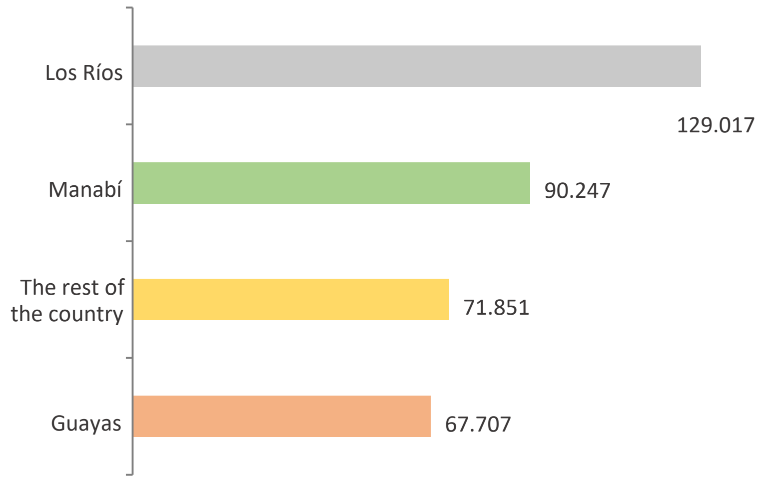
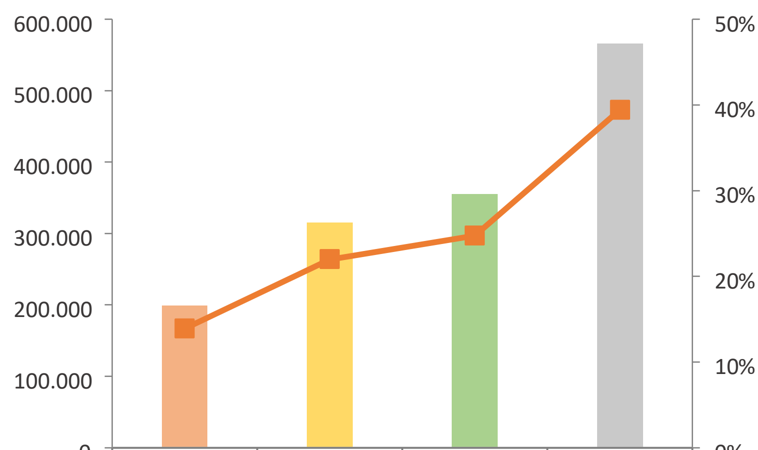


Fig. 1.15 National harvested area of dried corn plantations (ha). The year 2017. Compiled by the author based on data from the SEAN.



	The rest of the country	Guayas	Manabí	Los Ríos
Metric tons	199.443	315.390	355.230	566.043
National share	13,89%	21,96%	24,74%	39,42%

Fig. 1.16 National production of dried corn plantations (Tm). The year 2017. Compiled by the author based on data from the SEAN.

1.5 The need for a decision - support methodology

According to the report of the Ministry of Environment in 2000, the rapid growth of the Ecuadorian primary industry provokes alarming subnational annual deforestation rates between 1.7 (238,000 hectares) to 2.4 (340,000 hectares), which numbers are increasing (Vallejo, 2009). Similarly, according to the National Coalition for the Defense of Mangrove and the National Plan for Good Living, 70% of mangrove areas and saline areas disappeared between 1969 and 1999 (Yáñez-Arancibla and Lara-Domínguez, 1999). Thus, the lack of investment, the lack of incentives for the restoration and protection of water sources, among others, are responsible for the indiscriminate expansion of agricultural production at the expense of the remaining ecosystems (Ruiz Mantilla, 2000). This situation worsens attributable to the high concentration of land and water in few hands, the lawlessness in the land tenure and rural poverty. In 1973, at the national scale, about 1% of the farms owned more than 55% of the land in 1954, while 73% of land holdings represented less than 7% of the total land area. The agrarian land reforms of the 1960s and 1970s led to a redistribution of land ownership but also promoted the rapid colonization of so-called vacant lands, which were often covered by native forests. This fact was the beginning of the LU changes the country has suffered.

Among other drivers that has influenced in the loss of native forest land were mentioned by Vanacker *et al.* (2003), who emphasized that deforestation and forest degradation were caused by 1) rapid population growth; 2) The agrarian land reforms of the 1960s and 1970s already mentioned in this document and; 3) From the 1980s onwards, exotic tree species (mostly eucalyptus and pine) were increasingly used for plantation forests that now cover extensive areas. These change factors caused the expansion of the agricultural frontiers into the primary and secondary native forests. It is important to mention, that the conversion of native forests to agricultural lands is associated with the most negative ecosystem impacts. The only positive impact of the establishment of agricultural land was the provision and valuation of food products.

Nowadays, the effects of intensive LU change in the Ecuadorian landscape overview are the modifications of landscape compositions in cases like the Andean region were the introduction of exotic tree species might its main driver. The change in LC composition goes along with a change in LC configuration. On the other hand, another important effect is land fragmentation resulted from the gradual clearing of native forests, and the introduction of patches of pine plantations in high Andean open grasslands like the “Pangor”’s catchment case. In the mentioned case, changes in the LC pattern between 1963 and 2009 were characterized by an increase in the number of LC patches and a decrease in their mean size, by an order of magnitude in each case.

For all these reasons, there is an immediate need for a decision - support methodology which helps to manage ES in Ecuador, where ecological problems have increased social conflicts in the last 20 years. Although governments and international policymakers are embracing the concept of ecosystem services to provide new opportunities for local economies and to safeguard natural capital for future generations, there are evidences that ecosystem service assessments do not capture the core steps of the decision-making process, with much of the literature focused on quantifying and mapping the supply of ecosystem services (Martinez-Harms *et al.*, 2015). With this research, we aim at helping policy and decision-makers to (a) articulate objectives more clearly, (b) to evaluate the consequences of alternative management actions, and finally (and hopefully) (c) facilitate closer engagement between scientists and stakeholders.

1.5.1 Case studies

The Guayas River basin is constituted by the catchment area of the fluvial system that is composed of three major tributaries, the Daule, the Vinces and the Babahoyo rivers with their stream systems. The Daule and the Babahoyo rivers merge waters in the north area of Guayaquil city and form the Guayas River. This body of water is 60 km upstream of its mouth in the Gulf of Guayaquil (Pacific Ocean) and discharges annually approximately 30000 million cubic meters of water, after draining a vast geographical area of 44532 km^2. This basin includes an extensive and important agricultural area for the socio-economic development of the country (CEPAL, 2012).

As we have previously mentioned, to carry out this research we have chosen two cases at two different scales but the same geographic area. In the first place, we have selected the “Guayas” ecosystem. The analysis has been applied to the Guayas River basin of Ecuador. In this case, the basin is understood as an integrated tropical ecosystem called "Guayas Ecosystem” which includes the sub-ecosystems Gulf of Guayaquil, Guayas River Basin, the Guayas River estuary and the city of Guayaquil. It is necessary to emphasize that this ecosystem belongs to the largest tropical agricultural system on the Pacific coast of South America, where land use and different anthropogenic activities in the territory are present, such as agricultural, livestock and forestry activities. These activities have significantly modified vegetation cover structure and water system quality (e.g., AdM wetland territory, Province of Los Ríos, Guayas Ecosystem, Ecuador) due to the introduction of tree species such as teak, African palm, and raft plantations (Lacerda, Kremer and Salomons, 2002). The dimensions, in terms of km^2, of this ecosystem and its LULC values will allow us to evaluate fragmentation indices. As we will see in the following chapters, the methodological process to calculate these indices for different LULC values requires data in several orders of magnitude, particularly in land-use areas, which cannot be obtained from smaller ecosystems.

The AdM wetland territory located in the province of "Los Ríos" (part of the "Guayas" Ecosystem unit) is part of the "Municipal Association for the Sustainable Management of the AdM wetland" territory that has been selected as our second study area for ES assessment and analysis. There are several reasons for this. Firstly, it allows a significant change in scale compared to the Guayas ecosystem, a fact that influences the quantity, quality, and type of data that we can obtain regarding the assessment of ES in this area. On the other hand, the AdM is a RAMSAR[2] site in the middle of the Guayas River Basin, one of the main riverine ecosystems in Ecuador. The wetland has suffered the same pressure drivers as the Guayas River Basin: land use degradation, anthropogenic activities, and intense agricultural production. The AdM wetland territory was declared as a RAMSAR site in 2000, but in 2008 its area of influence was updated to 54.486 ha, comprising the jurisdictions of the five main districts: Vinces, Baba, Mocache, Ventana, and Puebloviejo. The common territory of the wetland is in the province of Los Rios, and it has an estimated population of 210,000 inhabitants in an area of 3.9000 km^2 in the rural sector. Its area of influence includes the western foothills of the Bolívar province of the Andes mountain range. The AdM wetland territory is a lagoon complex comprising 54,486 ha of seasonal or eutrophic lagoons fed by the winter floods of the Vinces River and which regulates the hydrological system through its groundwater accumulation. This water system also supplies most of the water needs for food and irrigation systems for agriculture during the dry season. These water bodies are fundamental for the economic, social, cultural and environmental development for the inhabitants in the middle and lower basins of the Vinces River (Freire *et al.*, 2012). Since October 2011, the native tropical forests of the AdM wetland territory have been dramatically reduced, on account of the pressure for land and the extension of the agricultural frontier (Freire *et al.*, 2012). Small farmers have taken refuge on the river's banks and estuaries intending to take advantage of the courses of the floods to plant seasonal crops while looking for product alternatives. According to the research carried out in 2012, only 1.3% of the native forests within the wetland area have been detected, that is, around 870 ha spread out over the total 67000 ha. Most of these forest remnants are found next to the natural water reserves of the wetland (Fig. 1.17).

[2] https://www.ramsar.org/

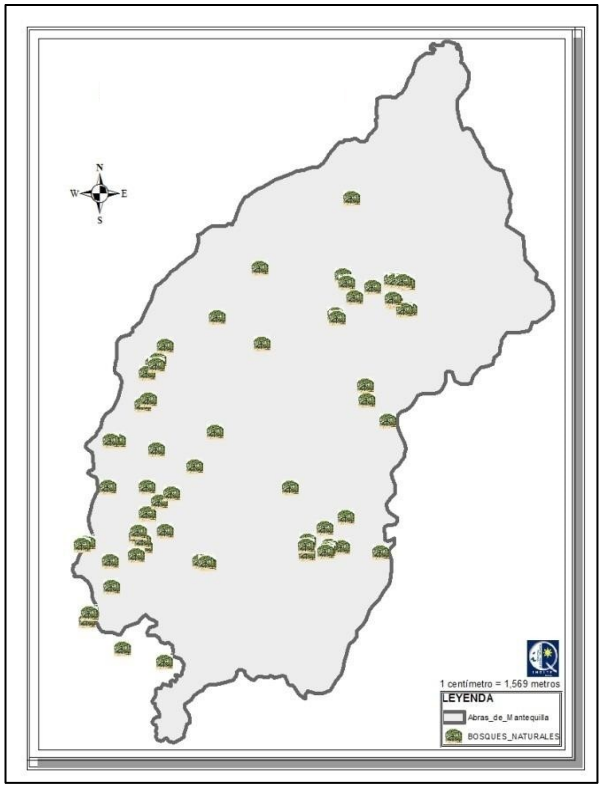


Fig. 1.17 Zoning of natural forest areas of the AdM wetland, province of Los Ríos, Guayas Ecosystem, Ecuador (Freire *et al.*, 2012).

Finally, when it comes to decision-making processes linked to ES, it is a well-stablished assumption that this type of research needs to be conducted at scales relevant to social processes and decision making, such as the municipality level (Raudsepp-Hearne, Peterson and Bennett, 2010). This is why an analysis of the impact of these human-driven actions at the AdM spatial scale can result in a better comprehension of the evolution of the ES in this region and better implementation of related decision - support methodologies.

1.6 Main points in review

- A key challenge of ecosystem management is determining how to manage multiple ecosystem services across landscapes. Enhancing provisioning ecosystem services (i.e., food, timber, etc.) might lead to tradeoffs between regulating and cultural ecosystem services (i.e., nutrient cycling, flood protection, tourism, etc.). Ecosystem service-bundle analysis can help to identify areas on a landscape where ecosystem (mis)management has produced (un)desirable sets of ecosystem services.

- Ecuador is now suffering the effects of intensive LU change, a fact that is reconfiguring landscapes at all spatial levels. This process generates (a) land fragmentation resulted from the gradual clearing of native forests, (b) the introduction of patches of plantations in open grasslands and sensible ecosystems, and finally (c) an impact to ES. It is thus primordial to develop a decision support methodology able to assess ES at different scales and to help decision-makers to articulate objectives more clearly and evaluate the consequences of alternative management actions.

- In this research we aim at setting the stage for developing this kind of decision support methodology, taking into account:

    - the many constraints regarding data availability in terms of types (i.e., numerical, spatial, imagery, etc.) and acquisition (i.e., remote sensing, open official information, on-site, etc.),

    - the temporal evolution and dynamic change of ES and ES-bundles, and

    - the influence of fragmentation in this change,

  being these last two aspects, not found in the literature so far.

- We consider two case studies at different spatial scales: Guayas ecosystem and Abras de Mantequilla (AdM) wetland. These have been chosen for their ecosystemic and environmental importance for the whole country, in terms both of regulating and provisioning ES, and for being important ecological sites now much under human pressure and land-use change dynamics. On the methodological side, although AdM offers the right scale to evaluate ES and implement decision-support methodologies, the Guayas ecosystem has a suitable scale to act as a proxy for variables and ES measures which cannot be found at lower scales.

- The main contribution of this thesis is to have been highly capable to design and obtain a protocol of action in the decision-making processes built from real and accurate data acquired through modern technologies -not necessarily implying that the data is of high quality-, socio-economic knowledge of the environment and recent complexity theories implementation.

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1.8 Appendices

1.8.1 Glossary of Acronyms

AdM	*Abras de Mantequilla*
CEPAL	*Comisión Económica para América Latina y el Caribe*
ES	Ecosystem service
FAO	Food and Agriculture Organization
FOB	Free On Board
GDP	Gross Domestic Product
INEC	*Instituto Nacional de Estadística y Censos*
ISA	Intensive study area
LC	Land-cover
LU	Land-use
LULC	Land-use and land-cover
RAMSAR	Ramsar Convention on Wetlands of International Importance especially as Waterfowl Habitat
SEAN	*Sistema Estadístico Agropecuario Nacional*
UNEP	United Nations Environment Programme

2

Analysis and management of geographic data for Ecuadorian ecosystems

The use of geographic information in decision-making is related to our daily activities and decisions. In science, geographic information has a predominant use in order to enable to ask and answer hypothesis associated with spatial information and spatial questions and software that helps us understand those premises. The geographic data permits to analyze digital information with a set of tools composed of software and data. Therefore, it allows the capacity of storing, managing and analyzing digital information, as well as making graphs and maps, and representing alphanumeric data (López Trigal, 2015).

This methodological chapter aims at justifying the necessity to define the proper steps needed in order to obtain, create and work with geographic data to analyze and manage a suitable GIS for our case study of an Ecuadorian ecosystem. Our rationale relays on the evidence of how extensive land-use conversions often lead to dramatic changes in regional hydrology (Bonell, 1998; Cronan, Piampiano and Patterson, 1999), alterations in biogeochemical cycles (Galloway *et al.*, 2004), losses of nutrients such as nitrogen and phosphorus (Howarth *et al.*, 1996; Parrotbill *et al.*, 2010), and soil degradation (Ojima, Galvin and Turner, 1994; Cole *et al.*, 2011). Previous studies in temperate and tropical areas have found strong links between large-scale changes in land use and associated nutrient flows in land and water (Galloway *et al.*, 1995; Valiela and Bowen, 2002; Filoso *et al.*, 2003). To understand the cause and the effect of land-use change, it is not enough considering the biophysical impacts described. It is also necessary to put focus on the social context. Socio-economic and environmental factors are important drivers to determine the alterations in land use/land cover (Fig. 2.1). These factors influence on land-use changes, which are connected to environmental changes as a contingent on the productivity of the land.

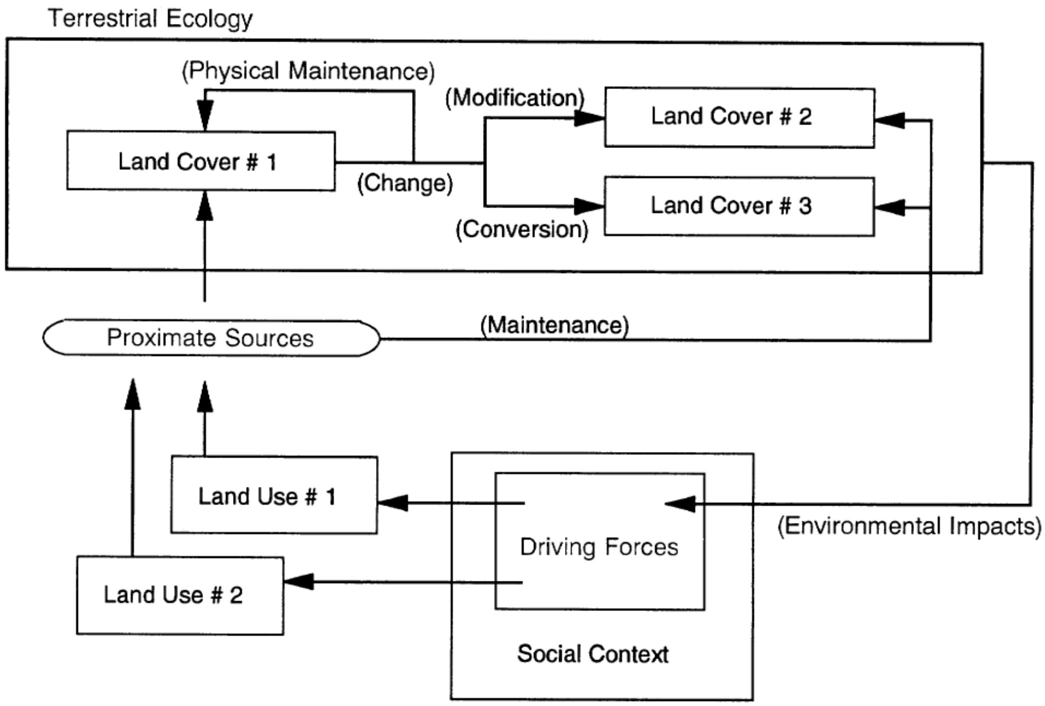


Fig. 2.1 Links between human activities and land use and land cover. (Ojima, Galvin and Turner, 1994)

Additionally, environmental changes can improve land productivity, and in other cases, they cause land detriment. Similarly, there are some land-use changes that may have a positive impact on its productivity and long-term sustainability while others cause negative effects in the systems, disrupting its resources' thresholds to collapse (Fig. 2.1). The most vulnerable systems are those with many monocultures in their land mosaic, and high variability in their climate indicators, causing them stress already constrained by limited resources (e.g. water availability) (Ojima, Galvin and Turner, 1994).

Latin America and the Caribbean include more than 48% of global forest cover, concentrates a vast number of countries (11 countries) with the utmost biodiversity worldwide, comprises 40% of global water availability and produces no less than 12% of the world´s agricultural commodities. Nevertheless, the side effects of the current climate crisis are causing radical changes in the region: altering agricultural production cycles, tides and reproductive cycles of fish, as well as introducing new pests and invasive species that put food production and the region land cover characterization at risk (FAO, 2019).

In the case of Ecuador, land-use changes on a large scale occur and have important implications for the future of freshwater and coastal marine ecosystems and their management (Yáñez-Arancibla and Lara-Domínguez, 1999). Rapid population growth and growing international demand for products have been a place for the conversion of land areas for intensive agricultural production in Ecuador, as is typical of many tropical regions in the development of the world (Houghton, 1994). Overall, Ecuador´s contemporary economic history has been distinguished by the damage of pristine vegetation cover due to changes in the use of land (e.g. erosion and deforestation), rising populations growth rates, a continuous decline of the biophysical capital (e.g. tropical forests) causing biodiversity destruction, a constant oil extraction economic policy (approximately 3.1 billion barrels between 1970 and 2002) and its negative social and environmental impacts (Falconí Benítez and Larrea, 2004). The economic benefit of producing the main Ecuadorian agricultural commodities such as banana, shrimps, cocoa, and rice, and oil palm, has been the engine of deforestation and land use in Ecuador and especially in the Guayas river basin (one of the largest water systems in the country).

As we have already presented in Chapter 1, both GE and AdM show the need to give them adequate support in terms of land-use change research using strategically satellite images, thematic cartography, and statistical data. The vast environmental, social and economic risks that we face in the current situation will be much more difficult to manage, if it is not possible to measure the key aspects of the problem, vg. natural capital (Brundtland, Ehrlich, and Hansen, 2016), especially in territories like our study cases, which are exposed to intensive land use and pressures related to water resources, agriculture activities conditioned by climate features of the area (e.g. short-cycle crops), and the expansion of monocultures.

Additionally, from a geographical and territorial perspective, Fig. 2.2 locates the complex dimension of the management of AdM wetland territory. The system comprises the Ecological Reserve Illinizas, which includes the following sub-systems: the glaciers emanating from the Illinizas, their underground aquifer systems, and the Macuchi volcanic and geological networks. This territory is located to the north of the La Maná district, 105.22 kilometers away from Puebloviejo, where it starts the confluence of the water resources supplies of the wetland system (underground networks) and of the entire territory that floods the province of Los Ríos. The proximity of the wetland system to the surrounding Andes mountain range makes satellite imagery a challenge because it is a zone of high cloudiness. But it is also its complexity and its wide area of influence that makes the wetland system a region to analyze its changes in land use and its effects on the mosaic of the territory.

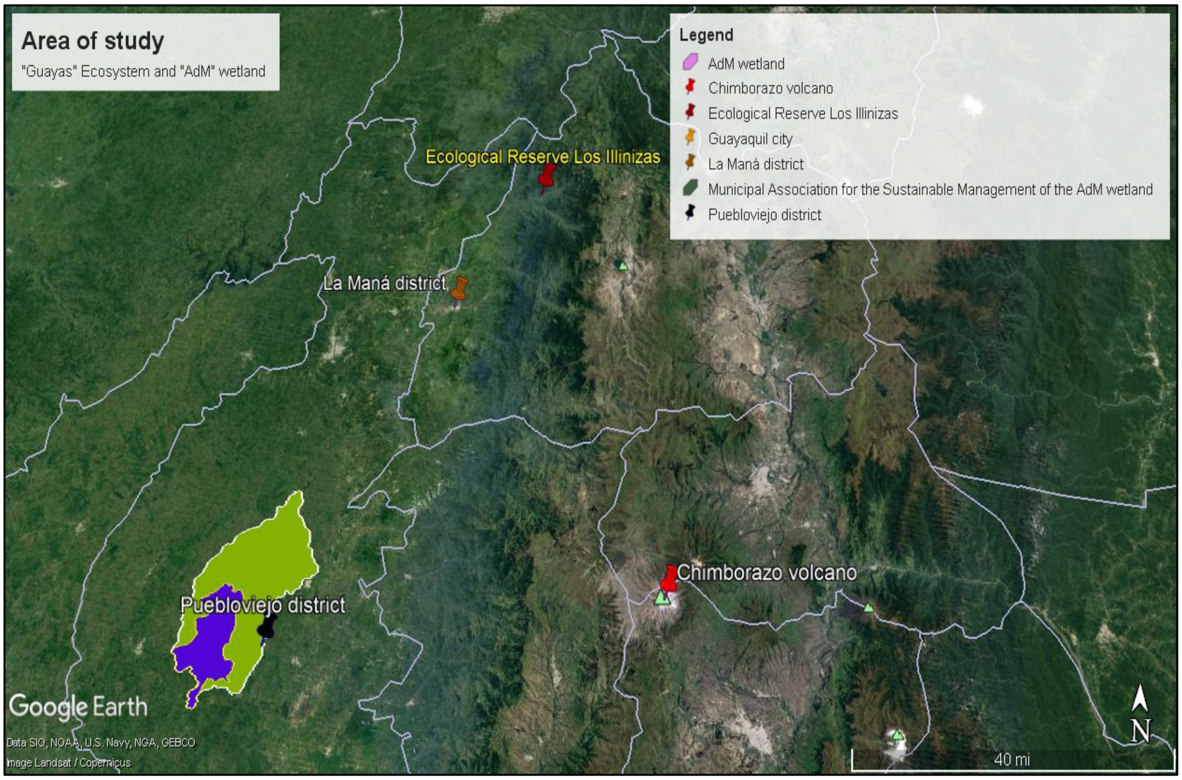


Fig. 2.2 Area of influence of the AdM water system network and AdM wetland territory.

In view of the foregoing, remote sensing has demonstrated its great value for monitoring changes in land use and land cover change. On the other hand, the immense availability of geographic data makes it imperative to adopt it in territorial planning. In the case of Ecuador, public and private institutions utilize cartographic and remote sensing data. For example, The Ecuadorian Space Institute (since 2009) has been collecting theme geographic information on a national scale. In addition, the Ministry of Agriculture, Livestock and Aquaculture and Fisheries (MAGAP) and the Ministry of the Environment (MAE), in a joint effort, generated the map of coverage and land use of the mainland Ecuadorian territory at a scale of 1:100.000 as an input for monitoring climate crisis, ecology issues and territorial planning. On the other hand, The National Institute of Statistics and Census of Ecuador (INEC), through the Directorate of Economic Statistics and the Agricultural Statistics Unit (ESAG), presents information regarding the compendium of data obtained through the Surface Survey and Continuous Agricultural Production (ESPAC) since 1990.

This work allowed to know the regional ("Guayas" ecosystem unit) and local ("Abras de Mantequilla" (AdM) wetland territory reality in terms of the distribution of the different coverages through a national classification system according to a hierarchical thematic legend based Methodological Protocol for the Preparation of the Coverage and Land Use Map of the Continental Ecuador 2013-2014, scale 1: 100,000. Among the inputs used are satellite images through extraction techniques and information generation, complementing with additional geographic information (vector and cartographic data) and agricultural statistical data. This legend system is the basis of the collected information in this research, whereby the same hierarchies have been used in order to be consistent with the national and official geographic protocol. There have been great difficulties in terms of collecting, processing and publishing geographic information at the national level, and the situation worsens when it comes to provincial, local, or any specific study area. The huge gap of geographic information at the local and regional level has been a constant and tangible reality. The collecting data process (geographical and statistical information) of the "Guayas" Ecosystem and AdM wetland territory in this research has shown the problem of scarcity and access to reliable data. Consequently, the assessed databases will be relevant for further projects and researches linked to monitoring the LU/LC management.

2.1 GIS data models

Despite the heterogeneity of geographic information, there are two basic approaches to model spatial data: the vector model, usually used to treat discrete geographical phenomena (communication routes, urban fabrics, vegetation cover) and the raster model is generally used to represent continuous phenomena. Both systems are complementary and coexist within GIS, although each of them is more appropriate for the study of a specific type of information (Del Bosque González *et al.*, 2012). Here we use both data models with the objective of analyzing the AdM wetland territory.

- **Vector model**. Vector data is used to define objects with distinct boundaries, such as roads, parks, and land parcels. To accurately represent these objects, a GIS provides different geometries to use depending on the object you are trying to represent. Vector data uses geographic coordinates to determine where features are located. It uses attribute information to determine what something is (ESRI, 2019). In this model, there are no fundamental units that divide the collected area, but the variability and characteristics of it are collected through geometric entities. For each geometric entity, the characteristics are constant. The form of these entities is explicitly coded because it models the geographical space through a series of geometric primitives that contain the most outstanding elements of a space. These primitives are of three types: points, lines, and polygons (Olaya, 2014).

- **Raster model**. Raster data is used in a GIS application when we want to display information that is continuous across an area and cannot easily be divided into vector features. A GIS represents this information using a raster data model based on a matrix of cells represented in rows and columns, each cell can store information of a variable (precipitation, temperature, relative humidity, solar radiation, wavelengths of the electromagnetic spectrum, etc.) (QGIS, 2019).

2.2 Geoprocessing tools

For this research project, we use ArcGIS desktop[1] and. ArcGIS is the most outstanding component of the variety of applications available from ESRI. This software contains the basic GIS functionalities. ArcGIS includes a diversity of tools that permits the visualization and the management of geographic data, and its extensible architecture structure allows users to add new functionalities, as Spatial Analyst (raster data analysis), 3D Analyst and Geostatistical Analyst (Olaya, 2014). ArcGIS has been used for managing vector and raster data from AdM wetland territory, which specifies a temporal geostatistical analysis from 2000 to 2018. This analysis will be deeply detailed in this chapter.

2.3 Remote sensing

When we talk about remote sensing, we refer to the group of techniques that allow users to obtain properties data of an object located to a certain distance from an x observer. Remote sensing is based on the measurement of electromagnetic radiation in the different bands of the electromagnetic spectrum of the land cover. This information is captured from satellites that orbit around the Earth. Remote sensing as a tool or technique that uses sensors to measure the amount of electromagnetic radiation (EMR) exiting in an object or geographic area from a distance and then extracting valuable information from data using mathematically and statistically base

[1] http://desktop.arcgis.com

algorithms is a scientific activity (Fussell, Rundquist, and Harrington-Jr., 1986). Thus, remote-sensing tools have been developed in order to analyze satellite data, permitting ecology researchers to examine temporary large-scale conservation issues. The diversity of users and developers of these tools, such as government institutions, open-source developers and private companies visualize their importance. Remote sensing comprehends a set of techniques for collecting and observing data about Earth from space or from airborne platforms by measuring energy reflected or emitted at various wavelengths. Researchers can use these data to conjecture, for example, the level of deforestation, land-use changes and other problems related to ecology sciences.

In the sense of remote sensing, the EMR reflected, emitted, or backscattered from an object or geographic area is used as a surrogate for the actual property under investigation. The electromagnetic energy measurements must be calibrated and turned into information using visual and/or digital processing techniques. The majority of remote sensing instruments record EMR that travels at a velocity of 4x108ms-1 from the source, directly through the vacuum of space or indirectly by reflection or reradiation to the sensor. The EMR represents a very efficient high-speed communications link between the sensor and the remote phenomenon (a valuable source of data for interpreting important properties of the phenomenon: temperature, color) (Jensen, 2015).

Remote sensing has a diversity of advantages related to the following techniques facilities (Jensen, 2015):

- Remote sensing offers techniques which do not disturb or the area of interest. The electromagnetic energy can be passively collected by a remote sensing tool.
- Data is gathered systematically by remote sensing devices. This systematic data collection helps to lead an impartial sampling method in some in-situ investigations.
- Remote sensing methods provide essential biophysical information, such as x,y location, z elevation or depth, biomass, temperature, and moisture content. Remote sensing data features systematic information over very large geographic areas. What is most crucial, this data is helping to contrast well-based modeling of several (water supply estimation, eutrophication studies, nonpoint source

pollution) and cultural (land-use conversion at the urban panorama, water demand estimation, population estimation) processes.

On the other hand, even though there is a range of remote sensing techniques, it also shows some limitations related to their instrumental and usage issues:

- Remote sensing techniques facilities can be overvalued. In fact, they provide some spatial, spectral, and temporal information, but they do not conduct any physical, biological, or social science research. Additionally, the nature of available remote sensed images (spatial and temporal resolution) could limit a sustainable and accurate data gathering process. In the case of the AdM wetland, the area usually is highly-cloud presence characteristic, which difficult the optical reach of the remote sensing instruments.

- The human method-produced error can occur because of the specification of remote sensing instrument and mission parameters

2.3.1 Multispectral scanning systems

Many remote sensing systems record energy over several separate wavelengths ranges at various spectral resolutions. These are referred to as multi-spectral sensors. Advanced multi-spectral sensors called hyperspectral sensors, detect hundreds of very narrow spectral bands throughout the visible, near-infrared, and mid-infrared portions of the electromagnetic spectrum. Their very high spectral resolution facilitates fine discrimination between different targets based on their spectral response in each of the narrow bands (Canada Centre for Remote Sensing, 2013). In the case of multispectral scanning systems, it is defined as the collection of reflected, emitted, or back-scattered energy from an object or area of interest in multiple bands (regions) of the electromagnetic spectrum. Most of the multispectral remote sensing systems collect data in a digital format. An overview of how digital remote sensor data are turned into useful information is shown in Fig. 2.3. When we work with digital images, the data is telemetered to Earth receiving stations directly or indirectly via tracking and data relay satellites (TDRS). In either case, it may be necessary to perform some radiometric or geometric processing of the digital remotely sensed data to improve its interpretability (Jensen, 2015).

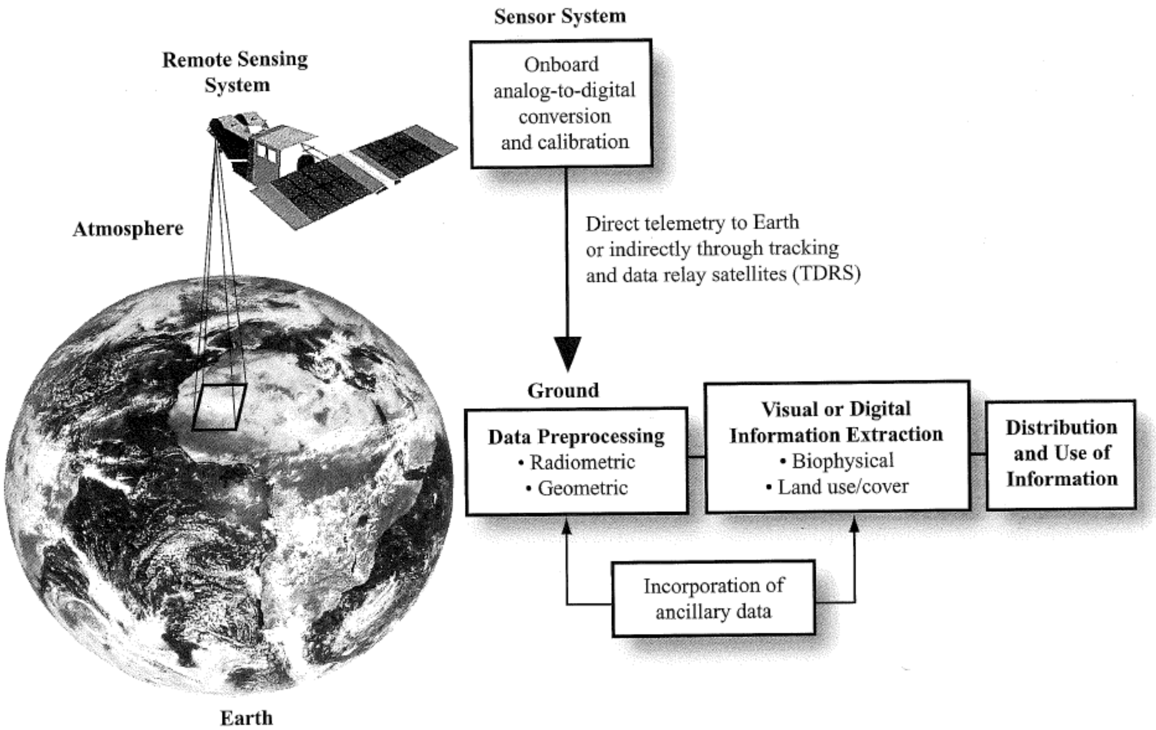


Fig. 2.3 An overview of the way digital remotely sensed data is transformed into useful information. The data recorded by the detectors are often converted from an analog to a digital value and calibrated. Ground processing removes geometric and radiometric distortions. This may involve the use of ephemeris or ancillary (collateral) data such as map x,y coordinates, a digital elevation model, etc. (Jensen, 2015).

2.3.2 The remote sensing processes

Spatially distributed data is fundamental for ecological, urban and land-use change modeling. Both, urban planners (e.g., land use, transportation, utility) and natural resource managers (e.g., wetlands, forest, grassland, rangeland) recognize remote sensing techniques benefits (Johannsen *et al.*, 2003). The remote sensing data collection and analysis procedures are named the remote sensing process. The procedures in the remote sensing process are summarized here (Jensen, 2015):

- A hypothesis is defined using a specific type of logic (e.g., inductive, deductive) and an appropriate processing model (e.g. deterministic, stochastic).
- In some cases, additional information (in-situ or secondary data) of the object (area) is previously collected: its geometric, radiometric, and thematic characteristics

- Passive or active Remote sensor data is gathered using digital remote sensing instruments.
- Previously collected data are processed with the following techniques: a) image processing, b) digital image processing, c) modeling, and d) n-dimensional visualization.
- Once the metadata and the processing lineage information is verified, the results can be transferred through images, graphs, statistical features, GIS databases, etc.

In the data collection phase previously described, it is important to remark on our two options in order to extract the information. The first is based on a quantitative analysis of each pixel of the image, and the second lies in a visual interpretation or photointerpretation, where the knowledge and experience of the analyst play a key role. In our case study, AdM wetland territory, the data collection will be conducted by quantitative analysis. The success of the quantitative analysis depends on the information provided in the key stages by the analyst (Richards and Jia, 2006).

To sum up, the techniques of quantitative analysis of digital classification, are carried out in four phases: statement of the problem, data collection, data-to-information conversion and information presentation (Table. 2.1). The first phase defines the hypothesis in the case it is needed and it is chosen the appropriate logic conduction of the research. The second step determines if the data collection will be in-situ or remote sensing data. The third phase identifies and characterizes the categories of interest and focuses on the grouping of the pixels of the image in one of those categories (Chuvieco, 2008), and finally in the information/presentation phase the precisions of the classifications are calculated through an accuracy assessment process and final products are delivered. (Congalton, 1991).

Statement of the Problem	**Data Collection**	**Data-to-Information Conversion**	**Information Presentation**
Formulate Hypothesis (if appropriate)	In Situ measurements: - Field - Laboratory	Analog image processing	Image Metadata: - Sources - Processing lineage
Select appropriate logic: - Inductive - Deductive - Technological	Collateral data: - Digital elevation models - Soil maps - Population density, etc.	Digital image processing: - Preprocessing: radiometric and geometric correction. - Enhancement. - Photogrammetric analysis - Parametric (e.g. max. likelihood) - Nonparametric (e.g. artificial neural networks) - Nonmetric (e.g. decision-tree cl., machine learning) - Hyperspectral analysis - Change detection - Modeling - Scientific geo-visualization	Accuracy Assessment: - Geometric - Radiometric - Thematic - Change detection
Select the appropriate model: - Deterministic - Stochastic	Remote sensing: - Passive analog - Passive digital: frame camera, scanners (multispectral, hyperspectral), linear and area arrays (multispectral, hyperspectral) - Active: microwave (RADAR), laser (LIDAR), acoustic (SONAR)	Hypothesis testing (if appropriate)	Digital: - Images (unrectified, orthoimages). - Orthophoto maps - Thematic maps - GIS databases
			Statistics: - Univariate - Multivariate
			Graphs

Table. 2.1 The remote sensing process. (Jensen, 2015).

2.3.3 Remote sensing collection

Remote sensing is carried out through sensors, instruments capable of detecting the electromagnetic signal (reflected or emitted radiation) that reaches them from Earth and the atmosphere and converts them into a physical quantity that can be treated and recorded. The sensors convert the EMR into a digital (image) format. The characteristics of the recorded image depend to a great extent on the properties of the sensor used and the distance to the ground from which the data acquisition is carried out (Sobrino *et al.*, 2000). Remote sensing sensors measure electromagnetic radiation in different bands of the electromagnetic spectrum of the terrestrial cover. This information is captured as an image from orbiting satellites (passive or active satellites) around the earth. The image is a two-dimensional representation of objects in a real scene. Remote sensing images are representations of parts of the earth's surface as seen from space. The images are always displayed in a digital format. Aerial photographs are examples of analog images while satellite images acquired using electronic sensors are examples of digital images (CRISP, 2011). In the case of satellite images, these are acquired through sensors, susceptible to detect EMR reflected or emitted radiation), located on platforms to carry out the observation of the terrain. It is called an electromagnetic spectrum to the energy distribution of all electromagnetic waves (Fig. 2.4).

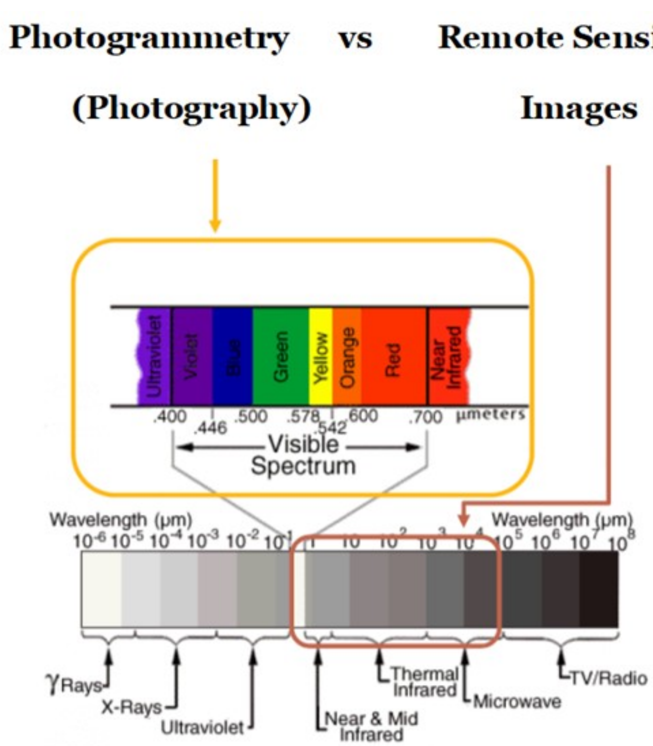


Fig. 2.4 Differences between photogrammetry and remote sensing images. (NASA, 2017)

Nowadays, there are several operational missions that capture information from space, which can be divided according to their application. On the one hand, there are the meteorological satellites, which focus on meteorological prediction topics, such as the GOES (Geostationary Operational Environment Satellite) series, the Meteosat satellite, etc. Furthermore, those responsible for monitoring natural resources are the satellites of the LANDSAT programs, SPOT (*Systeme Pour la Observation de la Terre*), IRS (Indian Remote Sensing Satellite), among others. Additionally, the satellites dedicated to oceanographic studies are Seasat, Nimbus 7, etc., and finally, there are those missions dedicated to the scientific aspect or with very high-resolution sensors (Sobrino *et al.*, 2000).

2.4 Land-use and land-cover approach and its application

Before starting with the description of the tools used to delimit the units of the land cover of this research, we establish a definition of what land cover is. It is well-defined as is the (bio) physical coverage that is observed on the surface of the Earth (FAO, 2009). It has also been conceptualized as an all-natural or artificial physical material that is found on the earth's surface (De la Rosa, 2008). Even though both concepts comprehend a similar statement about land cover, it highlights the importance of its analysis in terms of planning and modeling LU/LC change (Townsend *et al.*, 1992; Belward, Estes and Kline, 1999). Table. 2.2 shows a list of selected biophysical variables that can be remotely sensed and some useful sensors to acquire LU/LC data. Great strides have been made in remotely sensing many of these biophysical variables. They are important to the national and international efforts underway to model the global environment (Jensen, 2015).

Selected Hybrid Variables	Potential Remote Sensing System
Land Use	
-Commercial, residential, transportation, utilities, etc. -Cadastral -Tax Mapping	- Very high spatial resolution panchromatic, color and/or CIR stereoscopic aerial photography, high spatial resolution imagery (IKONOS, Quickbird, OrbView-3), SPOT (2.5.m), LIDAR, high spatial resolution hyperspectral systems (e.g. AVIRIS, HyMap, CASI)
Land Cover	
-Agriculture, forest, urban	- Color and CIR aerial photography, LANDSAT (MSS, TM, ETM), SPOT, ASTER, AVHRR, RADARSAT, IKONOS, Quickbird, Orb View-3, LIDAR, IFSAR, SeaWiFS, MODIS, MISR, hyperspectral systems (e.g. AVIRIS, HyMap, CASI)
Vegetation	
-Stress	- Color and CIR aerial photography, LANDSAT (TM, ETM), IKONOS, Quickbird, Orb View-3, AVHRR, SeaWiFS, MISR, MODIS, ASTER, airborne hyperspectral systems (e.g. AVIRIS, HyMap, CASI)

Table. 2.2 Biophysical and selected hybrid variables and potential remote sensing systems used to obtain LU/LC information. Adapted from (Jensen, 2015)

The use of the land implies the current use of the land, whether agricultural or not, where the land is located. The use of land has a great influence on the direction and the rate of soil formation; its registration considerably enhances the interpretative value of the soil data. For arable land, it should be mentioned the following characteristics: types of crops, soil management, fertilizer use, duration of fallow periods, rotation and yield systems (FAO, 2009). In the case of Ecuador, the land use panorama shows a high proportion of forest cover, occupying approximately 51% of the continental surface of the country (MAE-MAGAP, 2015).

2.4.1 Satellite images: LU/LC classification legends

The term "legend" implies the application of a systematic scheme. This scheme consists of the definition of every land area, where it also comprises its scale and data (aerial photographs or satellite images) to be used. When the research infers working with larger scales, classification legends with greater detail are required (Chuvieco, 2008).

In Ecuador, the projects developed by the Ministry of Agriculture, MAGAP and the MAE such as national thematic gathering information and the map of coverage and land use, apply a legend structured by levels, starting from a general level that follows the guidelines of the IPCC

(Intergovernmental Panel on Climate Change). The subsequent levels represent classes in a more specific detail that maintain coherence with the upper class (MAE-MAGAP, 2015). Based on this, the thematic legend was elaborated for the analysis of the study area of the Municipal Association for the Sustainable Management of the AdM wetland territory. Therefore, three legends levels were adapted to 1:50.000 scale.

- It has been taken as a reference to the legend used by the MAGAP-MAE, which is classified into four levels, where level I represents the categories defined by the IPCC.
- On the other hand, level II has been defined based on thematic information of coverage and land use, (legend compatibility for scales 1: 100,000).
- Finally, the levels III and IV, represent more detailed classes that maintain consistency with the definitions of the upper classes, which is effective for scales 1: 50,000 and 1: 25,000, respectively. In our case, the final scale is 1:50.000.

The selection of which scale it would be suitable for this research was based on the spatial resolution and the minimum mapping unit (MMU), especially when it comes to working with LANDSAT images with a resolution of 30 m. For this reason, it has not been included in the following MMU units at different scales (Table. 2.3). In addition, the classes with surfaces lower than 0.01% were not considered due to their scarce representativeness in the study area. Finally, the categories which were associated were not considered so a greater benefit will be reached during the digital classification process.

MMU units	Scale
‹ 0.3 Ha.	1: 25,000
‹ 1.25 Ha.	1: 50,000
‹ 5 Ha.	1: 100,000

Table. 2.3 MMU not included in this research at different map scales. (Lencinas and Siebert, 2009).

Due to the previous alignments, the thematic legend at a scale 1: 50,000 with three levels at a hierarchical order, has been elaborated and represented in Table. 2.4.

Level I	Level II	Level III	Land Use
Forest	Native Forest	Rain Forest	Conservation and protection
		Dry Forest	
	Forestry Plantation	Balsa Wood	Protection or Production
		Bamboo Cane	
		Pachaco	
		Teak Wood	
Shrubby and Herbaceous Vegetation	Shrub Vegetation	Wet Scrubland	Conservation and protection
		Dry Scrubland	
	Herbaceous Vegetation	Dry Herbaceous Vegetation	Conservation and protection
		Wet Herbaceous Vegetation	
Agricultural Land	Annual Crop	Cereals	Agricultural
		Vegetables	
		Legumes	
		Oilseeds	
		Roots and tubers	
	Semi-Permanent Crop	Fruit Trees	
		Industrial Crops	
	Permanent Crop	Fruit Trees	
	Pasture	Natural Pasture	Livestock
Anthropogenic Area	Populated Area	Populated Area	Anthropogenic
No Information	-----	-----	Clouds

Table. 2.4 Coverage and land use legends at 1: 25,000 scale. Based on MAE-MAGAP, 2015.

Additionally, the previous thematic legends are adaptable to 1: 50,000 (Table. 2.5) scale, at its hierarchical levels II and III, respectively.

Level I	Level II	Level III	Use
Forest	Native Forest	Rain Forest	Conservation and protection
		Dry Forest	
	Forestry Plantation	Forestry Plantation	Protection or production
Shrubby and Herbaceous Vegetation	Shrub Vegetation	Wet Scrubland	Conservation and protection
		Dry Scrubland	
	Herbaceous Vegetation	Herbaceous Vegetation	Conservation and production
Agricultural Land	Crops	Cereals	Agricultural
		Fruit Trees	
		Vegetables	
		Legumes	
		Oilseeds	
		Roots and tubers	
		Industrial Crops	
	Pasture	Cultivated Pasture	Livestock
Anthropogenic Area	Anthropogenic Area	Anthropogenic Area	Anthropogenic
No Information	-----	-----	Clouds

Table. 2.5 Coverage and land use legends at 1: 50,000 scale. Based on MAE-MAGAP, 2015.

2.5 LANDSAT (ETM+) and SENTINEL-2 images

Digital data can be used for biophysical, land-use, or land-cover analysis, which are the assets we will be using in both case studies of this research. Multispectral imaging using discrete detector ad scanning mirrors collection has been used in this research, such as:

- LANDSAT 7 Enhanced Thematic Mapper Plus (ETM+), and
- SENTINEL - 2

2.5.1 LANDSAT images

This section relays in the LANDSAT Program, which is constituted in a series of earth observation missions by satellite managed jointly by NASA and the United States Geological Survey (USGS) since 1972. The program is the longest historical data series designed and operated to repeatedly observe the earth's cover with a moderate resolution (IGAC-CIAF, 2013).

After 1992, the TM data started to be sensed by LANDSAT 4. Some of the advances in terms of collecting sensing data are higher spatial and radiometric resolution; finer spectral bands; seven spectral bands; and a rise in the number of detectors per band (16 for the nonthermal channels versus six for MSS). This increase improves the geometric and radiometric integrity of the data. Some of the features of TM data includes a spatial resolution of TM of 30 meters and a channel record capacity over a range of 256 digital numbers (8 bits). Table. 2.6 summarizes the spectral resolution of the individual ETM+ bands and some useful applications of each.

Band	Wavelength Range (μm)	Useful for mapping
Band 1	0.45 - 0.52 (blue)	Bathymetric mapping, distinguishing soil from vegetation and deciduous from coniferous vegetation
Band 2	0.52 - 0.60 (green)	Emphasizes peak vegetation, which is useful for assessing plant vigor
Band 3	0.63 - 0.69 (red)	Discriminates vegetation slopes
Band 4	0.76 - 0.90 (near infrared)	Emphasizes biomass content and shorelines
Band 5	1.55 - 1.75 (Short-wave infrared)	Discriminates moisture content of soil and vegetation; penetrates thin clouds
Band 6	10.4 - 12.5 (Thermal infrared)	Thermal mapping and estimated soil moisture
Band 7	2.09 - 2.35 Short-wave Infrared	Hydrothermally altered rocks associated with mineral deposits
Band 8	052 – 0.90 Panchromatic	A 15-meter resolution, sharper image definition

Table. 2.6 LANDSAT 7 Enhanced Thematic Mapper Plus (ETM+) system bands. (Canada Centre for Remote Sensing, 2013).

The LANDSAT series has been used in this research, specifically LANDSAT ETM+, through a serial-temporary data of our area of interest (AdM wetland territory) obtained from its sensors (Fig. 2.5).

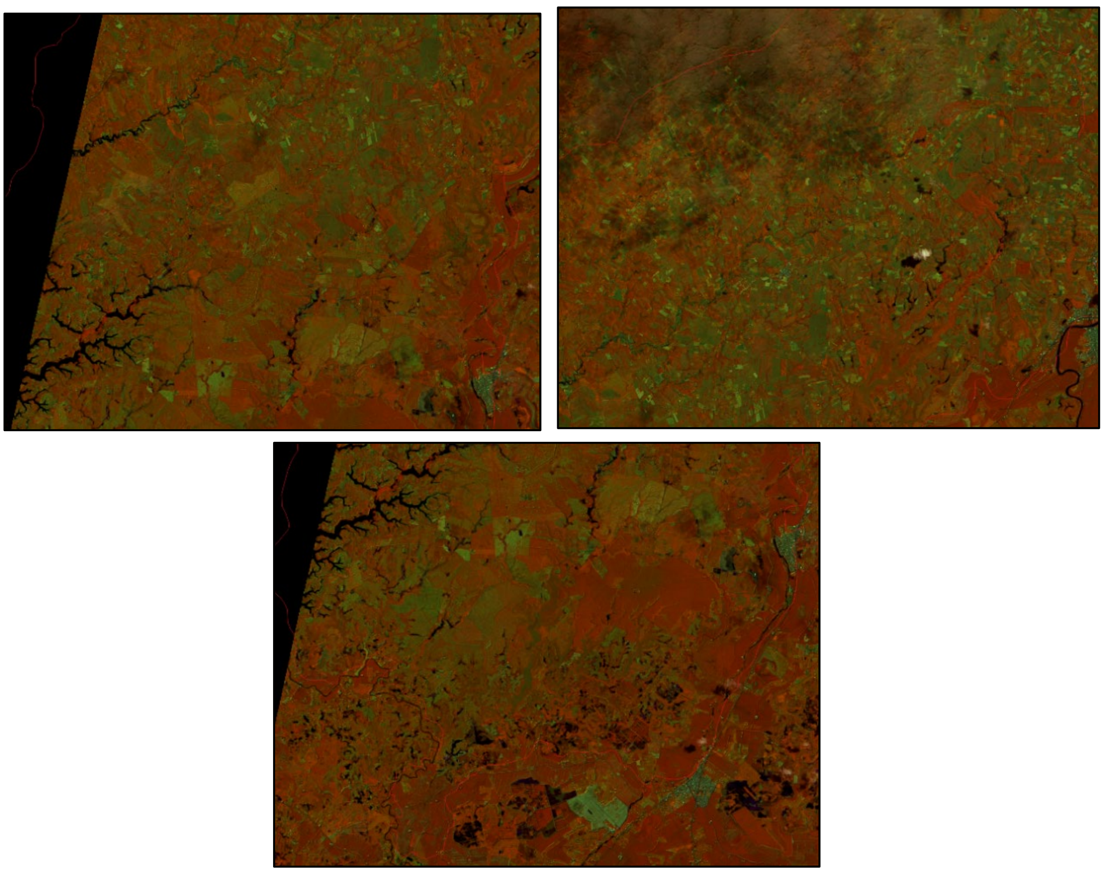


Fig. 2.5 LANDSAT ETM+ images of AdM wetland territory, with a 4-5-3 RGB combination for visualizing land cover related to farmland. Using a spatial resolution of 30 meters. Date: 06-09-2015.

LANDSAT success has been due to several factors, including a combination of sensors with spectral bands tailored to Earth observation, functional spatial resolution and good areal coverage (swath width and revisit period). The long lifespan of the program has provided a voluminous archive of Earth resource data facilitating long term monitoring and historical records and research. All LANDSAT satellites were placed in near-polar, sun-synchronous orbits. The first three satellites (LANDSAT 1-3) were at altitudes around 900 km and had revisit periods of 18 days while the later satellites were at around 700 km and had revisit periods of 16 days. All LANDSAT satellites have equator crossing times in the morning to optimize illumination conditions. Based on the characteristics of the program, it can be divided into two generations. The first one corresponds to the LANDSAT 1, 2 and 3 satellites, which were in a Heli synchronous polar orbit, with an inclination of 99º, at 920 km of height, and they swept the Earth in 18 days. The second generation began with the launch of LANDSAT 4, at an altitude of 705 km, with an inclination of 98º, a periodicity of 16 days and a notorious development in terms of technology (Sobrino *et al.*, 2000). Table. 2.7, specifies the spectral bands and the wavelength (λ of the second-generation satellites (LANDSAT 7 and 8), which have been incorporated in this research.

LANSAT 7 – Enhanced Thematic Mapper (ETM+)		**LANDSAT 8 – Operational Land Imager (OLI)**	
Bands	**λ (μm)**	**Bands**	**λ (μm)**
Band 1 (blue)	0,45 – 0,52	Band 1 – Coastal aerosol	0.433–0.453
Band 2 (green)	0,53 – 0,61	Band 2 (blue)	0.450–0.515
Band 3 (red)	0,63 – 0,69	Band 3 (green)	0.525–0.600
Band 4 (near infrared)	0,76 – 0,90	Band 4 (red)	0.630–0.680
Band 5 (mid-infrared)	1,55 – 1,75	Band 5 (near infrared)	0.845–0.885
Band 6 (thermal infrared)	10,4 – 12,5	Band 6 – SWIR 1	1.560–1.660
Band 7 (mid-infrared)	2,09 – 2,35	Band 7- SWIR 2	2.100–2.300
Band 8 (panchromatic)	0,52– 0,90	Band 8 (panchromatic)	0.500–0.680
		Band 9 (cirrus)	1.36-1.38

Table. 2.7 Spectral bands used by LANDSAT 7 (ETM+) and 8 (OLI). (USGS, 2019).

Fig. 2.6 shows some common RGB combinations for visualizing various vegetation composites. The first image is true-color visualization (3,2,1 in L7 is the approximate range of vision of human eye); the second image is a near-infrared composite (4,3,2 in L7 permits visualize vegetation in red and water bodies in black). The other two images are other infrared composite options, depending on what is the visualization objective.

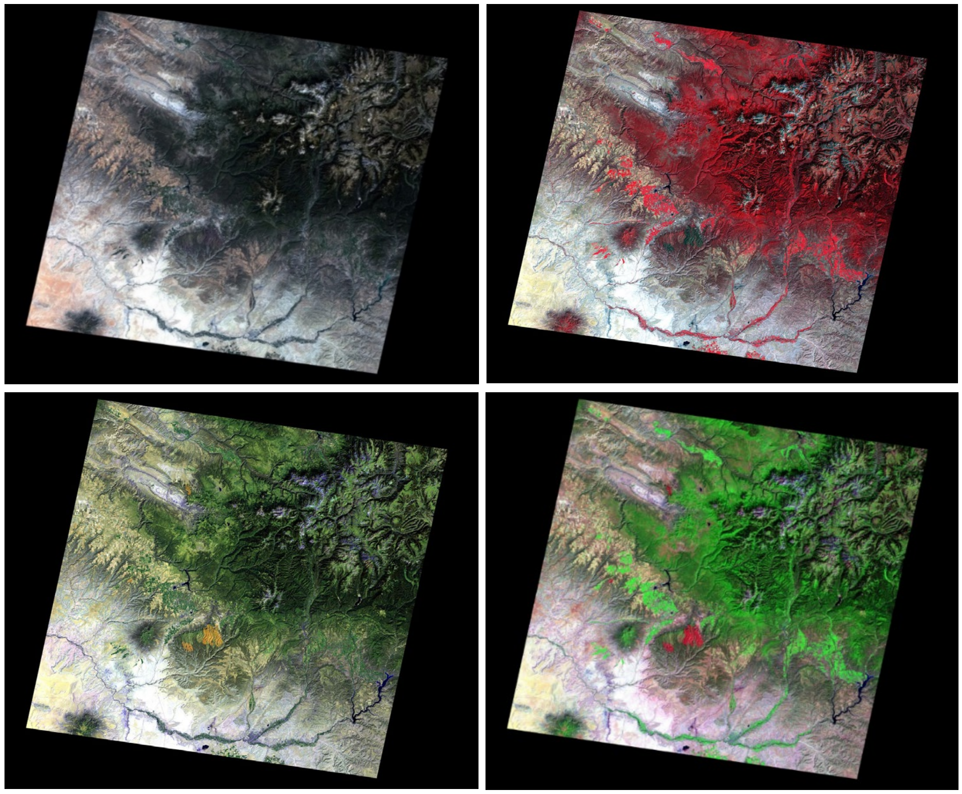


Fig. 2.6 Common RGB combinations for visualizing various vegetation composites in the image LANDSAT 7, Path 35 Row 34. Date: 09-12-00 (NASA, 2014).

2.5.2 SENTINEL – 2 images

In addition to LANDSAT ETM+, we also have used SENTINEL – 2 images of the AdM wetland, from its corresponding mission which owns the same name. Their two satellites provide multi-spectral imaging for the mapping of land-cover, classification and changing maps. They also permit the accurate assessment of bio-geophysical parameters such as Leaf Area Index (LAI) and Leaf Chlorophyll Content (LCC). The collected data from their bands (Table. 2.8) and the high-revisit frequency of 5 days at the Equator, covers a range of remotely sensed information at local, regional, national and international scales. The SENTINEL-2 data is designed to be modified and adapted by users interested in thematic areas such as spatial planning, agro-environmental monitoring, water monitoring, forest, and vegetation monitoring, land carbon, natural resource monitoring, and global crop monitoring. (European Space Agency, 2015)

Band number	Spatial Resolution	Central wavelength	Bandwidth	Lref (reference radiance) (W m-2 sr-1 μm-1)	SNR @ Lref
2	10 m	490	65	128	154
3	10 m	560	35	128	168
4	10 m	665	30	108	142
8	10 m	842	115	103	172
5	20 m	705	15	74.5	117
6	20 m	740	15	68	89
7	20 m	783	20	67	105
8b	20 m	865	20	52.5	72
11	20 m	1610	90	4	100
12	20 m	2190	180	1.5	100
1	60 m	443	20	129	129
9	60 m	945	20	9	114
10	60 m	1375	30	6	50

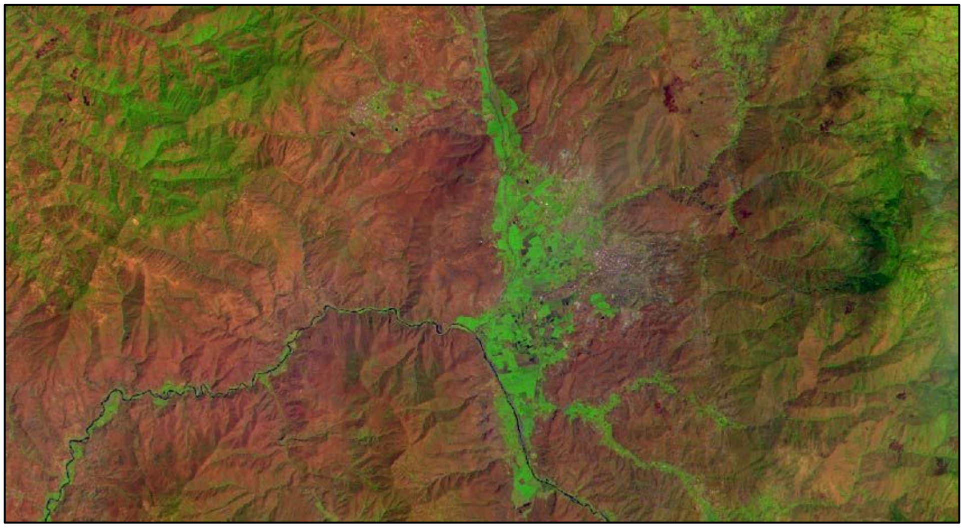
Table. 2.8 SENTINEL – 2 system bands at 10 m, 20 m and 60 m spatial resolution and their associated Signal to Noise ratio (SNR) (European Space Agency, 2015)

SENTINEL - 2 images are available since 2015, and with a resolution of 10, 20 and 60 meters. In Table. 2.9, there are some examples of the most common RGB combinations of the SENTINEL – 2 spectral bands in the red (R), green (G) and blue (B) channels.

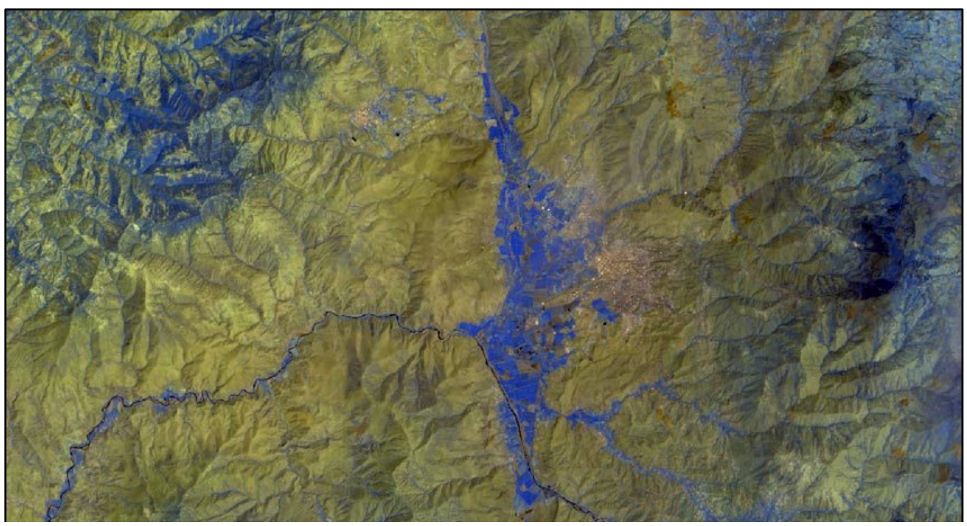
RGB combinations	R	G	B
Natural colours	4	3	2
False-colour infrared	8	4	3
False-colour urban	12	11	4
Agriculture	11	8	2
Atmospheric penetration	12	11	8a
Healthy vegetation	8	11	2
Land / water	8	11	4
Natural colours with atmospheric removal	12	8	3
Shortwave infrared	12	8	4
Vegetation analysis	11	8	4

Table. 2.9 RGB combinations used in SENTINEL – 2. (European Space Agency, 2015)

In Fig. 2.7 (a) and (b), we show two examples of combinations for atmospheric penetration (12-11-8a) and agriculture (11-8-2) from Catamayo city, located in the province of Loja, Ecuador.



(a)



(b)

Fig. 2.7 (a) Atmospheric penetration SENTINEL 2A (12 11 8a). (b) Agriculture SENTINEL 2A (11 8 2). Catamayo, Loja, Ecuador. Date: 18-11- 2017. (https://scihub.copernicus.eu/dhus/#/home)

2.6 Digital image pre-processing

In order to eliminate existing anomalies in the digital images, it is necessary to apply certain corrections, which allow data to be settled in the best possible way to a suitable analysis (Chuvieco, 2008). Most of the digital image processing (radiometric and geometric correction) consists of pattern recognition, image enhancement, neural network image analysis, and others. Therefore, a sequence of techniques aimed at achieving this purpose and putting into practice in our case study, AdM wetland territory, are presented below.

2.6.1 Radiometric correction and reflectance values

It is concerned about improving the accuracy of surface spectral reflectance, or back-scattered measurements obtained using any remote sensing system. This correction step is called preprocessing operations as well as geometric correction because they must be applied before the information extraction procedure. Some errors or noise contained in the digital remotely sensed imagery is related to electronic noise (internal error) or atmospheric scattering of light into the sensor´s field of view (environmental noise) (Jensen, 2015). The satellite images process starts when the energy reflected/emitted by the surface of Earth is measured at a distance by a sensor. Later, this data is encoded to numerical values or digital counts (DC) by using calibration coefficients. Thereby, the inverse process is applied with the objective to gather its coefficients permitting to obtain the radiance values (W m-2 sr-1 µm-1). These values, also called physical magnitudes, are compared with data from the same sensor or from the different scanning sensed imagery techniques over time (Chuvieco, 2008).

Radiometric corrections are necessarily a preprocess step before LULC classification and change detection. One of the noise elements that affect satellite images is reflectance of the terrain surface, specifically the bidirectional reflectance factor (BRF) of objects on the earth's surface. Therefore, it exists some models and theories of radiometric correction related to reflectance calculations. For example, it has been specifically developed an algorithm for surface reflectance valuation from LANDSAT Thematic Mapper (TM) over rugged terrain using the bi-directional reflectance distribution function (BRDF) and a radiative transfer´s model (Chen and Cheng, 2012). The reflectivity or reflectance surges from a dimensionless interaction between the energy reflected by any material and the incident energy. This interaction data captured by the sensor usually varies in a spectral range between 0, 3 and 3 µm (Sobrino *et al.*, 2000). This variable is acquired by using Top of Atmosphere (TOA) reflectance value. This means not considering the disturbances caused due to atmospheric effects, but using TOA parameters such as solar extraterrestrial irradiance ($E_{o,k}$), solar zenith angle (θ_i) and the Earth-Sun distance corrector factor (D) (Jensen, 2015). The atmosphere interposed between the surface and the sensor alters the signal, which makes dispersion controls the near-infrared visible spectrum. Thus, it is necessary to minimize this effect through radio-soundings, the usage of images for estimating the state of the atmosphere, physical models of radiative transfer or from the same image (Chuvieco, 2008). We have considered applying the last method based on Chavez (1996) work, whereby it is presumed those strong absorptivity zones should present zero-degree radiances (2.2):

$$\rho_{sup,k} = \frac{D\pi\left(L_{sen,k} - L_{a,k}\right)}{E_{o,k}\cos\theta_i\,\tau_{i,k}} \tag{2.2}$$

where $\rho_{sup,k}$ corresponds to surface reflectivity for the band k. $L_{a,k}$ is the radiance path, which can be estimated by the difference between the minimum radiance and $L_{1\%,k}$, the radiance at 1%, the first refers to the minimum radiance value for each band and the second is obtained by 2.3, and finally $\tau_{i,k}$ represents the descending atmospheric transmissivity:

$$L_{1\%,k} = \frac{0.01E_{o,k}\cos\theta_i\,\tau_{i,k}}{D\pi} \tag{2.3}$$

With the purpose of achieving the reflectance values at AdM images, it has been used FLAASH-ENVI's (Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubes) tool. The parameters for ENVI FLAASH include selecting an input radiance image, setting output file defaults, entering information about the sensor and scene, selecting an atmosphere and aerosol model, and setting options for the atmosphere correction model. In Fig. 2.8, the input parameters settings for the described territory are described in the following sections.

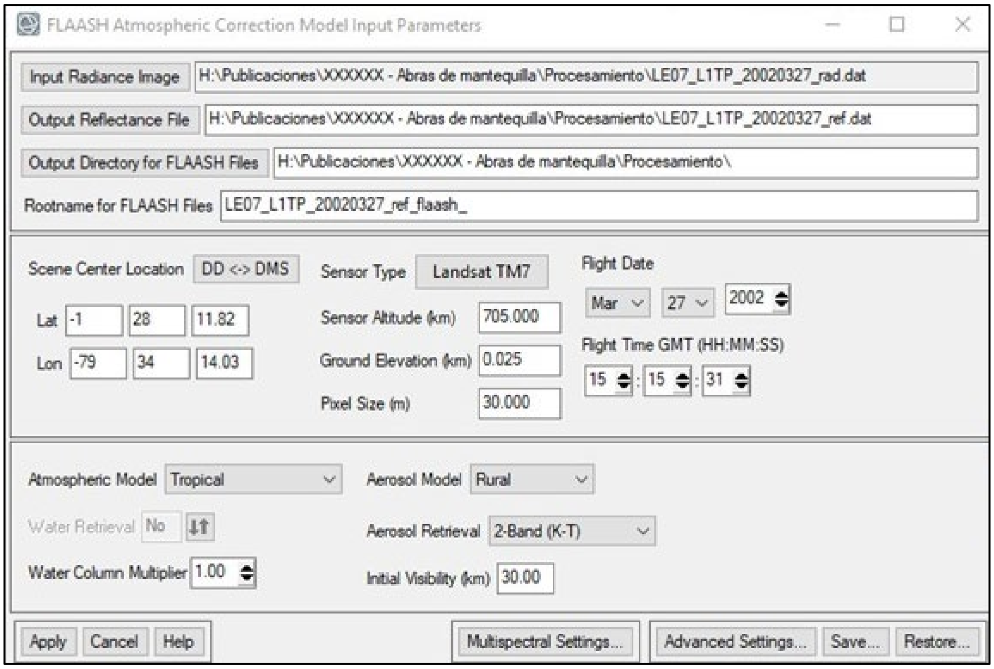


Fig. 2.8 FLAASH Atmospheric corrections model input parameters for area of interest: AdM wetland territory image.

2.6.2 Atmospheric correction

The purpose of this preprocessing step is to do an atmospheric correction with the objective to make a quantitative analysis. This correction transforms the radiance values in reflectance. Reflectance is the radiance proportion that strikes on a surface to the reflected radiation outside it. This means the image is in percentage values. Some materials can be identified by their reflectance spectra, so it is common to correct a reflectance image as a first step towards locating or identifying characteristics of an image (classification process). To transform radiance into reflectance it is necessary to relate the radiance values (the digital values of the pixels) with the radiance with which the object is illuminated. This is done by applying an atmospheric correction to the image, as the impact of the atmosphere on the radiance values is eliminated at the same time (Fig. 2.9) (MAE-MAGAP, 2015).

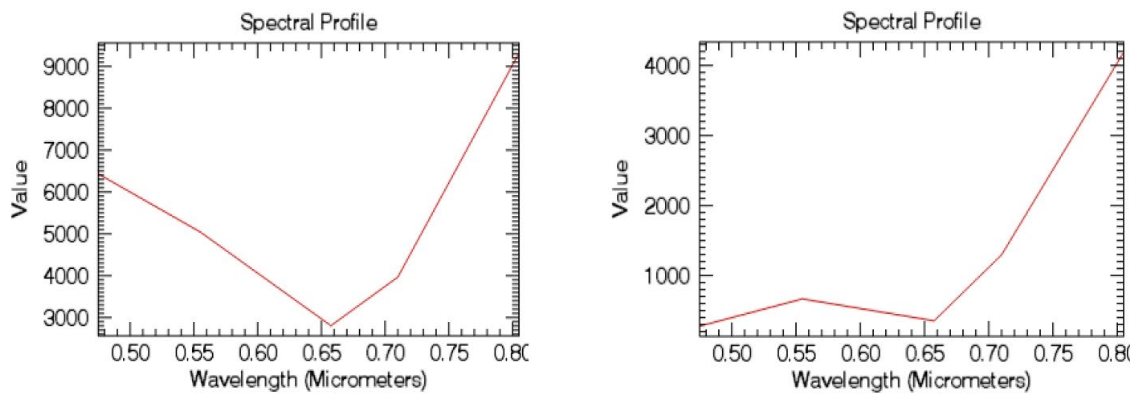


Fig. 2.9 Radiance vs reflectance in a vegetation spectral profile. The first (left) figure has no atmospheric correction. The second (right) figure is an atmospheric corrected image. From (MAE-MAGAP, 2015)

To perform the atmospheric correction in AdM images, FLAASH has been used again, which permits correct images for atmospheric water vapor, oxygen, carbon dioxide, methane, ozone, and molecular and aerosol scattering using a MODTRAN 4+ radiation transfer code solution. The code is applied in each image and in each pixel in the image. This tool also delivers a column water vapor image, a visibility value for the scene and a cloud map.

2.6.3 Spectral reflectance curves

Spectral reflectance curves (or signatures) show the behavior of reflected electromagnetic radiation by any cover in the different ranges of the electromagnetic spectrum. The variability of the curves is subject to changes due to lighting conditions, phenological conditions, type of soil, etc., which makes it difficult to discriminate between different objects. Currently, there are various mechanisms for extracting the spectral signatures, by using a spectral library, like Aster. Fig. 2.10 represents an example of spectral signatures for different covers from the Aster Spectral library. Another example of the spectral percent reflectance curve for selected urban-suburban phenomena is shown in Fig. 2.11.

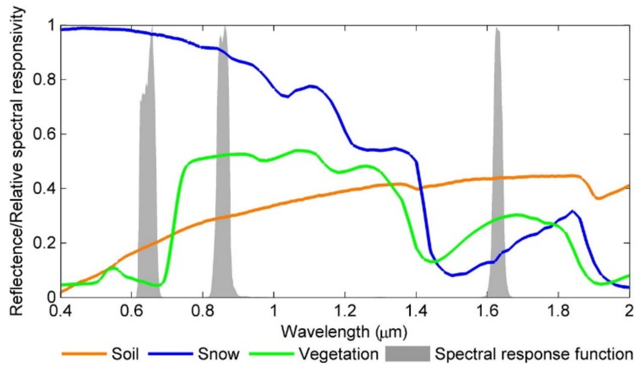


Fig. 2.10 Spectral reflectance curves from the Aster Spectral library and their spectral response function from MODIS, for the following covers: soil, snow, and vegetation. (Wang *et al.*, 2017)

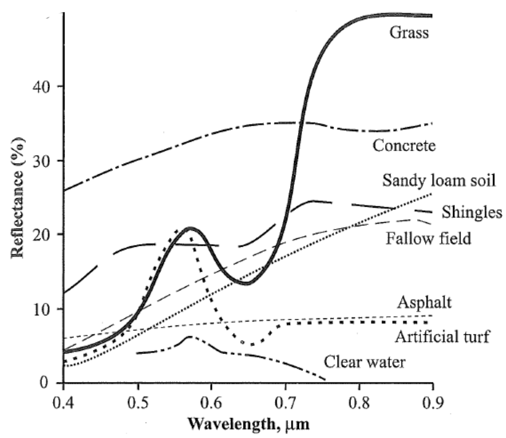


Fig. 2.11 Typical spectral reflectance curves for urban-suburban phenomena for selected material in the region 0.4 – 0.9 µm. Adapted from (Jensen, 2015)

Once the satellite images have been converted to reflectance images of the surface, it is necessary as a preliminary phase to obtain spectral signatures, which will be the inputs for the multispectral classification procedure. This process has been applied in AdM wetland territory images, with the aim of determining the training sites, run the test and ultimately obtaining vegetation cover and land use (LU/LC) for the years 2000, 2010 and 2018 (Fig. 2.12).

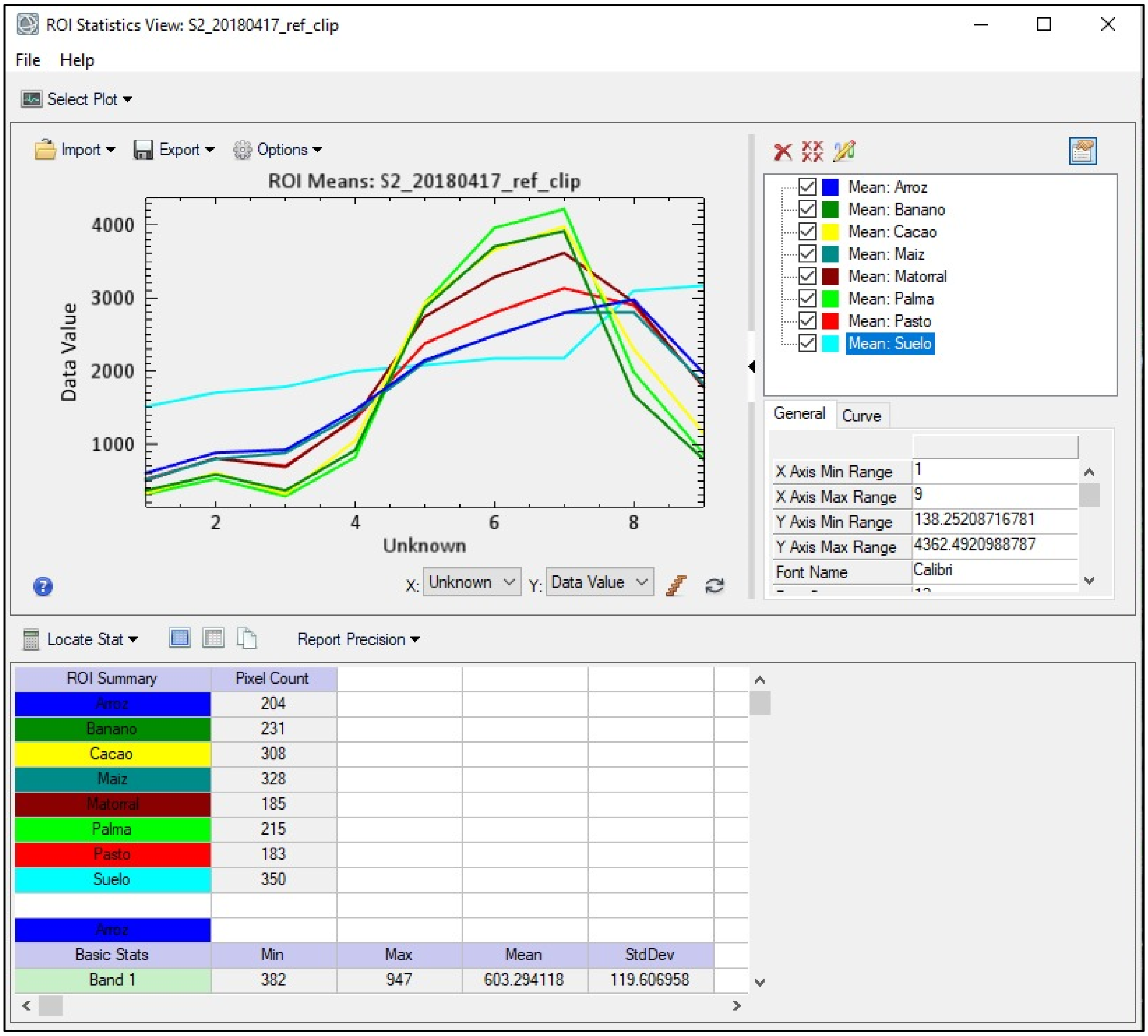


Fig. 2.12 Spectral curves for each LULC class obtained at the AdM wetland for the year 2018. The classes are rice, banana, cocoa, maize, scrubland, African palm oil, pastures, and other lands.

Images of surface reflectivity from the use of LANDSAT ETM + data, with a spatial resolution of 30 m have been obtained with GLOVIS[2] project (managed by NASA). The model was applied in scenes taken between 2000 and 2010, corresponding to the AdM wetland territory (The municipal association is integrated by five districts: Mocache, Ventanas, Puebloviejo, Vinces, and Baba). The

[2] The USGS Global Visualization Viewer (GloVis), managed by the NASA, has been available to users for accessing remote sensing data.

process flow to achieve this objective is based on a data calibration and calculation of TOA[3] reflectivity by using coefficients published by NASA, to then perform an atmospheric[4] correction using the MODIS methodology and the 6S radiative transfer code, in where variables such as the optical thickness of aerosols, ozone, water vapor, and atmospheric pressure are used. In our area of interest, we have faced limitations related to obtaining homogeneous time series with non-surface noise like changes in lighting and atmospheric effects. The application of this correction technique facilitates the mapping of land cover and the gathering of biophysical parameters of vegetation. In addition to this, a cloud mask is generated by the ACCA algorithm (Masek *et al.*, 2006) being very useful especially for those areas of the planet with a wide cloud cover, which is our case.

Complementarily, we have used a SENTINEL - 2 images for the year 2018 because of its good quality and recent availability. The images obtained by the SENTINEL - 2 satellites[5] have the possibility of being processed with its specific SNAP software. SNAP offers Sen2Cor component as a tool that offers excellent results in atmospheric and geometric correction of Sentinel satellite data. This is necessary when working with images released from atmospheric alterations or the presence of clouds, a process that was necessary to apply in the 2018-AdM wetland image.

2.7 Digital image classification

As we have previously premised through this chapter human activities have a great influence on any system or territory dynamics, as well these features are changing rapidly. This is the main reason why an accurate inventory of this land change information needs to be extracted from digital remote sensed data. Nowadays, the relevance of this study field is concerning more researches in fragile-dynamic systems, when it is believed that LU/LC change is the most spread component with a high impact on climate change. With the aim of elaborating diverse land cover cartography, the use of digital classification techniques is widely available as an alternative to run a visual interpretation of any object/area of interest. These techniques allow achieving a new digital image as a result. These new remote sensed items bring together all the data extracted from the original digital image RGB. What generates is a new scene named "thematic map", which

[3] TOA radiance is every light which reflects off the planet as seen from space measured in radiance units.
[4] It is assumed that the surface is Lambertian (energy reflected equally in all directions).
[5] It was launched by the Copernicus program of the European Space Agency (ESA)

could be a focus on forestry inventories, burnt areas in a specific region, water quality indexes, etc. (Sobrino *et al.*, 2000).

The extraction of this thematic remote sensed data implies integrate visual interpretation elements, such as identifying pictured-morphologic features in the image. These features comprise color, tone, texture, shape, context criteria, which define the conventional photointerpretation and the accuracy of the digital treatment of remote scanning data (e.g. geometric and atmospheric corrections, multispectral classification). Ideal cataloging involves a process where images present a bi-univocal interaction between informational c and spectral classes. The first ones are those the analyst pretends to detect according to his legend worksheet and the second ones are grouped with homogenous spectral values due to a similar reflectance among them, from the selected bands and for a specific date (Chuvieco, 2008).

On the other hand, there are two types of digital land cover classification.

- **Unsupervised classification**: When there is a lack of ground reference information or an inaccurate definition of surface feature within the scene, it is recommended to run an unsupervised classification with the aim of identifying land-cover types. The classes are assembled by similar spectral pixel´s characteristics, into unique clustering groups according to some statically determined criteria. Then they are relabeled and combine their spectral clusters into information classes (Jensen, 2015).

- **Supervised classification**: This process is based on the identification and location of land cover types such as agriculture, wetland, urban, etc., which is the result of various skills: fieldwork, interpretation of the analyst, map analysis and personal experience in the study area. The previous own- knowledge of our case study has permitted to locate specific sites in the sensed data, that are standardized samples of these land-cover types. The identified zones are denoted as "training sites" because the spectral features of these areas are used in the classification algorithm training process of the analyzed image. At the same time, multivariate statistical parameters are computed for all those training areas (e.g. means, standard deviations, covariance matrices, correlation matrices). Finally, every pixel that is located within or outside the referred training sites, is designated to the more similar-characterized specific class (Jensen, 2015).

The following subsection addresses issues related to obtaining training samples and supervised methods of digital classification, emphasizing those methods from ENVI software,[6] which have been applied in the collected sensed data of our case study.

2.7.1 Training sites data and testing process

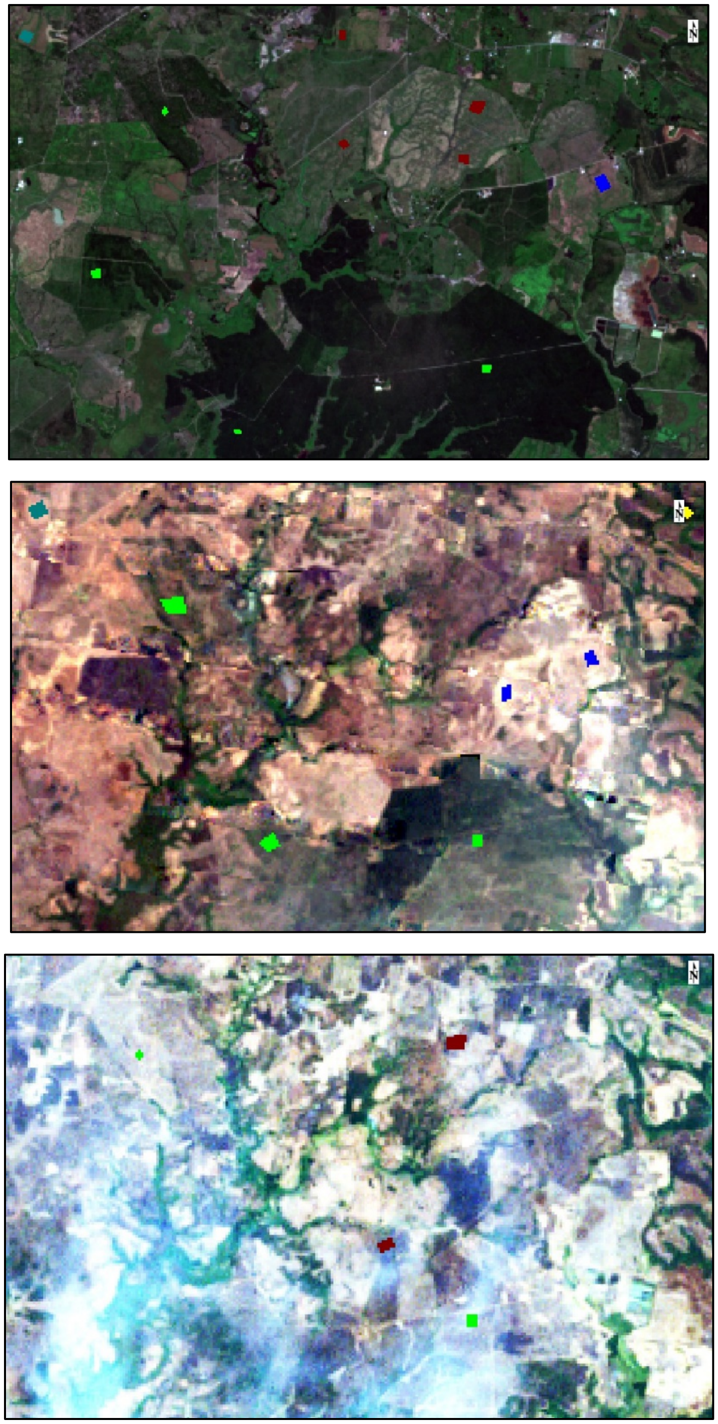
In this work, we have applied a supervised classification process based on the training sites designated by the MAGAP in 2010, as a reference for obtaining the "training sites" and being able to use them for the collected remote sensed data in the years 2000 and 2018. It has been accomplished the minimum number of pixels proposed by Jensen, 2015 and Congalton, 1991.

There are different ways to collect training site data. We have applied the *on-screen selection of polygonal training data, and /or on-screen seeding of training data*. The process resides in viewing the images on the color CRT screen and select polygonal regions of interest (ROI). Equally, it has been seeded a specific location in the images space and evaluated neighboring pixels' values in all bands of interest. Using the criteria on knowing the area of interest farmland mosaic, the seed algorithm expands if it finds pixel with spectral characteristics like the previously designated seed pixel. This procedure is considered very effective for collecting homogeneous training sites (Fig. 2.13).

[6] Specific software for the geospatial analysis and image processing. It is managed by Exelis Visual Information Solutions.

Fig. 2.13 Training sites scheme at the AdM wetland for the ROIs of the years 2000, 2010 and 2018.

When the ROIs are defined is important to consider their quantity, size and distribution features for a reliable classes' characterization. Also, when it approaches ROIs distribution is suggested to consider their own image features and adding the spatial variations of each class (e.g. density, orientation, pendent). It has been chosen a small size sample instead of an extended area size on the bases of which spectral separability analysis has been done. Thanks to the thematic cartography items elaborated by the IEE, MAGAP, and MAE; it enables to observe the spatial distribution of each class. Moreover, combination types such as SWIR, RED, and IRC, as visual support during the ROIs delimitation process (Fig. 2.14).



(a)

(b)

(c)

Fig. 2.14 Training sites gathering and ROIs delimitation testing process for the years 2000 (a), 2010 (b) and 2018 (c) done in ArcGIS software.

There are several methods for ensuring the accuracy of the ROIs selection process from the elemental reflectance curves graphic where bands are represented versus the average reflectivity values of each class. The accuracy process is relevant because, without this step, poorer classification accuracy can occur because of the large number of data bands and their inherent data noise, and limited training areas availability (Landgrebe, 2002)

The better option to diminish the biased classification process is to test the training sites calculating spectral separability. Separability indexes allow analyzing the significance of the distance between two samples for any pair of bands, which helps to evaluate which signatures are sufficiently viable to lead an accurate classification process. These indicators are obtained applying transformed divergence and Jeffries-Matusita mathematic calculations, which have been proven to be effective methods in order to evaluate vegetation, soil, land cover training sites, etc.(Landgrebe, 2005; Ustin *et al.*, 2009). Both methods have been applied in the remotely sensed image of the AdM wetland.

2.7.2 The neural networks classification technique

The aim of the neural network technique is to classify various types of remote scanning data which results sometimes are superior to those traditional statistical models. This classificatory enables us to simulates the thinking process of human brains through a multiple neuron interconnection to process income information. Among the advantages of neural networks applied in imagery data are a) normal distribution requirements flexibility and b) their adaptation to simulate the complexity of geographical and topographic assets which usually have nonlinear patterns.

The E (ANN) (Fig. 2.15), comprehends neurons organized into three categories of layer: an input layer, hidden layer (s) and an output layer. The input layer comprises data of individual training pixels like percent spectral reflectance in several bands and supplementary information related to slope, terrain elevation, texture, surface roughness, aspect, etc. Then, the connection interactions allow data to move into multiple directions, where backpropagation occurs and at the same time the network is trained. The weights of each of these interconnections are learned and stored in the hidden layer, with the purpose is to acquire a predicted value for every neuron in the output layer. Therefore, the output layer is consigned to an individual thematic maps class (e.g. agriculture, forest, moorland, water bodies). Natural networks technique has been applied during the classification procedure of the scenes taken between 2000 and 2018, corresponding to the study area of AdM wetland territory

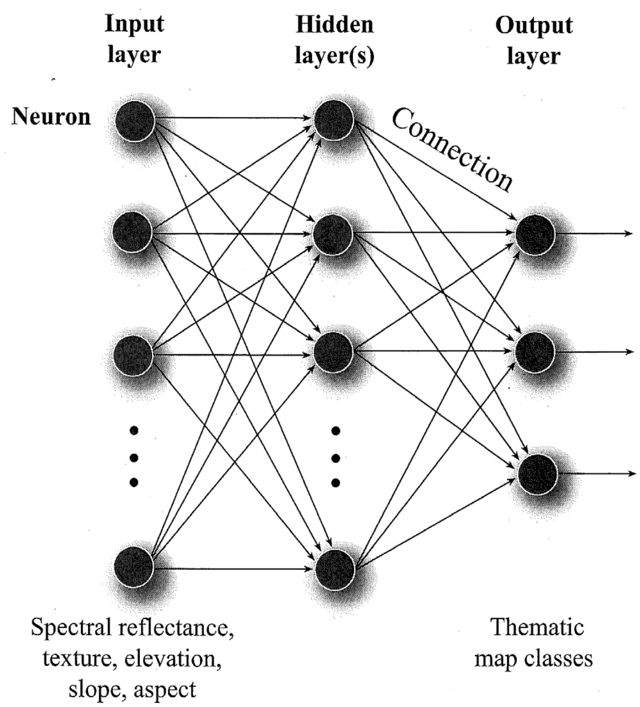


Fig. 2.15 Components of a typical back-propagation Artificial Neuronal Network (ANN) (Jensen, 2015).

2.7.3 Thematic map accuracy assessment

This step, also known as (outcome evaluation), is required as a protocol assessment, where a sampling frame is necessary to permit the reliability of the results obtained by comparing it with an external source. Therefore, the accuracy mapping process has been executed using the previous training sites. This phase is named the verification process. It is suggested to collect at least 50 pixels per category, and if the class surface is long, this number can be increased to 75 or 100 pixels. Regarding its distribution, it is advisable to use stratified random or simple random sampling

On the other hand, the method that has been used to validate the accuracy of our remote-sensing-derived thematic map of AdM wetland territory is design-based inference (statistical measurements) option. The design-based inference is those statistical principles that infer the statistical characteristics of a finite population based on the sampling frame. This accuracy statistical-based procedure is powerful because it provides unbiased map accuracy using consistent estimators. The most common estimator is the error matrix, which is expressed in the number of pixels or percentages, where its columns constitute the truth - ground data (Testing ROIs), while the rows, the values derived from the classification, and in the main diagonal are the successes obtained (Congalton, 1991). The error matrix can be used as a starting point to derive a series of statistical parameters, whereby the most common are overall accuracy (OA), kappa coefficient of agreement index (K), producer´s error, consumer´s error (CE) and omission errors (OE), which are estimators of reliability intervals, sensitivity, and specificity analysis, among others. The statistical measurements obtained from the thematic maps' error matrixes of our case study are described below.

- **Overall accuracy (OA).** It can be considered as the simplest descriptive statistic, which is obtained by the fraction between correctly classified samples and the total number of pixels in the error matrix. This estimator is not a point value but a confidence or reliability interval, the same that can be obtained under a level of significance.

- **Kappa coefficient of agreement index (K).** The K index measures the difference between the agreement and the one that could be expected through a random assignment, trying to delimit the degree of adjustment due only to the accuracy of the classification.

- **Producer´s error.** It is the probability of correctly labeling a pixel of the class Ci, instead, the **user's error** measures the probability that a pixel labeled in class Ci really corresponds to that class. Both errors have an inverse relationship with the **EO (false negatives)** and **EC (false positives)** respectively. In the case of those errors are low and similar, the classification can be considered as acceptable for the class Ci. On the other hand, if the error of omission exceeds the error of commission value, underestimations will predominate, and otherwise, overestimations will occur.

- Finally, **sensitivity** is the probability of identifying the interest class or positive cases, while specificity is the ability to discriminate in the study the unwanted classes or the true negatives.

2.8 Materials and methods

This research analyzes in time the spatial dynamics Land Use and Coverage (LULC) transformation for a period of 18years (2000-2018), through the digital processing of satellite images. Considering the conceptual framework of Ecosystem Services and LULC of our study area, it explicitly and cartographically identifies sites of importance in the territory in terms of their management and, at an evolutionary level, the analysis of statistical accuracy mapping data we found in the previous processed remote sensed information. The objective of this part of the research is the creation of a database that allows us to analyze, subsequently, the evolution of LULC at AdM wetland territory. It has also been obtained a database related to ecosystem services evolution and patterns (see Chapter 4) for an area of tropical forest on the Ecuadorian coast linked to the Guayas river basin, which includes the "Guayas" Ecosystem and the AdM wetland territory. To this end, two databases of different origin and spatial scales are created and used in a complementary way using information coming from:

- Vector information (i.e., shapefile) at the GE scale (see "Chapter 04").
- Satellite information (LANDSAT and SENTINEL - 2 images) at the AdM wetland territory scale. The training sites for this area were based on referenced thematic legend launched by the MAGAP in 2010 (at levels 1, 2 and 3).

This database should be able to allow:

1. The identification of the different vegetation covers and land uses in AdM wetland territory, as well as the analysis of the temporal evolution of its fragmentation/patchiness of both study areas, "Guayas" ecosystem and AdM wetland territory (see "Chapter 04"), in case there is one.
2. The development of a spatial and temporal model that allows the construction of a tool to support decisions regarding this space and its ecosystem services.

The future projection of the fragmentation trend in vegetation cover can be used in the possible scenarios that will allow establishing policies and actions for balanced territorial management. Finally, and as a secondary objective, we set out to show, in case there is one, the possible lack of coherence between the government data (referred to the EG) and those obtained at the satellite level (AdM wetland territory). Some of the inputs that will be considered in our research are shown below (Table. 2.10):

Input	Source	Scale	Date	Format
LANDSAT 7 image (ETM+ SLC-on)	USGS (GLOVIS[7])	30 m (PAN[8] 15 m)	2000-11-23	GeoTiff[9]
LANDSAT 7 image (ETM+ SLC-off)	USGS (GLOVIS)	30 m (PAN 15 m)	2010-10-02	GeoTiff
SENTINEL 2	ESA (Copernicus[10])	20 m	2018-04-17	GeoTiff
Land-use/land-cover map	MAGAP	1:25.000	2010	Jpg
Administrative Boundaries and case study limits	INEC (SNI[11]), CLIRSEN	1:50.000	2010/ 2012	Shp
Base geography map	IGM	1:50.000	14-01-2013	Shp

Table. 2.10 Primary and secondary inputs.

The input data was standardized under the same coordinate system (WGS84 UTM projection zone 17S) and framed in the same geographic space, which refers to the administrative limit of the AdM wetland territory. The vector data was carried out in the ArcGIS 10.2 software, and about the analysis and extraction of remote scanning information from the digital images, ENVI 5.0 software was used.

The selection of the satellite images was made by adapting to the period was the LULC National Survey was made by the MAGAP, MAE, and IEE (the year 2010), and collecting those images with minor presence of clouds. This task was relevant since the study area is in the intertropical convergence zone, which is why it has the highest cloud cover in the world. Considering the features of the collected data, three optimal images were obtained, captured by the ETM + (SLC-off) and SENTINEL 2 Sensors. Subsequently, three-band compositions were applied: visible spectrum, near-infrared and medium infrared, which are the most suitable to carry out studies of land cover (Fernandez and Herrero, 2001).

We summarize this working path in three diagrams, where the methodology used in this chapter is explained. The methods are divided into 3 sub-methods or steps:

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[7] Global Visualization Viewer.
[8] Panchromatic band.
[9] Format used for the treatment of images which incorporates a georeferencing file, the initials TIFF corresponds to Tagged Image File Format.
[10] European Program for the establishment of a European capacity for Earth Observation.
[11] National Information System (Ecuador)

1. **Data Collection and Analysis** (Fig. 2.16). Based on thematic cartography and satellite images, it includes a data-to-information conversion process to standardize and consolidate input data.

2. **Remote Sensed Data Processing** (Fig. 2.17). Based on digital image processing coming from SENTINEL 2 (the year 2018) and LANDSAT 7 ETM+ (2000 and 2010) and including clouds and shadows masking processes.

3. **Thematic Land-Cover Data Extraction** (Fig. 2.18). Based on image classification logic and algorithms, training sites based on the MAGAP 2010 thematic reference legend, and including Accuracy Mapping Assessment.

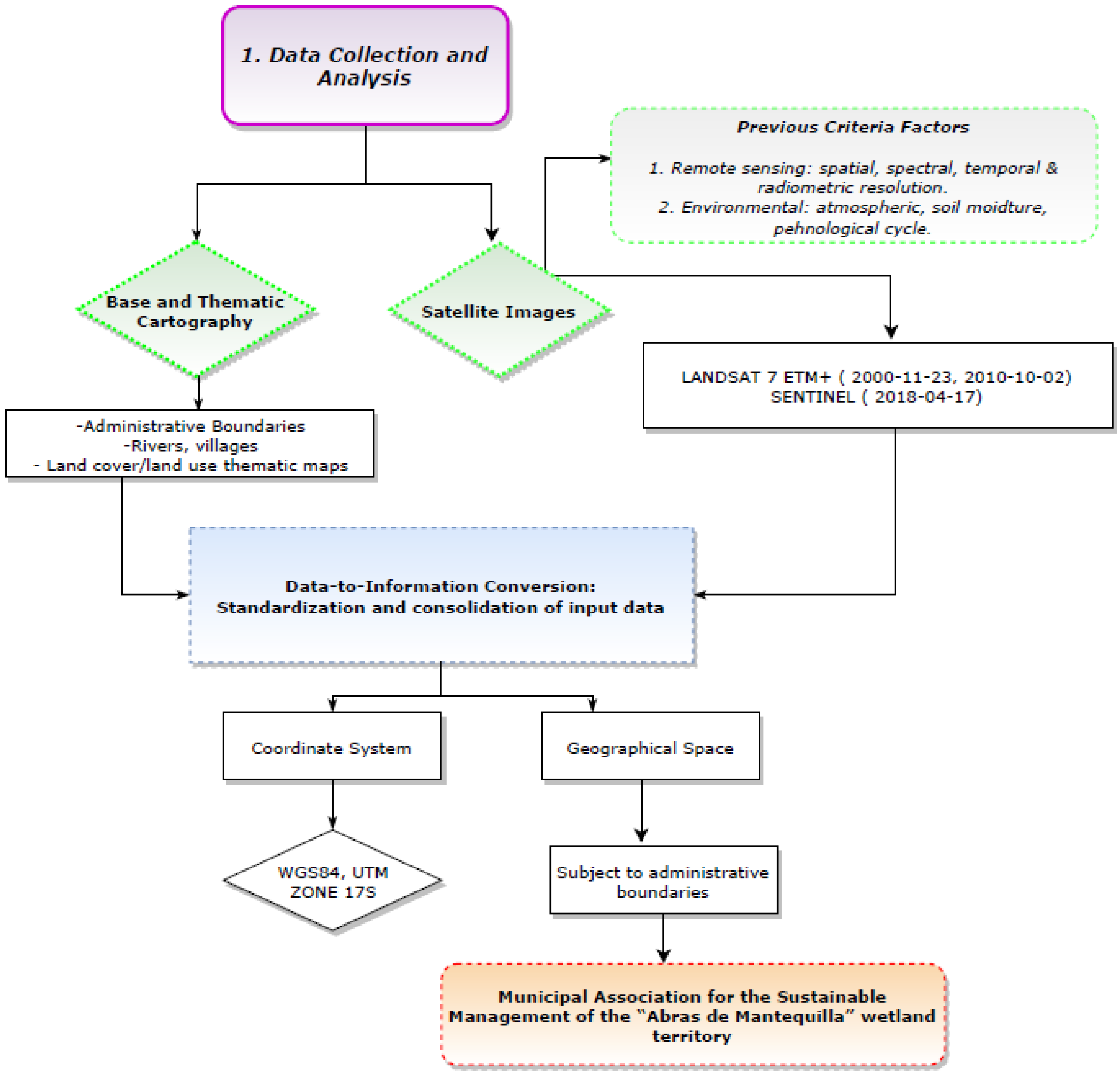

Fig. 2.16 Data collection and analysis of remotely sensed information diagram process.

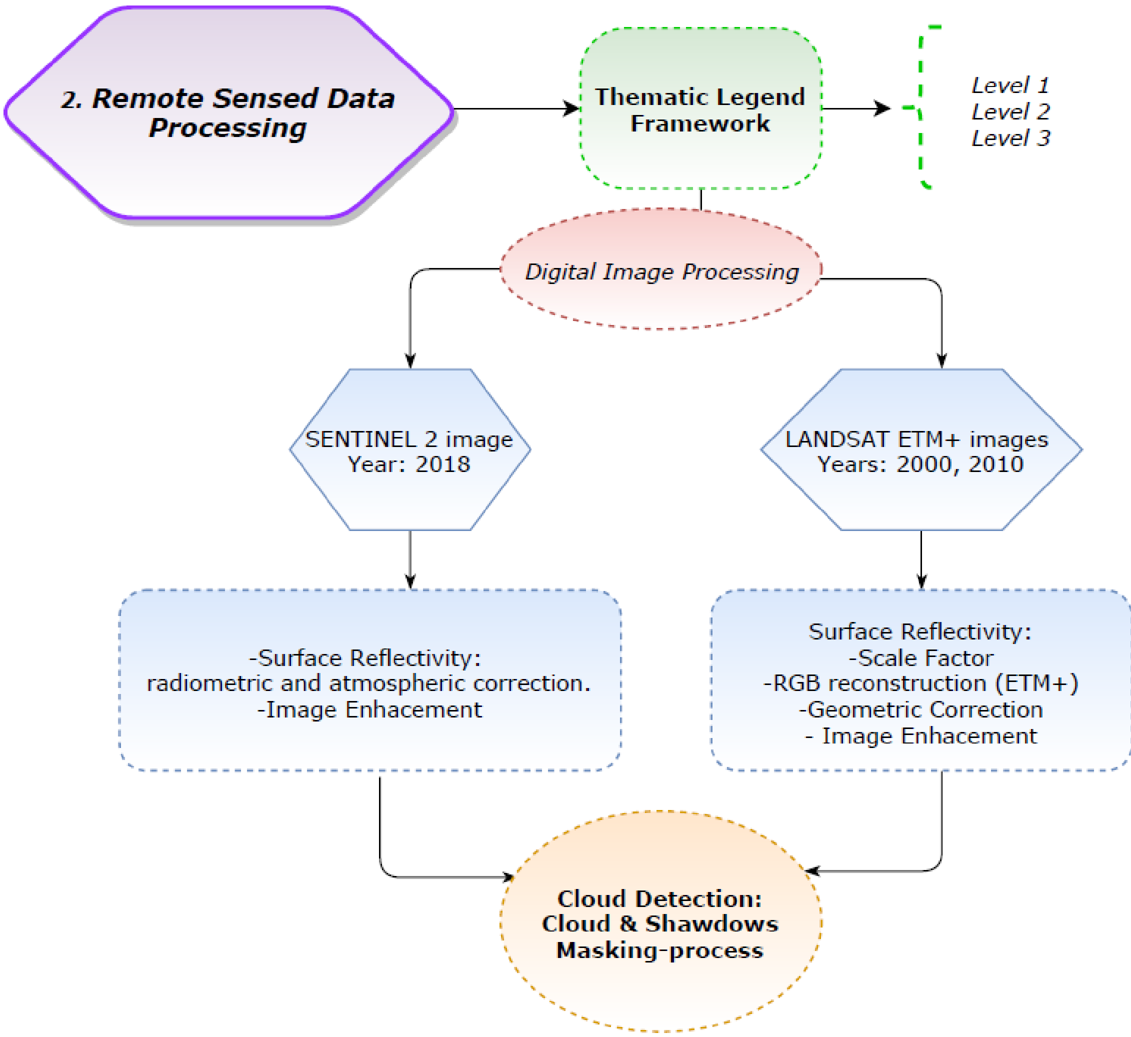

Fig. 2.17 Remote sensed data processing diagram.

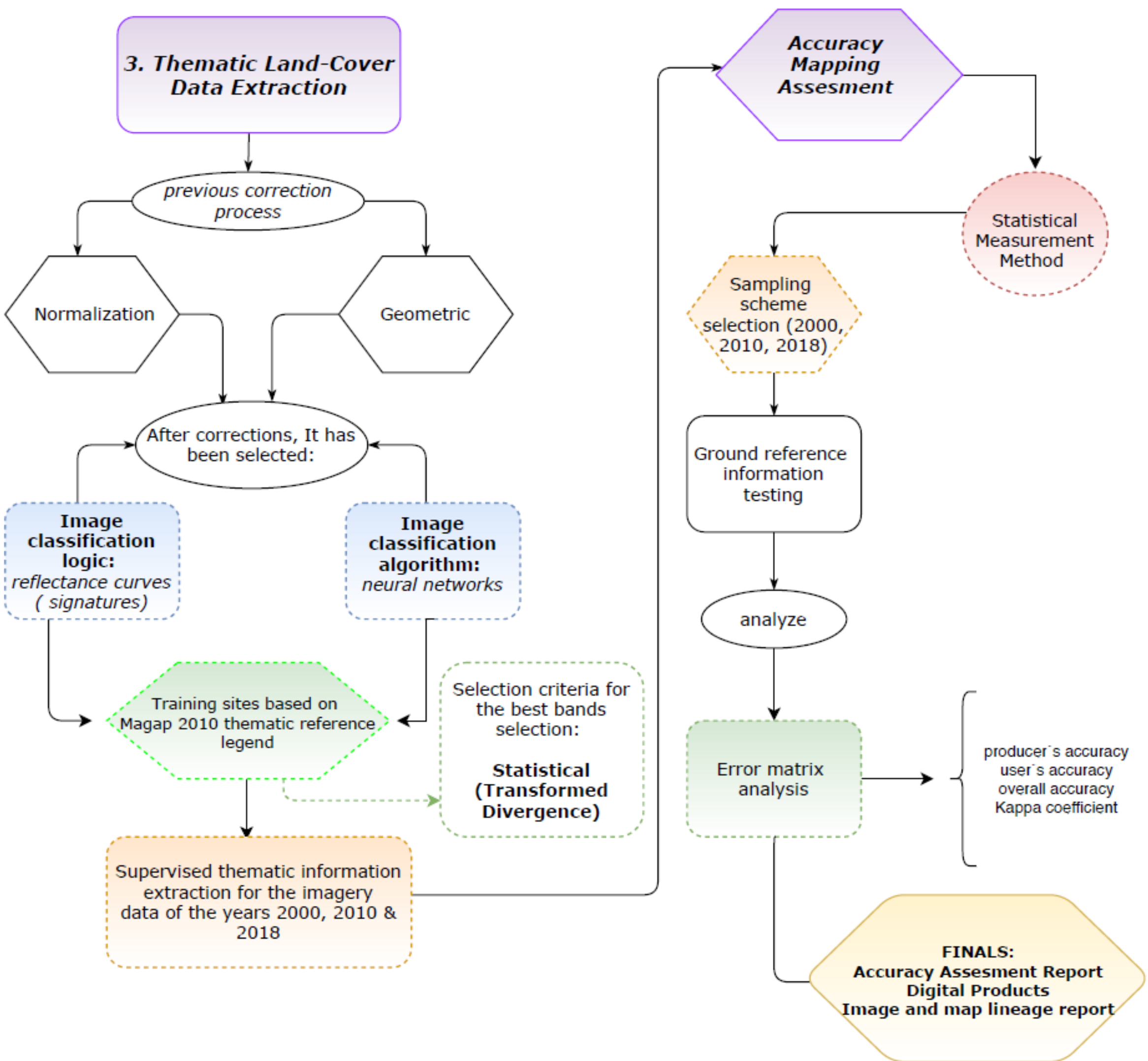

Fig. 2.18 Thematic land-cover data extraction and accuracy mapping assessment diagram.

2.9 Results

Final map data coming from the application of tools and techniques described in this chapter include those from the imagery data processing and the map accuracy assessment analysis. All data files, including training-sites, testing maps and the LULC maps for years 2000, 2010 and 2018 can be found in the following public URL:

- https://summlabbd.upc.edu/DelgadoMedina/PhDThesis/

After an accurate map analysis, based on the case study knowledge in terms of its most common land-cover types, fieldwork, and remote sensing skills, we have designated eight classes, which are detailed below (Table. 2.11, Fig. 2.19):

Class	2000		2010		2018	
	ha	%	ha	%	ha	%
Rice	5321	9.77%	881.61	1.63%	3514	6%
Banana	1875	3.44%	1622.29	3.00%	4273	8%
Cocoa	11711	21.49%	6372.52	11.80%	6516	12%
Maize	7043.88	12.93%	15205.99	28.15%	8467	16%
Scrubland	8330.58	15.29%	6662.64	12.34%	19339	35%
Palm oil	1502.75	2.76%	7467.11	13.82%	3595	7%
Natural Pasture	15913.38	29.21%	15705.63	29.08%	7452	14%
Other Land	2787.66	5.12%	95.07	0.18%	º1327	2%

Table. 2.11 Land-cover classes of the AdM wetland territory for years 2000, 2010, 2018).

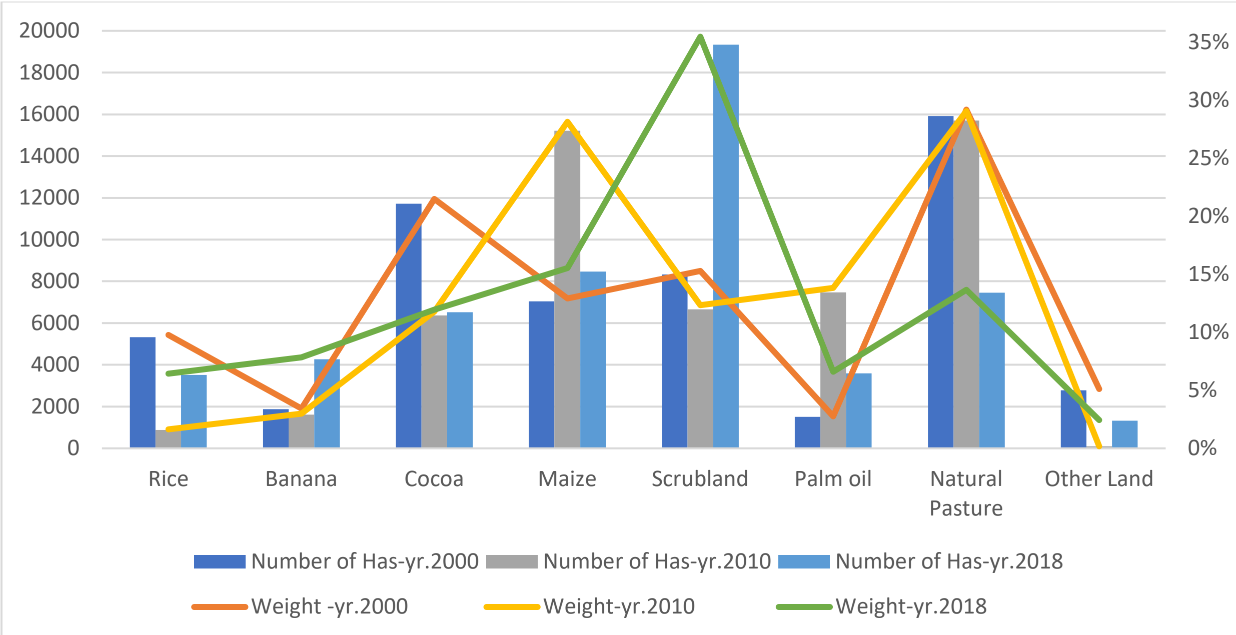

Fig. 2.19 Land-cover classes of the AdM wetland territory expressed in ha. And the weight percentage (For the years 2000, 2010, 2018).

An accurate method to verify the selection of training points is the calculation of spectral separability. Formulas like the Jeffries-Matusita or the Transformed Divergence distance show index values on a scale of 0 to 2 where 0 refers to complete overlapping and 2 indicates perfect separability (Csendes and Mucsi, 2017). The spectral distance analysis executed (Jeffries-Matusita and transformed divergence) resulted in different classes of pair coefficients, where a value > 1.8 corresponds to a good spectral distance based on transformed divergence value for each year (Table. 2.12), which permits forecast an accurate classification sampling. Most of the classes accomplish this parameter except for some pairs highlighted in the Table. 2.12. This is due to a reflectance curve confusion caused by the application of LEVEL IV- MAGAP thematic legend hierarchy (e.g. maize, rice, natural pastures). LEVEL IV is usually used at a 1:25.000 and 1:10.000 scale, which means, despite the confusion, the scale has been improved. In addition, the overall verification results deliver a very good outcome.

Pair Separation	Coefficient		
	2000	2010	2018
Maize and Scrubland	1.33	1.98	1.86
Rice and Maize	1.63	1.75	1.91
Rice and Scrubland	1.72	1.99	1.87
Scrubland and Natural Pasture	1.89	1.99	1.94
Rice and Natural Pasture	1.93	1.98	1.68
Rice and Palm oil	1.95	1.99	1.99
Scrubland and Palm oil	1.97	1.97	1.99
Rice and Other Land	1.96	1.89	1.99
Cocoa and Other Land	1.98	1.99	1.99
Maize and Palm oil	1.99	1.96	1.99
Palm oil and Other Land	1.99	1.99	2
Palm oil and Natural Pasture	1.99	1.83	1.99
Maize and Natural Pasture	1.99	1.62	1.98
Scrubland and Other Land	1.99	1.99	1.99
Banana and Cocoa	1.99	1.97	1.99
Cocoa and Scrubland	1.99	1.97	1.91
Natural Pasture and Other Land	1.99	1.99	1.99
Cocoa and Natural Pasture	1.99	1.98	1.98
Banana and Other Land	1.99	1.99	2
Maize and Other Land	1.99	1.98	1.99
Rice and Cocoa	1.99	1.99	1.98
Cocoa and Maize	1.99	1.99	1.99
Cocoa and Palm oil	2	1.77	1.88
Banana and Palma oil	2	1.86	1.99
Banana and Scrubland	2	1.99	1.99
Rice and Banana	2	1.99	1.99
Banana and Natural Pasture	2	1.99	1.99
Banana and Maize	2	1.99	1.99

Table. 2.12 Spectral distance coefficient verification for 2000, 2010, 2018.

The accuracy assessment of the maps 2000, 2010 and 2018 is based on the matrix error variables which compiles the Kappa coefficient of agreement and overall accuracy indexes for the neural network algorithm. The "Ground Truth" values (presented in a number of pixels and percentages) of each class per every year can be found in:

https://summlabbd.upc.edu/DelgadoMedina/PhDThesis/

The decision of using neural networks as an image classification algorithm reflects the high values in the accuracy indexes: overall accuracy (OA) and Kappa coefficient of agreement (K) at a scale of 1:50.000; for both LANDSAT and for SENTINEL 2 images. These results show that the products related to land-cover and land-use mapping, are more than efficient when the classification is based on reflectance curves values. The lowest OA and K values are 89% and 0.8723, respectively (Table. 2.13).

Image Classification Algorithm: neural networks					
1: 50.000					
LANDSAT 7ETM+ 2000-LULC map		LANDSAT 7ETM+ 2010-LULC map		SENTINEL 2 2018-LULC map	
OA	K	OA	K	OA	K
89.00	0.8723	97.89	0.9756	92.1158	0.9091

Table. 2.13 Digital classification evaluation based on reflectance curve values.

It has also been evaluated the producer's and consumer's accuracy of each year at a scale of 1:50.000 (Table. 2.14).

Class	2000		2010		2018	
	Prod. Acc. (%)	User Acc. (%)	Prod. Acc. (%)	User Acc. (%)	Prod. Acc. (%)	User Acc. (%)
Rice	87.01	93.06	95.61	100	76.96	99.37
Banana	100	100	100	100	100	100
Cocoa	100	100	100	100	95.78	91.05
Maize	100	70.00	98.22	97.08	97.56	96.39
Scrubland	43.64	100	100	82.26	84.32	77.61
Palm oil	100	88.89	92.36	100	79.53	100
Natural Pasture	100	95.12	100	97.79	90.71	70.04
Other Land	100	96.23	100	100	100	100

Table. 2.14 Producer´s and consumer´s accuracy at a scale of 1:50.000.

On average, the producer´s and consumer´s accuracy test for the eight classes show a good accuracy, with values ≥ 70%, due to the extension of each class and a good spectral distance. Rice, banana, cocoa, maize, palm oil, natural pasture, and other land present accuracy values between 70-100% for the years 2000, 2010 and 2018. Scrubland class shows an exception during 2000, with a value of ≤70% (43.64%), which has no relevant influence at the final accuracy result. Some classes do not appear due to their low reflectance curves values, little representativeness or a high spectral confusion, which is the case of those belonging to Native Forest class (LEVEL I).

2.10 Main points in review

- In cases where the massive amount of manual sampling required to compile these data sets places a practical limitation on their widespread collection, high-resolution remote sensing is an important input for detecting vegetation change patterns, and one that is particularly well suited for monitoring sparse vegetation in which individual tree coverages can be distinguished. The ease by which these data can be acquired allows for a more geographically widespread detection of large-scale spatial patterns.

- The final outputs generated by this work are fundamental in areas where the lack of reliable remote sensed information is an issue when making-decision frameworks and planning are set without accurate data.[12] It is remarkable the result concerning the Accuracy Assessment Mapping process in a region where the influence of atmospheric noise is high, due to its geographic location. This fact allows us to conclude that both processes, data collection analysis, and scanning data processing, were correctly executed.

- Thus, the final outputs of this chapter will be used in the following chapters as a baseline to analyze, calculate and determine patchiness and ecosystem services trade-off and bundles at the Municipal Association for the Sustainable Management of the AdM wetland landscape.

- Obtaining training samples and conduction testing is of utmost importance because the results depend on the quantity and distribution of these items, especially when ROIs dimensions are identified. The geographic ROI, in our case the Municipal Association for the Sustainable Management of the AdM wetland territory, is especially important in this

[12] Data can be accessed from: https://summlabbd.upc.edu/DelgadoMedina/PhDThesis/

change detection study because it has to be ensured that each of the multiple-date images (2000, 2010, 2018) covers the geographic area of interest.

- Performing the image statistical analysis of the training site was done to estimate the degree of separability between all the classes. The values of class separability in the AdM wetlands images were represented by Transformed Divergence and Jefferies-Matusita Distance. Both techniques are a feasible measure in order to set the quality of training areas. The results of spectral distance calculations based on transformed divergence, deliver better results where 89% (2000, 2010) and 96% (20198) of pairs of classes have a dimensionless value >1.8. The accuracy results suggested that this strategy for the selection of training samples and the classification scheme used were an important task in order to perform better classification results.

- The lack of atmospheric data could be an obstacle for proper and precise image correction. Therefore, it was applied to the dark object technique, which is used in several studies, obtaining good statistical results, especially when applying the neural network classification algorithm method.

- Applying an appropriate multivariate statistic is a way to assess the accuracy of the remote sensing-derived information. The three LULC maps (at a scale of 1:50.000) show good results in OA and K values. The lowest OA and K are 89% and 0.87 in 2000. The years 2010 and 2018 have an OA of 97.89% and 92.11% for each year. The K coefficient is also good in 2010 (0.97) and in 2018 (0.90)

- All classes of interest must be selected and defined carefully to classify remotely sensed data successfully into land-use and/or land-cover information. This requires the use of a classification scheme organized according to logical criteria. In our case, we have used a hierarchical classification system based on the thematic-legend scheme launched by the Ecuadorian institutions (MAGAP, MAE, IEE) in 2010 in order to have a coherent result in terms of classes and final outputs.

- In the study area, there is a predominance of different classes every year. In 2000, Natural Pasture and Cocoa covered around 52% of the land, followed by Natural pasture and maize class with a 57% in 2010. In 2018, the land-cover weight is focused on Scrubland and Maize with 51% of land coverage.

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2.12 Appendices

2.12.1 Glossary of acronyms

ACCA	Automated Cropland Classification Algorithm
AdM	*Abras de Mantequilla*
ANN	Artificial neural network
ASTER	Advanced Spaceborne Thermal Emission and Reflection
AVHRR	Advanced Very High-Resolution Radiometer
AVIRIS	Airborne Visible InfraRed Imaging Spectrometer
BRDF	Bi-directional reflectance distribution function
BRF	Bidirectional reflectance factor
CASI	Compact Airborne Spectrographic Imager
CE	Consumer´s error
CIR	Color-infrared
CLIRSEN	*Centro de Levantamientos Integrados de Recursos Naturales por Sensores Remotos*
CRISP	Centre for Remote Imaging, Sensing and Processing
CRT	Cathode-ray tube
DC	Digital counts
EMR	Electromagnetic Radiation
ENVI	Environment for Visualizing Images
ESA	European Space Agency
ESAG	*Estadísticas Agropecuarias*
ESPAC	*Encuesta de Superficie y Producción Agropecuaria Continua*
ESRI	Environmental Systems Research Institute
ETM	Enhanced Thematic Mapper
ETM+	Enhanced Thematic Mapper Plus
FAO	Food and Agriculture Organization
FLAASH	Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubes
GE	Guayas ecosystem
GIS	Geographic information system
GLOVIS	Global Visualization Viewer
GOES	Geostationary Operational Environmental Satellite
IEE	*Instituto Espacial Ecuatoriano*
IFSAR	Interferometric Synthetic Aperture Radar
IGAC-CIAF	*Instituto Geográfico Agustín Codazzi - Centro de Investigación y Desarrollo en Información Geográfica*
IGM	*Instituto Geográfico Militar*
INEC	*Instituto Nacional de Estadística y Censos*
IPCC	Intergovernmental Panel on Climate Change
IRC	Integrated Radiometric Correction
IRS	Indian Remote Sensing
K	Kappa coefficient of agreement index

LAI	Leaf Area Index
LCC	Leaf Chlorophyll Content
LIDAR	Light Detection and Ranging
LU/LC	Land-use and land-cover
MAE	*Ministerio del Ambiente*
MAGAP	*Ministerio de Agricultura, Ganadería, Acuicultura y Pesca*
MISR	Multi-angle imaging spectro-radiometer
MMU	Minimum mapping unit
MODIS	Moderate resolution imaging spectro -adiometer
MODTRAN	Moderate resolution atmospheric Transmission
MSS	Multi-Spectral Scanner
NASA	National Aeronautics and Space Administration
OA	Overall accuracy
OE	Omission errors
PAN	Panchromatic band
QGIS	Quantum GIS
RADAR	Radio Detection and Ranging
RED	Red reflectance
RGB	Red, green, blue
ROI	Regions of interest
SeaWIFS	Sea-Viewing Wide Field-of-View Sensor
SHP	Shapefile
SLC	Scan Line Corrector
SNAP	Sentinel Application Platform
SNI	Sistema Nacional de Información
SNR	Signal to Noise ratio
SONAR	Sound Navigation Ranging
SPOT	*Satellite Pour l'Observation de la Terre*
SWIR	Short-wave Infrared
TDRSS	Tracking and Data Relay Satellite System
TM	Thematic Mapper
TOA	Top of Atmosphere
USGS	United States Geological Survey
UTM	Universal Transverse Mercator

3

Criticality, fragmentation and potential impact to ecosystem services

In the previous century, human activities have influenced global biogeochemical cycles, with one of the most dramatic changes being the replacement of 40% of Earth's formerly biodiverse land areas with landscapes that contain only a few species of crop plants, domestic animals and humans (Bonan, 2008; Foley *et al.*, 2011). These local changes have accumulated over time and now constitute a global forcing (Barnosky *et al.*, 2012). Another global scale force that is tied to habitat destruction is fragmentation, which is defined as the division of a continuous habitat into separate portions that are smaller and more isolated. Fragmentation produces multiple interwoven effects: reductions of biodiversity between 13% and 75%, decreasing forest biomass, and changes in nutrient cycling (Haddad *et al.*, 2015). The effects of fragmentation are not only important from an ecological point of view but also that of human activities, as ecosystem services are deeply influenced by the level of landscape fragmentation (Rudel *et al.*, 2005).

External forces can produce abrupt changes from one state to another, called critical phenomena or transitions (Stanley, 1987; Scheffer, 2009). Complex systems can experience two general classes of critical transitions (Sole *et al.*, 1996).

- **First-order transitions**. Here, a catastrophic regime shift that is mostly irreversible occurs because of the existence of alternative stable states. This class of transitions is present in a variety of ecosystems such as lakes, woodlands, coral reefs, semi-arid grasslands, and fish populations. They can be the result of positive feedback mechanisms.
- **Second-order transitions**. In these cases, there is a narrow region where the system suddenly changes from one domain to another in a continuous and reversible way. Such transitions have been suggested for tropical forests, semi-arid mountain ecosystems, and tundra scrublands. The transition happens at a critical point where we can observe scale-invariant fractal structures characterized by power-law patch distributions.

The spatial phenomena observed in this last type of continuous critical transitions are related to connectivity, and we can observe two domains or phases separated by a threshold: one dominated by short-range interactions, and another in which long-range interactions are possible and information can spread throughout the system. In ecology, it is shown that pushing the system below the threshold could produce a biodiversity collapse (Solé, Alonso and Saldaña, 2004); conversely, being in a connected state (above the threshold) could accelerate the invasion of the forest into prairie (Naito and Cairns, 2015).

One of the main challenges with systems that can experience critical transitions–of any kind– is that the value of the critical threshold is not known in advance. In addition, because near the critical point a small change can precipitate a state shift in the system, they are difficult to predict.

In this chapter, we aim at looking for evidence for fragmentation and criticality in the different land cover types observed in the Guayas Ecosystem and the “Abras de Mantequilla” (AdM) wetland territory, and its evolution during years 1998 to 2015. We evaluate if landscape patch distribution at both, regional and local scales, can be described by a power-law distribution and then examine the fluctuations of the largest patch. In our case, and in contrast with those examples which use data at a continental scale (Saravia, Doyle and Bond-Lamberty, 2018), transitions are not sharp and somehow difficult to detect, since noise might mask the signals of the transition.

Some of the questions that we would like to answer here are the following:

- Does the replacement of vegetation areas with an important anthropic influence lead to a fragmented landscape?
- Are the temporal force spatial data and statistical information a reliable source for detecting a critical transition in landscape fragmentation in fragile ecosystems?
- What are the costs and benefits, if there are, of land fragmentation in landscapes connected to basins (Guayas Ecosystem) and wetlands (AdM wetland), with high plantations presence?

In order to answer these questions, we will integrate more than one specific methodological framework to our analysis. This has been considered because ES definitions and their respective analysis is a research field with high economic and social impact in tropical landscapes, which is our case. Therefore, we would like to detect critical transitions for the different landscapes using a combination of three indicators:

- Spatial indicators:
    - Patch size distribution.
    - The proportion of the largest patch relative to the total area.
- Statistical indicator:

- Distribution of temporal fluctuations in the largest patch size.

3.1. Land cover types patch size distribution

From our data, and within the constraints commented in the previous chapter, we analyze land cover types patch distribution both, in the Guayas and "Abras de Mantequilla" (AdM). Although temporal evolution for every class is not available, our analysis discriminates between the following land-cover classes/types Table. 3.1:

LULC classes
Annual crops
Anthropic
Arboriculture
Banana
Farmland
Forestry and natural vegetation
Other
Water

Table. 3.1 Land-cover and land-use classes for both case studies: Guayas Ecosystem and "Abras de Mantequilla" (AdM) wetland.

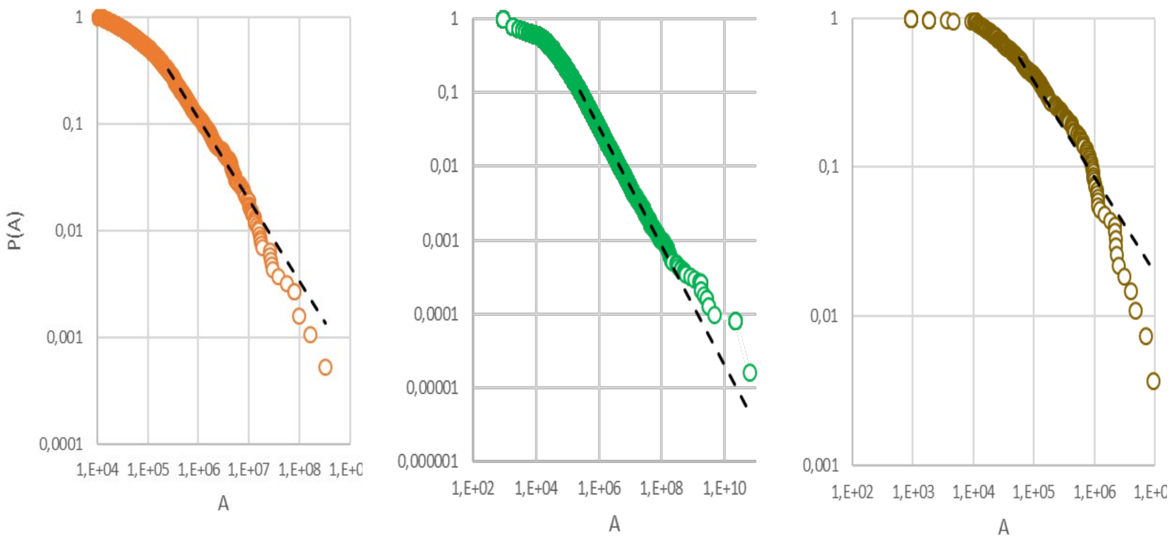
Near the critical point, several scaling laws arise: the structure of the patch that spans the area is fractal, the size distribution of the patches is power-law (or at least heavy-tailed[1] in real cases, where size limits are at play), and other quantities also follow power-law scaling (Stauffer and Aharony, 1991). Close to the critical point, the distribution of patch sizes is:

$$\boldsymbol{n_s(p) \sim s^{-\alpha}} \qquad (1)$$

where $n_s(p)$ is the number of patches of size s. We fitted the empirical distribution of land cover and land use (LULC) patches to four distributions (see Appendices): power-law, power-

[1] In probability theory, heavy-tailed distributions are probability distributions whose tails are not exponentially bounded: that is, they have heavier tails than the exponential distribution.

law with exponential cut-off, log-normal, and exponential. We have used maximum likelihood and have followed well-established procedures concerning methodology and accuracy (Clauset, Shalizi, and Newman, 2009). We assumed that the patch size distribution is a continuous variable discretized by the remote sensing data acquisition procedure.[2]



(a) *(b)* *(c)*

Fig. 3.1 Examples of cumulative distribution functions $P(A)$ of patch sizes A with maximum likelihood power law fit (discontinuous line). Guayas ecosystem: (a) banana (year 2008, power-law + cutoff) and (b) forestry and natural vegetation (year 2014, power-law). AdM ecosystem: (c) farmland (year 2000, power-law + cutoff).

Our results for both, the Guayas and AdM wetland ecosystems, show that the power-law distribution cannot be selected as the best model, although results for power-law with-cutoff and lognormal cannot be trusted either in the majority of the cases. The exponential distribution is definitely ruled out as a possible model for almost all LULC and years. The stretched exponential accumulates also most of the trustable results to be rejected. The most conclusive results are those shown in Table. 3.2 (see Appendices for complete results) and four selected examples are shown in Figure 3.1. In finite-size systems, the favored model should be the power-law with exponential cut-off because the power-law tails are truncated to the size of

[2] Python package 'powerlaw' (https://pypi.org/project/powerlaw/) has been used to obtain these results.

the system. We observe, nonetheless, the appearance of lognormal distributions which could be also the effect of some size constraint (Sornette, 2009; Cristelli, Batty and Pietronero, 2012).

Ecosystem	LULC	Year	Support for
Guayas	Arboriculture	2008	Power law + cutoff
	Banana	2008	Power law + cutoff
	Farmland	2008	Lognormal
	Forestry and nat. Veg.	1990	Lognormal
		2000	Lognormal
		2008	Lognormal
		2014	Power law
	Other	1990	Lognormal
		2000	Lognormal
	Water	2008	Power law + cutoff
		2014	Power law + cutoff
AdM	Banana	2008	Power law + cutoff
	Farmland	2000	Power law + cutoff

Table. 3.2 Most conclusive results for supporting fat-tailed distributions by LULC, ecosystem and year.

Considering our results, though, we might assume that most of our probability distributions exhibit a large skewness or kurtosis, relative to that of either a normal distribution or an exponential distribution. In this class of fat-tailed distributions, we include those whose tails decay like a power law, which would be the extreme case, or such as the log-normal. Figures 3.2 and 3.3 show the evolution of the would-be scaling exponent α if the power-law function was favored in front of the rest. For the Guayas ecosystem (Fig. 3.2), there is a clear tendency for α to decrease after the year 2000, for all LULC and across the years, with a slight increase in the last 10 years. Arboriculture, farmland and forest and natural vegetation retain their decreasing tendency to lower values of α. Recall that with lower α, the fluctuations of patch sizes are higher and vice versa (Newman, 2005).

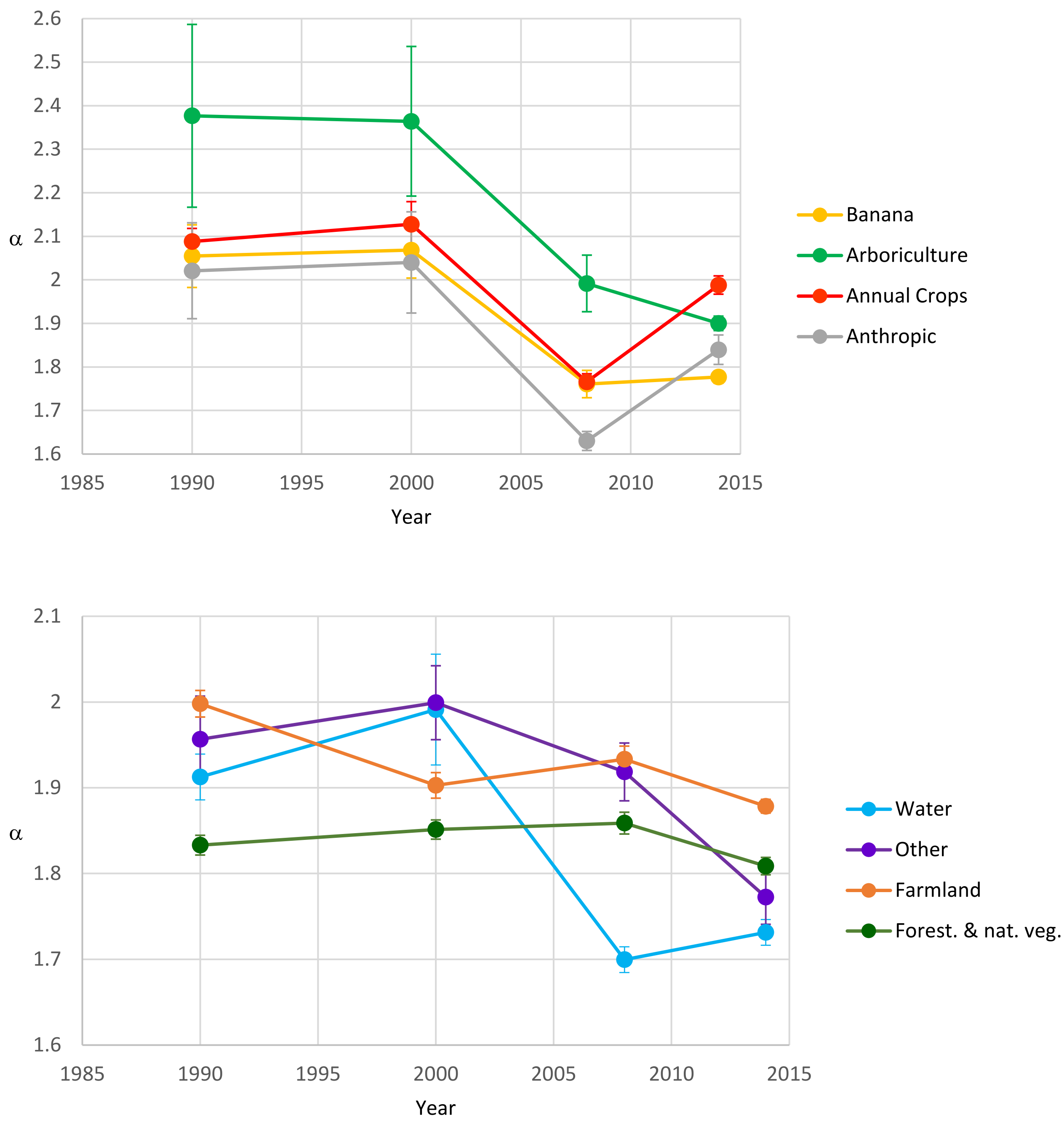


Fig. 3.2 Evolution of power-law exponents α by LULC patch distributions and year, for the Guayas ecosystem, during the period 1985-2015, with 95% confidence interval error bars (estimated by bootstrap resampling).

In the case of AdM (Fig. 3.3), and for those results coming from statistically significant data (i.e., for all years see Appendices) in water, banana, annual crops, and farmland, this decreasing tendency is observed only for banana and annual crops, with a slight increase in the last years. Water and farmland results for α fluctuate, due to the scaling constraints of the system on our data.

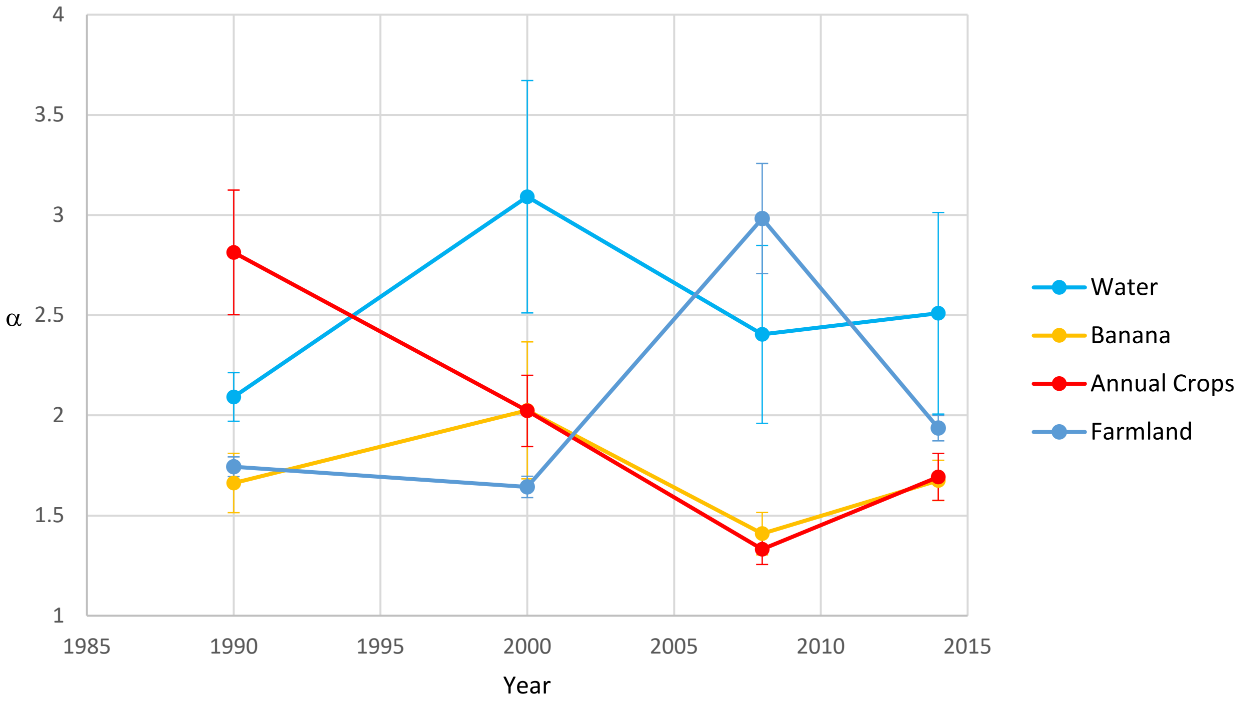


Fig. 3.3 Evolution of power-law exponents α by LULC patch distributions and year, for the AdM wetland territory, with 95% confidence interval error bars (estimated by bootstrap resampling).

3.2. Largest patch dynamics

The largest patch S_{max} connects the highest number of sites in the area and has been used to indicate fragmentation (Ochoa-Quintero *et al.*, 2015). When the system is in a connected state, the landscape is almost insensitive to the loss of a small fraction of a type of landscape. But close to the critical point a minor loss can have important effects (Bascompte and Sole, 1996) because at this point the largest patch will have a filamentary structure. Small losses can thus produce large fluctuations. To evaluate the fragmentation of the different LULC cover classes, the proportion of the largest patch against the total area can be calculated (Keitt, Urban, and Milne, 1997). We calculate the proportion of the largest patch for each year, dividing S_{max} by the total forest area of the same year:

$$\boldsymbol{RS_{max}} = \frac{\boldsymbol{S_{max}}}{\sum_i \boldsymbol{S_i}} \tag{2}$$

When RS_{max} is large (more than 60%), the largest patch contains most of the landscape so there are fewer small patches and the system is probably in a connected phase. Conversely, when it is low (less than 20%), the system is probably in a fragmented phase (Saravia and Momo, 2018).

We observe how, except for water (up to the year 2010) and arboriculture, all LULC for the Guayas ecosystem are in a fragmented state, that is $\langle RS_{max} \rangle < 0.2$ (Fig. 3.4). Water has turned into a fragmented state in 2014, while arboriculture has returned to a connected state in 2014, after more than 10 years of fragmentation. Although most LULC has recovered from their previous values in the last 5 years, the case of water is particularly worrying, reaching its lowest value in 2014 (0.053), after a dramatic and continuous decrease. On the contrary, all four LULC analyzed in the case of the AdM wetland ecosystem cannot be considered in the fragmented state (Fig. 3.5). Farmland reaches its lower level with $\langle RS_{max} \rangle = 0.21$, while annual crops show the highest index.

We expect that large fluctuations near a critical point have heavy tails (i.e., log-normal or power-law) and that fluctuations far from a critical point have exponential tails, corresponding to Gaussian processes. Thus, complementarily, it would have been relevant to evaluate if the LULC is near a critical transition by means of the fluctuations of the largest patch:

$$\Delta \boldsymbol{RS_{max}} = \boldsymbol{RS_{max}(t)} - \langle \boldsymbol{RS_{max}} \rangle \qquad (3)$$

and try to fit results to some empirical distribution (i.e., power-law, log-normal, and exponential) using the same methods described previously. Unfortunately, our data does not span a sufficient amount of time to perform such calculation with enough statistical confidence.

Finally, we must emphasize that criticality analysis is usually performed in a static way, that is equation 3 is computed on the statistics of all components except S_{max}, considering that a configuration at any given time is (or it is not) close to the critical point (Newman, Strogatz and Watts, 2000). In our case, though, fluctuations are obtained from historical (i.e., time) dynamics on S_{max}. It is precisely its variation in time what gives us the critical character of its state.

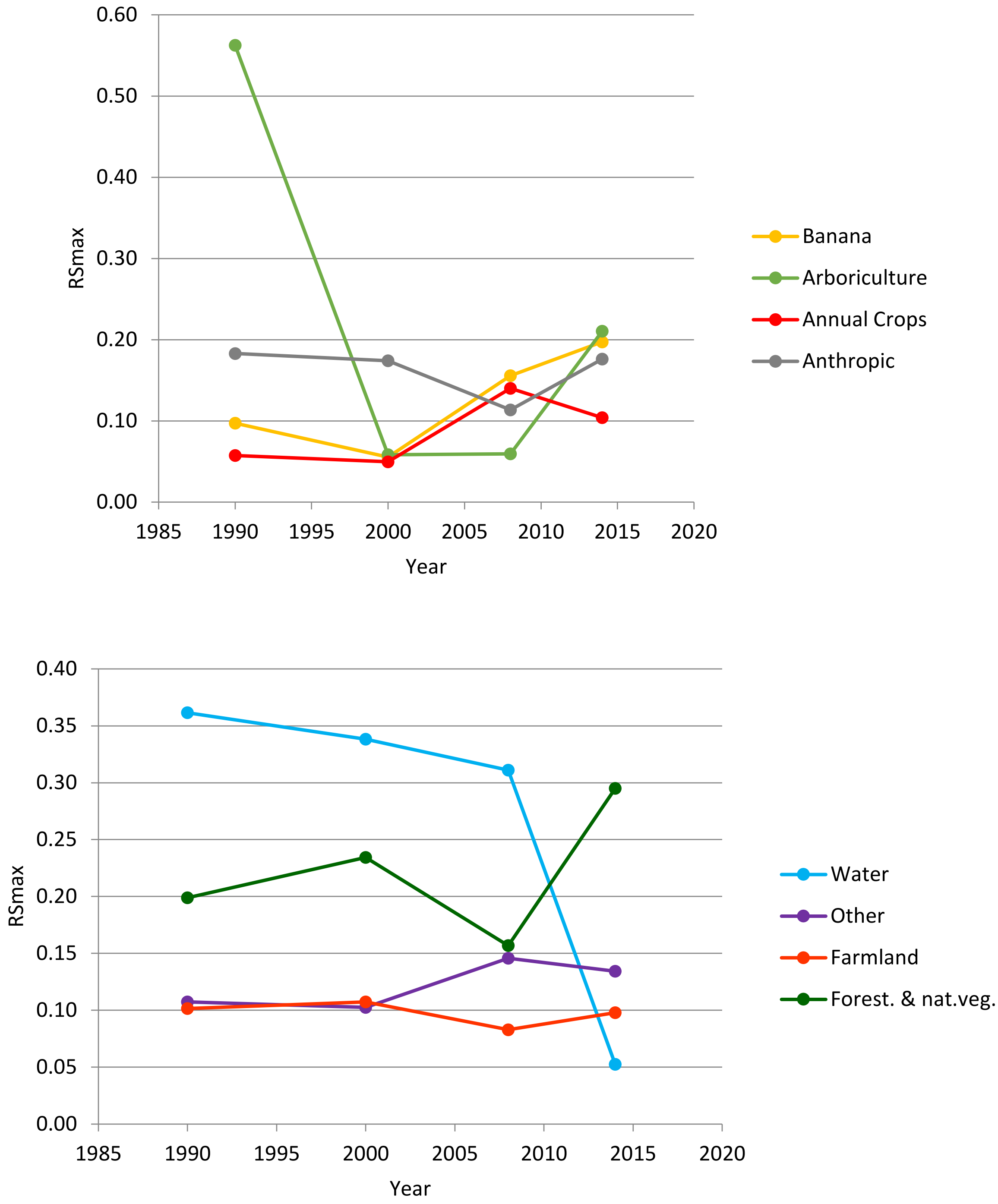


Fig. 3.4 Largest patch proportion relative to total LULC area, for the Guayas ecosystem. We show here the RS_{max} *calculated using a threshold of 20% of the total LULC area.*

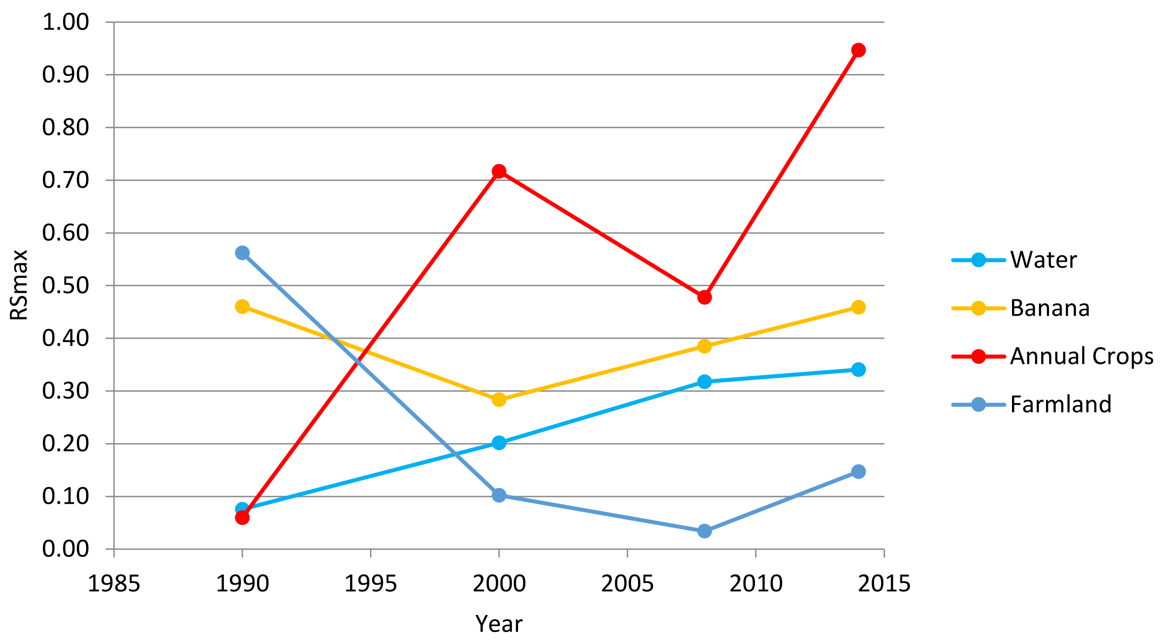


Fig. 3.5 Largest patch proportion relative to total LULC area, for the "Abras de Mantequilla" (AdM) wetland. We show here the RS_{max} calculated using a threshold of 20% of the total LULC area.

3.3. The potential impact on ecosystem services

There exists a huge amount of literature concerning how the fragmentation of a habitat implies final negative effects on a specific area (Bascompte and Sole, 1996; Savard, Clergeau and Mennechez, 2000; Solé, Alonso and Saldaña, 2004; Haddad *et al.*, 2015). On the contrary, in areas where crops and anthropic landscapes are mixed with natural ones, the patchiness due to the presence of crops and other anthropic interventions in the environment might be positive for the overall sustainability of the system, as we move away from large landholdings and go toward to a major presence of permaculture: small-scale polyculture results in high biodiversity and major benefits than large estates because the impacts that agriculture has on biodiversity are mitigated when the scale is small and compared to similar other variables (Bengtsson *et al.*, 2003). The agricultural patch would work as a small disturbance that at one time can even increase biodiversity because it creates a niche for other species that did not exist before, and it allows those that were already in the area to continue living. If the crop scale is small, its capacity to break the ecological continuity is lower (that is, fragmentation would not occur, or it would be minimized). In ecology, this would be the hypothesis of intermediate disturbance as a maximizer of biodiversity (Wilkinson, 1999), which in the Mediterranean, for example, is quite proven (Marull *et al.*, 2014). In areas like the tropics, where the anthropic pressure has not been so much and so continued for millennia, this hypothesis might not work at the same level.

In any sense, the importance of quantifying fragmentation for the final evaluation of ES in a region relays in our final capacity to evaluate sustainability and biodiversity as a whole, an issue that we confront in Chapter 4. Here we consider the assumption that a combination of spatial and temporal indicators is more reliable for detecting fragmentation and critical transitions (Kéfi *et al.*, 2014). In the literature, we can find even five criteria applied at the same time to evaluate the closeness of the system to a fragmentation threshold: patch size distribution, the proportion of the largest patch relative to the total area RS_{max}, the distribution of temporal fluctuations in the largest patch size, the trend in the variance, and the skewness of the fluctuations (Saravia, Doyle and Bond-Lamberty, 2018). In our case, unfortunately, three of them cannot be applied with our temporal resolution due to the difficulties of fitting and comparing heavy-tailed distributions. Nonetheless, we have calculated the temporal trend in the fluctuations of the largest patch size ratio ΔRS_{max} (results not shown in the text, see Appendices for numerical values), assuming that an increase in the fluctuation suggests that the critical threshold is approached. The combination of these three indicators into one weighted and normalized fragmentation index f_i, gives us some degree of confidence about the system being close to a critical transition (Table. 3.3).

Temporal trends in								
Ecosystem	**LULC**	α	**Fragmentation**	RS_{max}	**Fragmented?**	ΔRS_{max}	**Fragmentation**	f_i
Guayas	Annual crops	Decrease	Increase	< 0.2	Yes	Increase	Increase	**1.0**
	Anthropic	Decrease	Increase	< 0.2	Yes	Decrease	Decrease	**0.6**
	Arboriculture	Decrease	Increase	> 0.2	No	Decrease	Decrease	**0.3**
	Banana	Decrease	Increase	< 0.2	Yes	Increase	Increase	**1.0**
	Farmland	Decrease	Increase	< 0.2	Yes	Decrease	Decrease	**0.6**
	Forestry and nat. Veg.	Decrease	Increase	> 0.2	No	Increase	Increase	**0.6**
	Other	Decrease	Increase	< 0.2	Yes	Increase	Increase	**1.0**
	Water	Decrease	Increase	> 0.2	No	Decrease	Decrease	**0.3**
AdM	Annual crops	Decrease	Increase	> 0.2	No	Increase	Increase	**0.6**
	Anthropic	-	-	-		-	-	**-**
	Arboriculture	-	-	-		-	-	**-**
	Banana	Decrease	Increase	> 0.2	No	Increase	Increase	**0.6**
	Farmland	Increase	Decrease	< 0.2	Yes	Decrease	Decrease	**0.3**
	Forestry and nat. Veg.	-	-	-		-	-	**-**
	Other	-	-	-		-	-	**-**
	Water	Increase	Decrease	> 0.2	No	Increase	Increase	**0.3**

Table. 3.3 LULC and temporal trends for α, RS_{max} and ΔRS_{max} suggest different levels of proximity to a critical fragmentation point f_i (maximum for f_i = 1) for both ecosystems, Guayas and "Abras de Mantequilla" (AdM) wetland.

We observe that $0.3 \leq f_i \leq 1.0$, depending on how many (1, 2 or 3) indicators support that LULC, in particular, being close to a fragmented state. In the case of Guayas, we observe that annual crops and banana show $f_i = 1.0$, while arboriculture and water show $f_i = 0.3$, the least fragmented state. The rest of LULC present an intermediate fragmented state. In the case of AdM, farmland and water are minimally fragmented while banana presents an intermediate fragmented state.

The case of banana plantations, and regarding the previous biodiversity discussion, is significant. At the national level, Ecuadorian exports make the country the largest supplier of bananas globally, showing an expansion by an estimated 4 percent, to reach a new height of 6.7 million tons in 2018, thanks to favorable weather conditions, especially at the Guayas ecosystem area. In our study area (GE), banana plantations are 166972 ha., which represents 93% of the total national area. If we only consider the province of "Los Ríos", where the AdM wetland is located, it concentrates 31.3% of the national banana surface (Fig. 3.6). During the last land registry of 2013, there were registered 558 banana venues with a total of 28051 ha (Fig. 3.7). Thus, fragmentation might not be due to loss of habitat or plantations, but rather on the contrary: an uncontrolled increase in smallholdings spread over the ecosystem's geography.

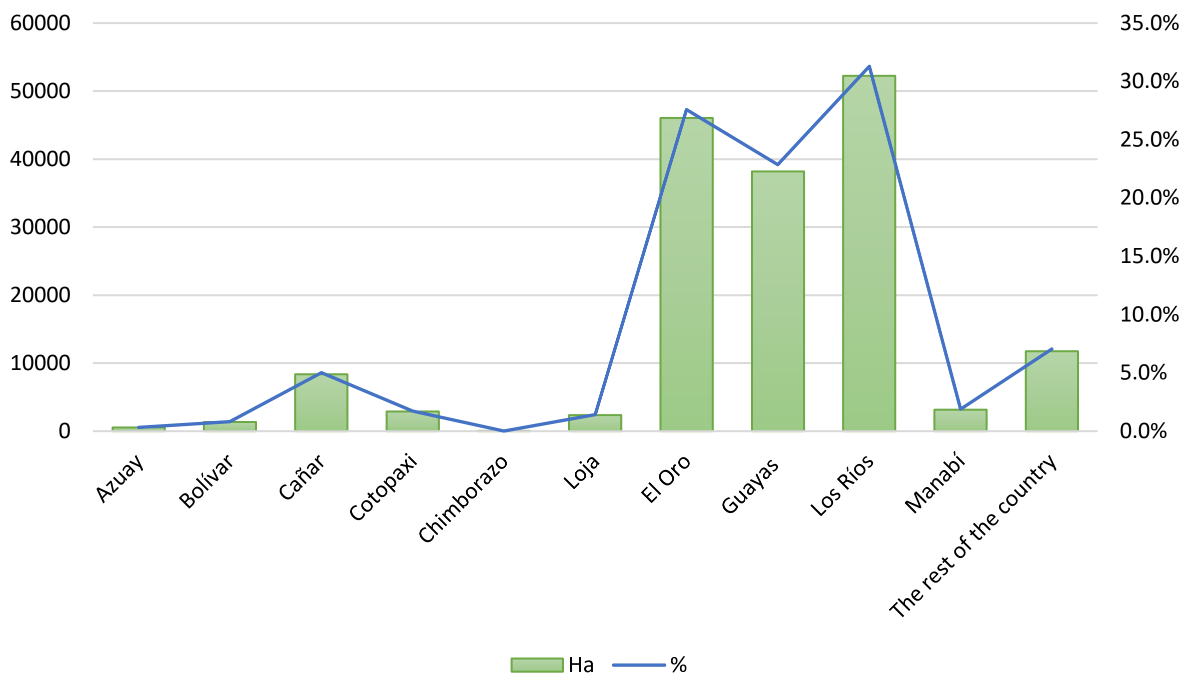


Fig. 3.6 Guayas ecosystem area vs national area of banana plantations. The year 2017.

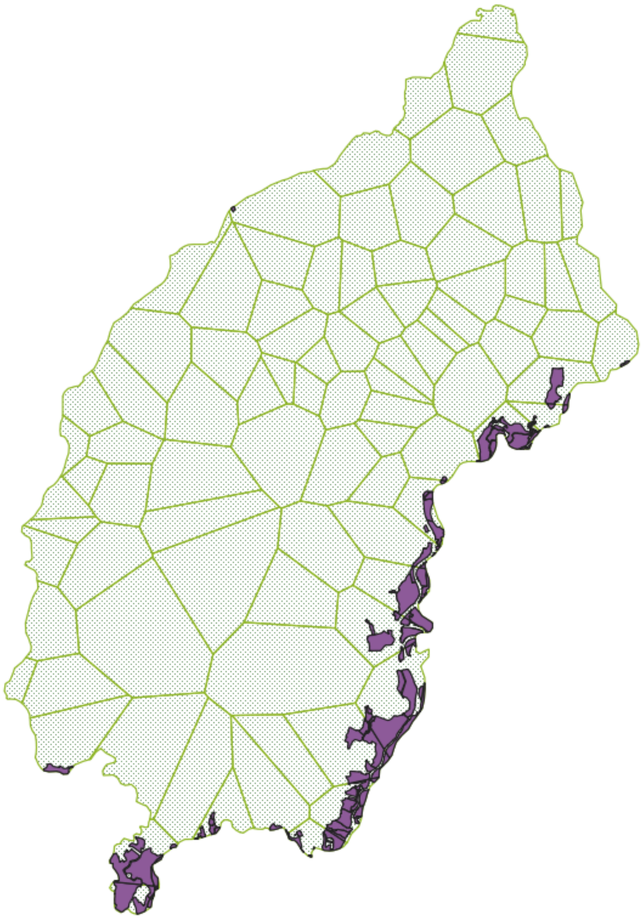


Fig. 3.7 Banana venues registry at AdM wetland territory. The year 2013.

On the other hand, farmland (includes livestock surface mixed with other agricultural activities) and annual crops also evidence a high impact at the Guayas Ecosystem. Stochasticity, spatial heterogeneities, overgrazing mixed with cultivating temporary crops and monocultures (e.g. banana plantations) influence on land degradation and deforestation, which leads to a land mosaic fragmentation, poor land management, and fragile crops units exposed to unpredictable climate conditions (e.g. El Niño and La Niña climate phenomenon's).

3.4. Main points in review

- Fragmentation implies, in general, species loss and degradation of ecosystems services. It produces multiple interwoven effects like reductions of biodiversity, decreasing forest biomass, and changes in nutrient cycling. The effects of fragmentation are not only important from an ecological point of view but also that of human activities, as ES are deeply influenced by the level of landscape fragmentation.

- On the contrary, when fragmentation affects not pristine or forested areas, but agricultural and livestock landscapes, it might entail significant benefits for biodiversity and sustainability as a whole, since the impacts that agriculture has on biodiversity are mitigated when the scale is small. At this point of analysis, we cannot discern whether fragmentation affects significantly the trade-offs and synergies of ES and Guayas and AdM ecosystems.
- In this chapter, and given the amount and type of data available, we have used three indicators to assess fragmentation in Guayas and AdM ecosystems: (1) the scaling exponent α of the patch size distribution, (2) the proportion of the largest patch relative to the total area RS_{max}, and (3) temporal trend in the fluctuations of the largest patch size ratio ΔRS_{max}. We define a fragmentation index f_i as the simple and normalized addition of the results given by the indicators in the form of binary values.
- In the Guayas and AdM ecosystems, fragmentation has increased in the period of study. This can be due to a decrease in regulating landscapes areas, or an increase in the different provisioning plantations. In order to detect fragmentation impact on ES and its evolution, fragmentation must be integrated into a methodology to assess ES. We use f_i in Chapter 4 to perform this assessment.

3.5. References

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3.6. Appendices

3.6.1. Power-law scaling parameter value α, lower bound to the power-law behavior x_{min}, occurrences in the power-law tail n_{tail}, 95% error, and test of power-law behavior by LULC and year, for the Guayas ecosystem. Positive values of the likelihood ratio R favor the power-law model. Values of $p < 0.1$ (in bold) imply that results can be trusted.

						PL + cutoff		Lognormal		Exponential		Stretched exp.	
LULC (Guayas)	**Year**	**α**	**x_{min}**	**n_{tail}**	**error**	**R**	**p**	**R**	**p**	**R**	**p**	**R**	**p**
Water	1990	1,9126	175500	1163	0,0267	-0,4363	0,5047	-0,7498	0,4533	2,9268	**0,0034**	0,4752	0,6346
	2000	1,9912	1020600	235	0,0646	-0,3041	0,8442	0,0281	0,9775	2,633	**0,0084**	0,7733	0,4392
	2008	1,6996	45000	2149	0,015	-1,3055	**0,0148**	-1,4917	0,1357	5,1813	**0.000**	0,1679	0,8666
	2014	1,7314	45900	2364	0,015	-2,8464	**0,0425**	0,5194	0,6034	14,2738	**0.000**	3,6765	**0,0002**
Arboriculture	1990	2,3768	375300	43	0,2099	0,0007	0,9996	-0,992	0,3211	2,4034	**0,0162**	1,0592	0,2894
	2000	2,3643	370800	63	0,1718	-1,0423	0,1951	-0,67	0,5028	1,5162	0,1294	-0,6995	0,4841
	2008	1,9919	372600	233	0,06498	-1,8669	**0,0221**	-1,2106	0,226	3,9445	**0.000**	-1,2512	0,2108
	2014	1,9002	157500	2917	0,0166	-0,689	0,4625	-0,2685	0,7882	5,2634	**0.000**	2,2067	**0,0273**
Banana	1990	2,0545	536400	215	0,0719	-1,0615	0,1796	-0,5086	0,611	3,3351	**0,0008**	-0,0549	0,9561
	2000	2,0685	604800	276	0,0643	-1,1615	0,3181	-0,2097	0,8338	5,4341	**0.000**	0,6845	0,4936
	2008	1,7608	250200	586	0,0314	-1,7108	**0,0139**	-1,2866	0,1982	4,9049	**0.000**	-0,8361	0,403
	2014	1,7767	61200	3099	0,0139	-1,0252	0,309	-1,0429	0,2969	6,3767	**0.000**	1,3304	0,1833
Annual Crops	1990	2,0884	468900	1332	0,0298	-0,3899	0,9258	-0,885	0,3761	7,1615	**0.000**	2,383	**0,0171**
	2000	2,1278	1615500	472	0,0519	-0,6924	0,6296	0,2898	0,7719	5,3958	**0.000**	1,4572	0,145
	2008	1,7658	144900	1692	0,0186	-1,1	0,4428	-1,1833	0,2366	6,6728	**0.000**	0,0882	0,9296
	2014	1,9882	319500	2211	0,021	-0,2171	0,9874	0,1372	0,8908	7,114	**0.000**	1,9234	**0,0544**
Other	1990	1,9567	351900	362	0,0502	-0,6837	0,7685	-2,0993	**0,0357**	6,2199	**0.000**	2,0862	**0,0369**
	2000	1,9992	313200	536	0,0431	-0,5679	0,8393	-1,7732	**0,0761**	6,3591	**0.000**	2,2065	**0,0273**
	2008	1,9185	125100	740	0,0337	0,0503	0,8921	0,3155	0,7523	6,1063	**0.000**	1,5296	0,126
	2014	1,7725	100800	592	0,0317	-1,4574	0,1805	-0,3345	0,7379	6,2261	**0.000**	1,0414	0,2976
Anthropic	1990	2,021	693000	86	0,1101	-0,7037	0,4469	-0,3027	0,7621	2,4645	**0,0137**	0,0181	0,9854
	2000	2,0401	1049400	80	0,1162	-0,7612	0,3826	-0,4698	0,6384	2,2367	**0,0253**	-0,33677	0,7362
	2008	1,6301	37800	829	0,0218	-2,9986	**0.000**	-2,5808	**0,0098**	6,922	**0.000**	-2,5852	**0,0097**
	2014	1,8397	166500	614	0,0338	-1,2082	0,1097	-0,7303	0,4651	4,5324	**0.000**	0,1329	0,8942
Farmland	1990	1,998	497700	4103	0,0155	0,0022	0,9972	-1,917	**0,0552**	9,4648	**0.000**	4,2299	**0.000**
	2000	1,9028	473400	3672	0,0149	-0,4435	0,9489	-1,407	0,1594	9,904	**0.000**	3,964	**0.000**
	2008	1,9333	552600	3675	0,0153	0,0067	0,9948	-2,8468	**0,0044**	14,052	**0.000**	3,8639	**0.000**
	2014	1,8785	129600	11936	0,008	0,1413	0,7752	0,9715	0,3312	12,4846	**0.000**	5,4964	**0.000**
Forestry and natural vegetation	1990	1,8331	321300	5238	0,0115	-0,0302	0,9962	1,8427	**0,0653**	10,3535	**0.000**	4,6455	**0.000**
	2000	1,8513	311400	5712	0,0112	0,085	0,9942	-1,7397	**0,0819**	9,1348	**0.000**	4,4395	**0.000**
	2008	1,8588	479700	4555	0,0127	-0,0177	0,9932	-2,1397	**0,0323**	9,6743	**0.000**	4,0204	**0.000**
	2014	1,8087	250200	6376	0,0101	2,9931	**0.000**	-1,0878	0,2766	9,1361	**0.000**	4,9983	**0.000**

3.6.2. Power-law scaling parameter value α, lower bound to the power-law behavior x_{min}, occurrences in the power-law tail n_{tail}, 95% error, and test of power-law behavior by LULC and year, for the Abras de Mantequilla (AdM) wetland ecosystem. Positive values of the likelihood ratio R favor the power-law model. Values of $p < 0.1$ (in bold) imply that results can be trusted.

						PL + cutoff		**Lognormal**		**Exponential**		**Stretched exp**	
LULC (AdM)	**Year**	α	x_{min}	n_{tail}	**error**	**R**	**p**	**R**	**p**	**R**	**p**	**R**	**p**
Water	1990	2,0919	28800	81	0,1213	-1,1781	0,1555	-0,5966	0,5507	2,5505	**0,0107**	-0,588	0,5565
	2000	3,0915	75600	13	0,58	0,0018	0,9968	-1,1799	0,238	1,4575	0,1449	0,5837	0,5593
	2008	2,4042	35100	10	0,444	-0,3231	0,7162	-0,1131	0,9098	0,9201	0,3574	-0,0513	0,959
	2014	2,5095	227700	9	0,5031	-0,0326	0,9839	-1,2574	0,2085	1,903	**0,057**	0,8691	0,3847
Arboriculture	2014	1,9634	16200	174	0,073	-0,3826	0,7125	-0,179	0,8579	2,2646	**0,0235**	0,3491	0,7269
Banana	1990	1,6624	135900	20	0,1481	-0,7504	0,4196	-0,2732	0,7846	2,5203	**0,0117**	-0,1928	0,8471
	2000	2,025	1206000	9	0,3419	-0,5789	0,3982	-0,3575	0,7206	0,39293	0,6943	-0,3667	0,7137
	2008	1,4095	49500	15	0,1057	-1,2096	**0,0851**	-0,8531	0,3935	1,6851	**0,0919**	-0,8782	0,3798
	2014	1,6752	68400	45	0,1006	-0,7687	0,4618	-0,0529	0,9577	3,0801	**0,002**	0,3736	0,7086
Annual Crops	1990	2,8135	639000	34	0,311	-0,6131	0,4484	-0,3828	0,7018	0,9002	0,3679	-0,3959	0,6921
	2000	2,0221	485100	33	0,1779	-0,002	0,9991	-1,015	0,31	3,122	**0,0017**	1,2479	0,212
	2008	1,3317	115200	19	0,0761	-0,9347	0,3235	-0,2803	0,7791	6,0959	**0.0000**	0,018	0,9856
	2014	1,6931	148500	35	0,1171	-0,2499	0,9601	-1,018	0,3086	5,0455	**0.0000**	1,0846	0,278
Anthropic	2014	1,7122	11700	25	0,1424	-0,5617	0,6414	-1,3714	0,1702	5,058	**0.0000**	0,8504	0,395
Farmland	1990	1,7436	41400	228	0,0492	-0,6777	0,4598	-1,0782	0,2809	2,6744	**0.0000**	-1,0442	0,2963
	2000	1,6427	56700	145	0,0533	-2,7442	**0.0000**	-2,2158	**0,0267**	2,401	**0,0163**	-2,3218	**0,0202**
	2008	2,9827	662400	52	0,2749	-0,741	0,3381	-0,4811	0,6304	0,8684	0,3851	-0,4963	0,6196
	2014	1,9359	72900	220	0,0631	-1,0524	0,1974	-0,5147	0,6067	3,4475	**0,0005**	-0,043	0,9656
Forestry and natural vegetation	2014	2,0435	19800	113	0,0981	-0,3207	0,8351	-0,0513	0,959	2,3995	**0,0164**	0,4569	0,6476

3.6.3. RS_{max}, $\langle RS_{max}\rangle$, ΔRS_{max}, S_{max}, $\langle S_{max}\rangle$, ΔS_{max}, by LULC and year, for the Guayas ecosystem. Bold values indicate a fragmented state while underlined ones indicate a connected state.

LULC (Guayas)	Year	RS_{max}	$\langle RS_{max}\rangle$	ΔRS_{max}	S_{max}	$\langle S_{max}\rangle$	ΔS_{max}
Water	1990	0,361	0,265	0,095	1002604500	780673050	221931450
	2000	0,338		0,072	915697800		135024750
	2008	0,311		0,045	1027528200		246855150
	2014	**0,053**		-0,213	176861700		-603811350
Arboriculture	1990	0,562	0,222	0,339	68833800	420112575	-351278775
	2000	**0,058**		-0,164	4953600		-415158975
	2008	**0,060**		-0,163	28428300		-391684275
	2014	0,210		-0,012	1578234600		1158122025
Banana	1990	**0,097**	**0,126**	-0,029	66352500	443156850	-376804350
	2000	**0,055**		-0,071	56845800		-386311050
	2008	**0,156**		0,029	319007700		-124149150
	2014	**0,197**		0,071	1330421400		887264550
Annual Crops	1990	**0,057**	**0,087**	-0,030	342434700	850623300	-508188600
	2000	**0,050**		-0,038	283864500		-566758800
	2008	**0,140**		0,052	1339427700		488804400
	2014	**0,104**		0,016	1436766300		586143000
Other	1990	**0,107**	**0,122**	-0,015	160858800	191922975	-31064175
	2000	**0,103**		-0,019	190049400		-1873575
	2008	**0,146**		0,023	263942100		72019125
	2014	**0,134**		0,011	152841600		-39081375
Anthropic	1990	**0,183**	**0,161**	0,021	72513900	116948925	-44435025
	2000	**0,174**		0,012	87975000		-28973925
	2008	**0,114**		-0,048	85798800		-31150125
	2014	**0,176**		0,014	221508000		104559075
Farmland	1990	**0,102**	**0,097**	0,004	5738964300	9353932425	-3614968125
	2000	**0,107**		0,010	6308510400		-3045422025
	2008	**0,083**		-0,014	1,7554E+10		8200049175
	2014	**0,098**		0,001	7814273400		-1539659025
Forestry and natural vegetation	1990	**0,199**	0,221	-0,022	8,1654E+10	6,1969E+10	19685083950
	2000	0,234		0,013	6,826E+10		6290357850
	2008	**0,157**		-0,064	3,8744E+10		-23225741550
	2014	0,295		0,073	5,922E+10		-2749700250

3.6.4. RS_{max}, $\langle RS_{max} \rangle$, ΔRS_{max}, S_{max}, $\langle S_{max} \rangle$, ΔS_{max}, by LULC and year, for the Abras de Mantequilla (AdM) wetland ecosystem. Bold values indicate a fragmented state while underlined ones indicate a connected state.

LULC (AdM)	Year	RS_{max}	$\langle RS_{max} \rangle$	ΔRS_{max}	S_{max}	$\langle S_{max} \rangle$	ΔS_{max}
Water	1990	**0,076**	0,233	-0,158	778500	1026225	-247725
	2000	0,202		-0,031	550800		-475425
	2008	0,317		0,083	356400		-669825
	2014	0,341		0,106	2419200		1392975
Arboriculture	2014	0,409	0,408	-	10304100	10304100	-
Banana	1990	0,460	0,397	0,063	20619000	20361375	257625
	2000	0,283		-0,113	11992500		-8368875
	2008	0,385		-0,012	15273900		-5087475
	2014	0,459		0,062	33560100		13198725
Annual Crops	1990	**0,060**	0,550	-0,490	4654800	600375600	-595720800
	2000	<u>0,717</u>		0,166	172364400		-428011200
	2008	0,478		-0,073	1339427700		739052100
	2014	<u>0,947</u>		0,396	885055500		284679900
Anthropic	2014	0,378	0,377	-	2137500	2137500	-
Farmland	1990	0,562	0,211	0,350	131238900	40819500	90419400
	2000	**0,102**		-0,109	9337500		-31482000
	2008	**0,034**		-0,177	4269600		-36549900
	2014	**0,147**		-0,064	18432000		-22387500
Forestry and natural vegetation	2014	0,356	0,356	-	5727600	5727600	-

3.6.5. Glossary of acronyms

AdM	*Abras de Mantequilla*
ES	Ecosystem service
GE	Guayas ecosystem
LULC	Land-use and land-cover

4

Ecosystem service bundles. Trade-offs, synergies, and dynamics

One important challenge of ecosystem management is determining how to manage multiple ecosystem services (ES) in diverse landscapes. Actions to enhance the supply of some ES, mainly provisioning (i.e., food and timber) have led to declines in many other ES, including regulating and cultural ones (i.e., nutrient cycling, flood regulation, opportunities for recreation, etc.) (Millennium Ecosystem Assessment, 2005; Raudsepp-Hearne, Peterson and Bennett, 2010). According to The Millennium Ecosystem Assessment (MA), a major international assessment of the world's ecosystem services, addressing this challenge requires identifying trade-offs and synergies that exist among ES at different scales. The MA and others suggest that ecological management that considers and manages these ecosystem-service interactions is likely to be able to produce far better outcomes for societies (Carpenter *et al.*, 2009; Nelson *et al.*, 2009).

A natural system formed by the set of existing living organisms and the environment where they live can be defined as an ecosystem. According to the Millennium Ecosystem Assessment (2005), 10 types can be distinguished according to their characteristics: marine, coastal, inland waters, forests, deserts, islands, mountains, poles, crops, and urban ecosystems. Thus, ecosystems are systems that, if operated in optimal conditions, are capable of regulating the quantity and quality of water, providing productive soils and a series of services designed to guarantee the well-being of life support systems and human life. To perform these functions, ecosystems require protection and management, without which serious environmental, social and economic consequences would be generated. Therefore, it is clear that to achieve sustainable management, for example, of water resources and their ecosystem functions, taking into account human needs, a comprehensive approach is needed. This comprehensive approach is evident from the term "environmental services", which implies the sum of the benefits that human societies receive from ecosystems and that allow a quality of life to be maintained directly or indirectly. Environmental services, according to the Millennium Ecosystem Assessment (2005), can be classified into four types: supply, regulatory, cultural or support. This ecosystem approach is presented as a timely strategy to maintain these ES through conservation of the structure and functioning of ecosystems within the processes that aim to establish imbalances and synergies between social, economic and environmental variables (Herbert *et al.*, 2010). Even the Convention on Biological Diversity (CBD) defines this "ecosystem approach" as "a strategy for the integrated management of land, water, and living resources that promotes conservation and sustainable use in an equitable manner" (Elmqvist and Tuvendal, 2011). In the case of Latin America, large-scale changes in land use are occurring and have important implications for the future of freshwater and coastal marine ecosystems and their management (Yáñez-Arancibla and Lara-Domínguez, 1999). However, relatively little is known about the potential impact of land use and the alteration in large-scale biogeochemistry of tropical aquatic ecosystems (Bonell, 1998). Rapid population growth and increasing international demand for tropical products have resulted in the conversion of vast areas of land for intensive agricultural production in Ecuador, as is typical of many other tropical developing regions of the world (Houghton, 1994). Agricultural production was dominated by cocoa in the 1920s and 1930s, and from the 1950s to the present, bananas have been Ecuador's most important agricultural export product. Recently, the area devoted to these export crops has increased; between 1980 and 2000 the harvest area increased by close to 140 thousand hectares of banana and 160 thousand hectares for cocoa (FAO, 2019). Other export products, such as oil during the 1970s and shrimp farming in the 1980s, have exacerbated the deforestation of the Amazon region and the mangrove forest in coastal areas. The economic benefit of exporting these products to meet international demands has been the engine of deforestation and land use in Ecuador and especially in the Guayas river basin. Extensive land use conversions often result in dramatic changes in land use. regional hydrology (Cronan, Piampiano and Patterson, 1999; Sampurno Bruijnzeel, 2006), alterations of biogeochemical cycles (Galloway *et al.*, 2004; Borbor-Cordova *et al.*, 2006), losses of nutrients such as nitrogen and phosphorus (Howarth *et al.*, 1996; Cole *et al.*, 2011), and soil degradation (Ojima, Galvin and Turner, 2006). Previous studies in temperate and tropical areas have found strong links between large-scale changes in land use and associated nutrient flows in land and water (Valiela and Bowen, 2002; Filoso *et al.*, 2003; Galloway *et al.*, 2004).

In this chapter, we modify an existing methodology to quantify the provision of and interactions among multiple ES across landscapes. This existing methodology is based on the concept of *ecosystem service* (ES) *bundles* to analyze interactions among ES (Raudsepp-Hearne, Peterson and Bennett, 2010). Most definitions of ES bundles (explicit or implied) focus on the spatial coincidence of the delivery of a range of services. Some authors expand the definition: Raudsepp-Hearne et al. (2010) suggest that they are “sets of the ES that repeatedly appear together across space or time”, while García-Nieto et al. (2013) extend the idea to the relationships between ES supply and ES demand bundles. Here we assume that ES bundles are defined as “a set of associated ES that is linked to a given ecosystem and that usually appear together repeatedly in time and/or space” (Berry *et al.*, 2016). This definition applies to the ES supply bundles, as those on the demand side have different natures and we define them as "A set of associated to the ES that is demanded by humans from the ecosystem(s)". In an ecosystem or landscape, this set of services could be demanded by different groups of stakeholders. For example, in the Sierra Nevada, Berry *et al.* (2016), found that a bundle of ES (i.e. water regulation, erosion control, soil fertility, food from traditional farming) mostly demanded by farmers who manage the land extensively, while tourists mostly demanded other bundles (recreation, aesthetic values, air purification, carbon sequestration). The first bundle is more related to agroecosystems and the second one is more related to forests, although both take place in the same multifunctional landscape.

The ES within these bundles can interact with each other, potentially leading to synergies and trade-offs, although there may be limits on the extent of realization of the synergies due to constraints on the ability of the ecosystem to deliver each service to the desired level and/or management practices and/or the negative interactions between certain ES.[1] A synergy is can be viewed as where the use of one service increases the benefits supplied by another and a trade-off as a situation in which the use of one service decreases the benefits supplied by another service, now or in the future (Raudsepp-Hearne, Peterson and Bennett, 2010; Felipe-Lucia *et al.*, 2015). ES synergies and trade-offs are causally linked (i.e. respond to the same driver or truly (functionally) interact), but it is not essential that they occur in the same location.

Our modification of the above-mentioned methodology draws on the concept of fragmentation and fragmentation index f_i presented in Chapter 3, which we include as a weight for some of the ES considered, and its influence on the temporal evolution of these ES. We analyze the status and provision of a group of the ES identified across various territories within an ecosystem unit, which permits to present empirical evidence of trade-offs, synergies, and regional clusters. The analysis has been applied to the “Abras de Mantequilla” (AdM) wetland sub-ecosystem of the Guayas ecosystem. In this final chapter, we aim at assessing ES in this Ecuadorian ecosystem and analyzing their evolution in the last twenty years. Some of the questions that we would like to answer here are the following:

- Are certain ES always bundled together, or does this differ across landscapes, time, and space?
- Are there are general social or ecological conditions that change how ES is bundled?
- How fragmentation affects ES and social or ecological conditions?
- Are some ES or categories of ES more or less tightly bundled than others?

[1] http://www.openness-project.eu/library/reference-book/sp-ES-bundles

4.1 Evolution of ES bundles in AdM

Following (Raudsepp-Hearne, Peterson and Bennett, 2010), ecosystem service bundles have been identified using spatial data. As a novelty, we compare ES bundles in time, with temporal data spanning 18 years (i.e., from years 2000, 2010 and 2018). We use administrative boundaries, if social processes shape the production and consumption of ES and that the use of socially defined boundaries allows us to identify different social-ecological systems on a landscape. We also specifically examine interactions among provisioning, regulating, and cultural ecosystem services, because many regulating services underlie the production of provisioning and cultural services.

Ecosystem service	Aggregate level	Unit	f_i
Provisioning			
Crops			
Palm oil	Farmland	Percent of land in crop	0.3
Banana	Banana	Percent of land in crop	0.6
Cocoa	Arboriculture	Percent of land in crop	0.3
Maize	Annual crop	Percent of land in crop	0.6
Rice	Annual crop	Percent of land in crop	0.6
Livestock activity			
Livestock	Forestry and nat. veg.	Percent of land in pasture	0.6
Water			
Quality	-	Average WQI	-
Cultural			
Forest recreation	-	Percent of sustainable, public and cultural sites	0.6
Regulating			
Carbon sequestration	-	kgC/km^2	-
Soil nutrients	-	Percent of N, P, K values	-
Scrubland	Forestry and nat. veg.	Percent of land in scrubland	0.6

Table 4.1 Description of ES analyzed, units, data source, and associated fragmentation index f_i.

We have identified patterns of interactions among 11 ES (Table 4.1) through the analysis of ecosystem service bundles in "Abras de Mantequilla" wetland, and we have quantified provisioning, regulating, and cultural ES across *recintos* ($N = 91$), defined as rural villages. Data sources for the different ES can be found in the Annexes. Table 4.1 includes also a column for the aggregate level where each ES can be classified, and the fragmentation index f_i (see Chapter 3). For each ecosystem service, f_i has been chosen for the closest level of aggregation.

For example, Cocoa has been determined as a provisioning ES with a f_i of 0.3, which is the "arboriculture" land-cover fragmentation coefficient calculated in Chapter 3. The usage of each fragmentation value has been designated according to its closest or similar land-use-land-cover nature detailed in the previous chapter. In the case of "Forest recreation" ES, it has been used a f_i of 0.6 from the "Forest" land-cover fragmentation coefficient found at the Guayas ecosystem scale. We rather consider this value at a GE scale, due to the scarcity of "Forest" class patches at AdM wetland. We have considered every sustainable-public-cultural site within the AdM limits as a percentage of units of forest recreation. Every unit value means a *recinto* unit that belongs to the wetland territory.

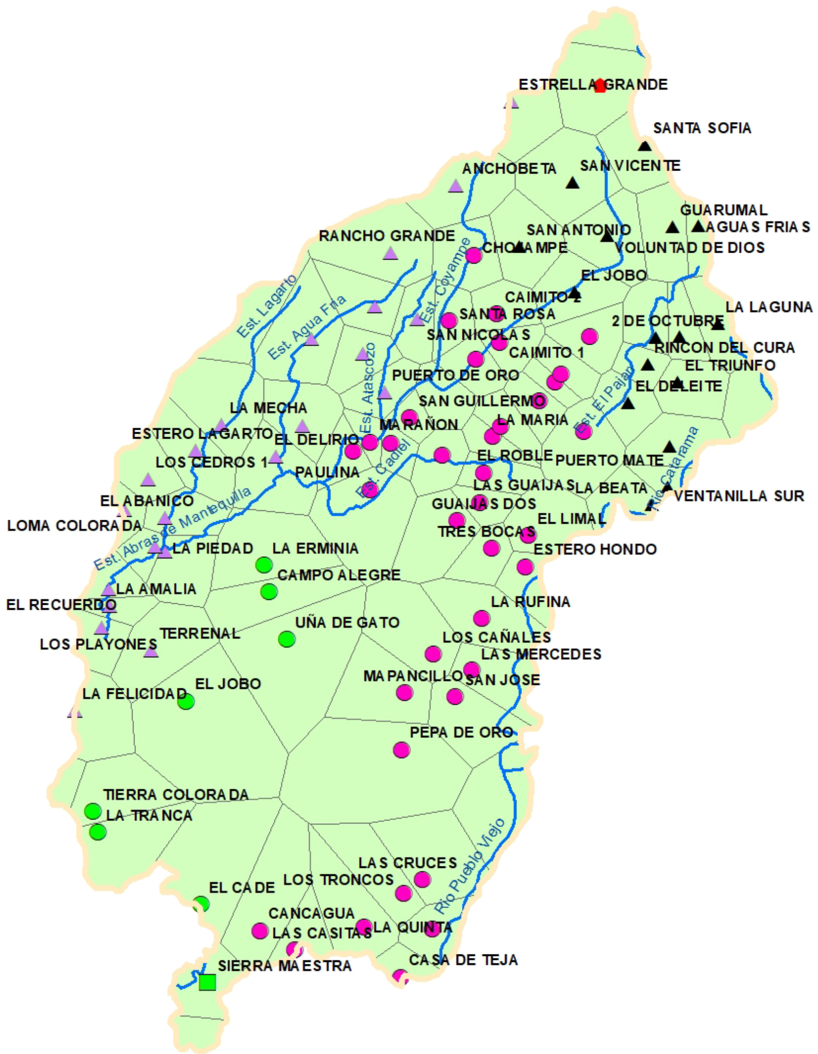


Fig. 4.1 Voronoi cells distribution and recintos as seed for the AdM region, identified by every district.

We chose our study site for analyzing its ES trade-offs, synergies and bundles, because of its RAMSAR-site status that houses a diverse biodiversity that constitutes the habitat of numerous species of animals and plants, many of which are now threatened or on the verge of extinction as a result of the destruction of their habitats and the irrational exploitation to which they are subjected. Mammals such as Lontra Longicaudata, Alouatta palliata, Leucopternis Occidentalis, Crypturellus transfasciatus, Pachyramphus Spodiurus, Acestrura Bombus, Brotogeris pyrrhopterus and Onychorhynchus occidentalis are under threat. Regarding birds and according to the Red Book of Threatened Birds of Ecuador,[2] at least about 20 species of waterfowl are "Critically Endangered", "Endangered" or are "Vulnerable" species.

In addition, as a RAMSAR site, the AdM is obliged to maintain its the ecological conditions as a wetland, promote its rational use and establish a zone that ensures the conservation of its ecosystem services, or at least a resilient balance in this typical agricultural landscape in the Ecuadorian region coast. The 11 ecosystem services included in this study aim at reflecting varied uses of the land, from agricultural, recreational and environmental perspectives. We have used a diversity of available public datasets, such as regional and local reports, census and imagery scanning data, which have permitted to apply associated performance measures, the evaluation of trade-offs and synergies assessments and the identification of ES bundles.

In order to define a workable administrative area and use it with the spatial analysis, a Voronoi diagram has been created in order to make a partitioning of the AdM plane into regions, based on the distance to the aforementioned *recintos*, used as seeds for the Voronoi algorithm. The Voronoi algorithm denotes the Euclidean distance between two points p and q by dist (p,q):

$$\text{dist}\,(p,q) \coloneqq \sqrt{(p_x - q_x)^2 + \left(p_y - q_y\right)^2} \tag{4.1}$$

where $P \coloneqq (p_{1,}p_2 \dots, p_n)$ is a set of n distinct points in the plane. These points are the *recintos'* sites within the limits of the AdM wetland. We define the Voronoi diagram of a P the subdivision of the plane into n cells, one for each *recinto* in *P,* with the property that a point q lies in the cell corresponding to a site p_i if and only if $dist\ (q, p_i) < dist\ (q, p_j)$ for each $p_j \in P\ with\ j \neq i$. The subdivisions induced by this model are called the Voronoi diagram, created according to our set of 90 sites located within the limits of the AdM wetland (Fig. 4.1). From this Voronoi diagram, we can derive all kinds of information about the areas of the *recintos* and their ES behaviors along with the wetland territory. We have chosen the Voronoi diagram

[2] https://www.nationalredlist.org

because is a versatile geometric structure than can be applied to a social-ecological-geographical context like our study site.

Our approach comprises of four parts, with and without including the fragmentation index:

1. Analysis of trade-offs and synergies between all pairs of ES and between categories of ES.
2. Identification and analysis of ES bundles.
3. Analysis of the temporal evolution of individual ES, trade-offs, and synergies between all pairs of the ES, and including the impact of fragmentation.

4.1.1 Interactions among ES

Interaction among ES implies correlation analysis. It was performed on each pair of services using R statistical software (R Core Team, 2014) for all *recintos* considered ($N = 90$). Correlations were analyzed using the Pearson parametric correlation test. We only present years 2000 and 2018, since variations in the correlation matrix for years 2000 and 2010 were not statistically significant, suggesting that the most important variation in ES for the AdM wetland happened in the last 10 years.

- **The year 2000**. Of the 55 possible pairs of ecosystem services, 25 pairs (45%) are significantly correlated. Although none of them are highly correlated (Pearson coefficient $r \geq 0.5$), 14 of them (25%) are moderately correlated ($r \geq 0.3$) and 11 (20%) are weakly correlated ($r < 0.3$). At the landscape scale, we observe trade-offs between palm oil, banana, and cocoa (provisioning) and the rest of the ES services. Scrubland (regulating) has significant negative correlations with most of the ES, especially with maize, rice, livestock, and water quality index. Banana and cocoa, accumulate the highest number of significant negative correlations with other services (Fig. 4.2). Livestock is negatively correlated with scrubland and banana. Water quality (highly dependent on regulating ES throughout watersheds) is also negatively correlated with cocoa and scrubland. Somehow unexpectedly, carbon sequestration and soil nutrients are negatively correlated. We also find potential synergies among ecosystem services. Maize, rice, and livestock are positively correlated with regulating and cultural ES, except scrubland. Carbon sequestration and forest recreation have the highest number of significant positive, except with palm oil and banana. Finally, soil nutrients are positively correlated with scrubland. Trade-offs between provisioning and regulating ES are problematic since regulating ones support the sustainable production of provisioning and cultural ones. Thus, they are important to the resilience of social-ecological systems. It has been suggested that the loss of regulating and cultural services in areas of high provisioning service production may undermine the sustainability of this production, diminish the possibility of diversifying economic activities, and impact local human wellbeing directly (Bennett, Peterson and Gordon, 2009).

Palm oil										
-0.07	**Banana**									
-0.06	0.26*	**Cocoa**								
-0.18	-0.40***	-0.45***	**Maize**							
-0.13	-0.32*	-0.46***	0.45***	**Rice**						
-0.32**	-0.47***	-0.27*	0.30**	0.37***	**Livestock**					
-0.17	-0.07	-0.25*	0.36***	0.17	0.26*	**Water.Q.**				
0.03	-0.03	0.08	-0.02	0.04	0.11	0.25*	**Forest. R.**			
-0.14	-0.21*	-0.01	0.08	0.04	0.27**	0.04	0.16	**Carbon**		
0.25*	-0.20	-0.04	-0.09	-0.15	0.07	-0.09	-0.03	-0.29**	**Soil**	
0.21*	-0.16	-0.17	-0.28**	-0.32**	-0.46***	-0.30**	-0.09	-0.04	0.30**	**Scrubland**

Provisioning Regulating Cultural

*Fig. 4.2 Significant correlations between pairs of the ES for year 2000 (*p<0.05, ** p<0.01, ***p<0.001). Red implies a negative correlation while blue implies a positive one.*

- **The year 2018**. After 18 years, of the 55 possible pairs of ecosystem services, 18 pairs (32.7%) are significantly correlated. In this case, one of them (1.8%) is highly correlated (Pearson coefficient $r \geq 0.5$), 6 of them (11%) are moderately correlated ($r \geq 0.3$) and 11 (20%) are weakly correlated ($r < 0.3$). These ES pairs were not included but they had a significant p-value: banana-cocoa (p-value = 0.08), cocoa-carbon (p-value = 0.08), rice-carbon (p-value =0.073) and rice-scrubland (p-value = 0.085). The main differences between the year 2000 and the year 2018 can be found in terms of trade-offs and synergies (Fig. 4.3).

Palm oil										
-0.01	Banana									
0.25*	-0.18	Cocoa								
-0.36***	-0.47***	-0.42***	Maize							
-0.10	0.05	0.17	-0.42***	Rice						
-0.11	-0.15	0.03	-0.10	-0.11	Livestock					
0.33**	-0.14	0.05	-0.04	-0.13	-0.12	Water Q.				
0.16	-0.05	0.21*	-0.24*	0.20*	-0.16	0.25*	Forest R.			
0.08	-0.23*	0.15	-0.15	0.19	0.10	0.04	0.16	Carbon		
-0.06	-0.27**	0.18	0.32**	-0.09	-0.23*	-0.09	-0.03	-0.29**	Soil	
-0.04	-0.51***	0.04	-0.01	-0.18	-0.11	0.26**	0.16	0.27**	-0.04	Scrubland

Provisioning Regulating Cultural

Fig. 4.3 Significant correlations between pairs of the ES for year 2018 ($p<0.05$, ** $p<0.01$, ***$p<0.001$). Red implies a negative correlation while blue implies a positive one.*

Palm oil and maize have increased their negative correlation and it is now highly significant, though palm oil has reversed its positive relation with soil nutrients and scrubland, which is now negative. This might be the result of several external and national factors that have influenced on palm oil negative correlations behavior. For example, the international prices have had a volatile tendency from 2008 to 2017, which is due to global demand increase from China and India. During the last 10 years, the maximum peak reached in 2011, with a price of USD 1,125/t, while the lowest value was in 2015, priced at USD 622/t (World Bank Group, 2018). The pricing variability has affected the Ecuadorian exports of crude and refined palm oil showing a decrease of 9% in 2017. In a national context, the palm oil agricultural sector has suffered the presence of pests since the 1990s. In 2017 24% of the land dedicated to the production of the oil palm crop was affected by the presence of pests and diseases. In terms of yield production, it is observed that from 2012 there is a downward trend, until 2014. Subsequently, it is evident that it begins to slightly recover since 2015, to finally be in 2017 at 11.2 t/ha (Fig. 4.4).

Palm oil cultivations are a permanent crop, which requires high production costs. For example, for the establishment of one hectare of palm, the cost ranges from USD 2,200 to USD 4,700; where 93% of the costs correspond to the preparation of the land and the crop planting process. The province "Los Ríos", where the AdM wetland is located, concentrates 14% of the national production, with a yield of 11.14 t/ha which is quite below the highest production yield which is 13.66 t/ha.

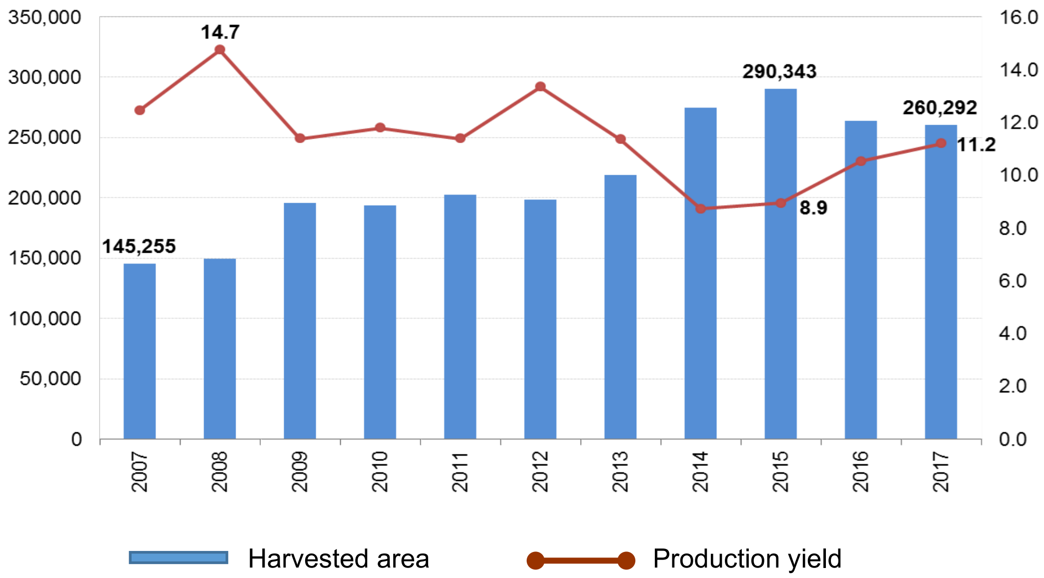
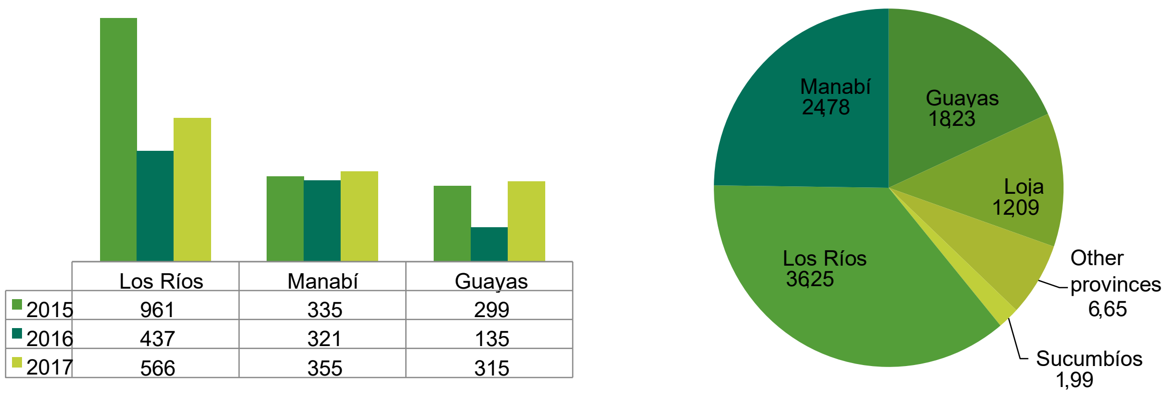


Fig. 4.4 National area and yield of oil palm during period 2007-2017, expressed in harvested area (left- y-axis) and in tm/ha (right-x-axis). (Salazar et al., 2017)

When it comes to analyzing the increase in maize negative correlations, the factors that influence this pattern are more related to phenological and phytosanitary conditions of this crop and how extreme climatic phenomena affect its production. The province of "Los Ríos" is the main producer of dry hard maize, with 36.25% of the national production and with the highest yield per ha, even though there is a remarkable decrease in 2016. (Fig. 4.5).



	Los Ríos	Manabí	Guayas
2015	961	335	299
2016	437	321	135
2017	566	355	315

*Fig. 4.5 Dry hard maize production (thousands of Tm) and the national area is sown in 2017. (Salazar et al., 2017). * The values recorded in production and sales correspond to the primary state of the product, with which the producer quantifies the crop, that is, it contains a percentage of moisture and impurities.*

The sowing and harvesting calendar of maize varies two seasons (winter and summer). In Los Ríos the harvest months are between May and June. And in the summer season, it is harvested between October and November. Its dependence on climate and seasonal conditions makes maize a vulnerable crop when extreme climate events like El Niño occurs in the area. The last phenomenon (2015-2016), was characterized by extreme variations in precipitation and temperature worsening droughts, rainfalls, and floods. For example, our study area was exposed to warmer anomalies in air temperature (up to +4°C) and excess of rainfall. Additionally, economic losses of the Ecuadorian agricultural sector were estimated at USD 3.5 million with more than 2,000 farmers between medium and small producers, were affected. In the Coast region, the result of high temperatures and excess humidity affected short-cycle crops (i.e. maize and rice) and banana plantations.

In 2018, Banana is now negatively correlated with all ES, reaching its highest value against scrubland and maize. Maize has also reversed its correlation patterns from positive in 2000 to negative in 2018. Rice and livestock offer a similar pattern. Maize and rice are annual crops, both highly dependent on climatic conditions and generating lands usually filled with agrochemicals that might change the pattern of synergies and trade-offs during this amount of time. In this sense, a remarkable change happens with cocoa, which is now mostly positively correlated with all ES except maize, and scrubland, which is now positively correlated with water, forest recreation and carbon sequestration. Other reasons that might explain this change in ES in these 20 years can be found in the fact the AdM wetland was declared a RAMSAR site in 2000 (22500 ha.), but in 2008 its declared area was updated to 54886 ha. Then, in 2010 the "Municipal Association for the Sustainable Management of the AdM wetland" was created with the purpose of reinforcing the social, economic and ecological management capacities of the territory influence by the wetland. This municipal institution has been running sustainable agricultural projects related to the recovery, better management practices and technical advice of national fine/flavor cocoa plantations owned by small farmers. One of these initiatives is the "Peasant Training Network for the joint territory of the Abras de Mantequilla Wetland - Los Ríos Province", from 2015 to 2017. This project was promoted by the Ministry of Agriculture, Livestock, Aquaculture, and Fisheries (MAGAP), through the Rural Good Living Program with the participation of several local peasant organizations, given the need to train and/or strengthen the capacities of the farmers to improve their production processes. The participants were trained in the management of agroforestry systems, focusing on cocoa, which includes shadow management, integrated pest, and disease management, cocoa and fruit pruning, selection of vegetative material and clonal multiplication of cocoa plants (Fig. 4.6).

Fig. 4.6 Cocoa management practices in pruning techniques and phytosanitary controls during the training school for local peasants of the AdM. Photograph made by the author.

- **The year 2018 with fragmentation.** The introduction of the fragmentation index in the previous ES assessment offers a similar view, but now correlation coefficients have increased on average, both in positive and negative values. Fragmentation has been considered for those ES quantified by means of percent of the land (see Table 4.1) in the following way. Let a_i be the percentage of land with ecosystem service i in the year 2018. We assume that a process of fragmentation will tend to homogenize the probability distribution of areas, $p(a_i)$, reducing both ES with higher percentages and increasing those ES with lower percentages of the corresponding land. The percentage of land a_i^f with ecosystem service i in the year 2018 affected by fragmentation f_i can be quantified and normalized as:

$$a_i^f = \frac{(1-f_i)\cdot a_i}{\sum_i (1-f_i)\cdot a_i} \tag{4.2}$$

In this way, fragmentation induces a homogenization process (Fig. 4.7), where ES occupying higher percentages of land and with high indices of fragmentation are highly reduced (i.e., banana in Fig. 4.7), while others with a lower percentage of occupation and lower fragmentation index are increased.

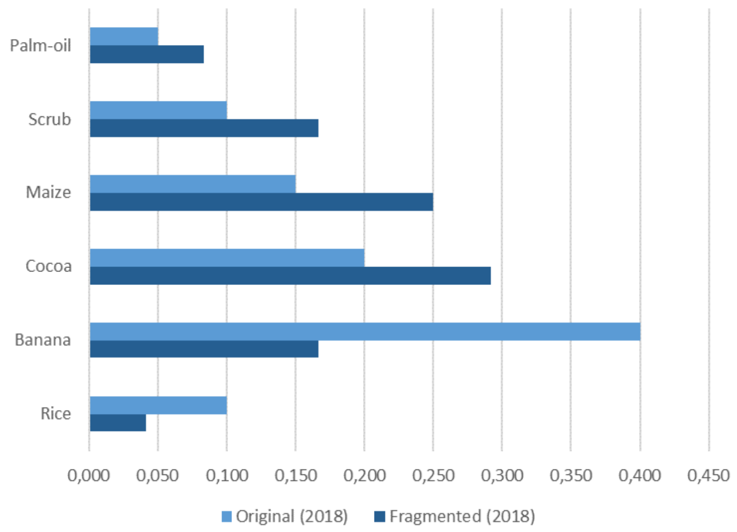


Fig. 4.7 Example of quantification of fragmentation for one particular recinto.

Palm oil										
0.02	**Banana**									
0.31**	-0.17	**Cocoa**								
-0.34***	-0.49***	-0.38***	**Maize**							
-0.08	0.05	0.18	-0.44***	**Rice**						
-0.05	-0.16	0.08	-0.13	-0.10	**Livestock**					
0.31**	-0.13	0.06	-0.06	-0.12	-0.12	**Water Q.**				
0.16	-0.05	0.22*	-0.24*	0.22*	-0.15	0.25*	**Forest R.**			
0.07	-0.24*	0.12	-0.16	0.19*	0.09	0.04	0.16	**Carbon**		
-0.05	-0.28**	0.21*	0.36***	-0.08	-0.19	-0.09	-0.03	-0.29**	**Soil**	
0.08	-0.56***	0.16	-0.08	-0.19	-0.14	0.29**	0.20*	0.26**	0.02	**Scrubland**

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*Fig. 4.8 Significant correlations between pairs of the ES for year 2018 considering fragmentation (*p<0.05, ** p<0.01, ***p<0.001). Red implies a negative correlation while blue implies a positive one.*

Of the 55 possible pairs of ecosystem services, 25 pairs (45%) are significantly correlated but two of them are highly correlated (Pearson coefficient $r \geq 0.5$): banana with maize and scrubland. In some sense, the inclusion of the fragmentation index intensifies the different correlations between ES (Fig. 4.8). This pattern could be the result of the fragmentation procedure explained previously and implemented at this point. The fact that fragmentation implies homogenization of the probability distribution of areas dedicated to crops, might result in less dispersed correlations and higher correlation coefficients between some of the ES pairs considered. At this point in the analysis, we cannot suggest any plausible hypothesis or mechanism that explains this pattern.

4.1.2 Identification and analysis of ES bundles

Cluster analysis has been used to identify groups of *recintos* with similar sets of ES (i.e., ecosystem service bundle types) where tradeoffs and synergies between ES are consistent. ES bundles are visualized using radial plots in Excel spreadsheet software. Clusters in the ecosystem service data have been identified and studied using cluster analysis by K-means in R with the cluster package. Scree plots and dendrograms, with WSS (within-cluster sum of a square) procedure, were used to determine the appropriate number of clusters.

- **The year 2000 (Fig. 4.9)**. Cluster analysis examining the provision of all 11 ES grouped the 91 municipalities into four data clusters (i.e., four types of ecosystem service bundles types). We classify and give a different name for each type, based on the ES provided and the principal activities occurring in these subsystems.
    - **Permanent provisioning (N = 11)**. Includes *recintos* that have significant amounts of permanent agriculture, like banana and cocoa, and very low values for all other ES, including regulating and cultural.
    - **Annual provisioning (N = 24)**. Comprises *recintos* that have significant amounts of annual agriculture, like maize and rice, and very low values for all other ES, except for water quality.
    - **Agro-recreation (N = 50)**. Thus, type presents for the year 2000 the highest share of *recintos* (55%) giving an idea of the predominant ES type of this zone twenty years ago. It includes *recintos* with moderate amounts of agriculture but significant forested areas that allowed livestock and, at the same time, the highest carbon sequestration values at that time.
    - **Regulating pristine (N = 6)**. Finally, this type includes those few *recintos* with very low levels of agriculture, including palm oil, but the highest values of regulating ES, like soil nutrients and scrubland.

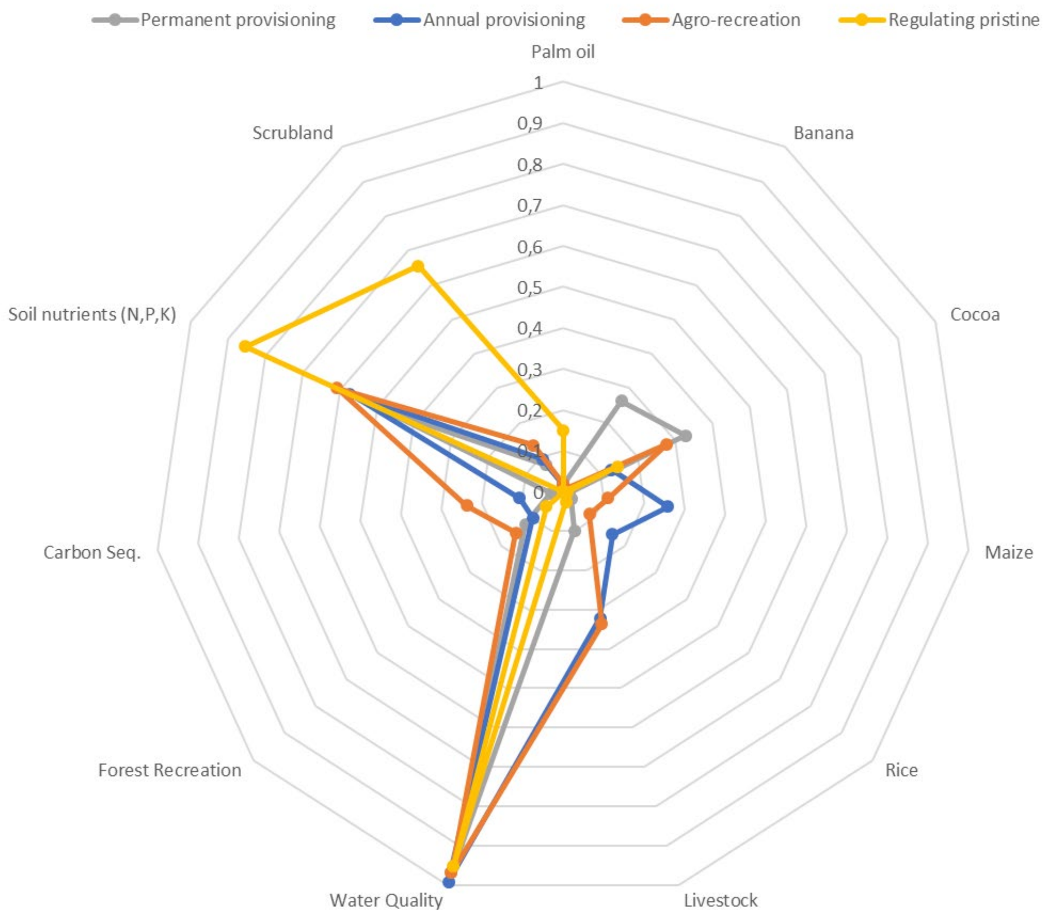

Fig. 4.9 ES bundle types for the year 2000. Values represent the average ES found within each cluster.

- **The year 2018 (Fig. 4.10)**. For this year cluster analysis examining the provision of all 11 ES grouped the 91 municipalities into four data clusters as well, but now with two significant differences: (a) a trend to monoculture is detected, for both permanent and annual provisioning ES, and (b) regulating ES seems to have been derived to, and mixed with, recreation ES on one side, and to have received the impact of some level of anthropogenic activity on the other. We classify and give a different name for each type, based on the ES provided and the principal activities occurring in these subsystems.
    - **(Banana) Permanent provisioning (*N* = 13)**. Includes *recintos* that have a significant amount of one permanent agriculture: banana. Cocoa has disappeared, and it keeps on maintaining very low values for all other ES, including regulating and cultural.
    - **(Maize) Annual provisioning (*N* = 44)**. This type has increased the number of *recintos* up to 83% and comprises now *recintos* that have a

significant amount of one annual agriculture: maize. Again, it shows low values for all other ES, except for water quality.

- **Agro-recreation-regulating (N = 18)**. Compared to the year 2000, this type has been reduced by 64% in numbers of *recintos*. It includes the highest levels of regulating ES, like soil nutrients and scrubland, but also cultural ones, like forest recreation. This change suggests a dynamic process to include tourism and recreation in mixed landscapes with regulating activities.
- **Regulating Anthropocene (N = 16)**. This type includes now those *recintos* with highest regulating values, like carbon sequestration, but also moderate ones, compared to the year 2000, like soil nutrients and scrubland, which have been clearly reduced. Since we observe an increase in rice and livestock, we termed this type "Regulating Anthropocene" to imply human impact in regulating ES, not present twenty years ago.

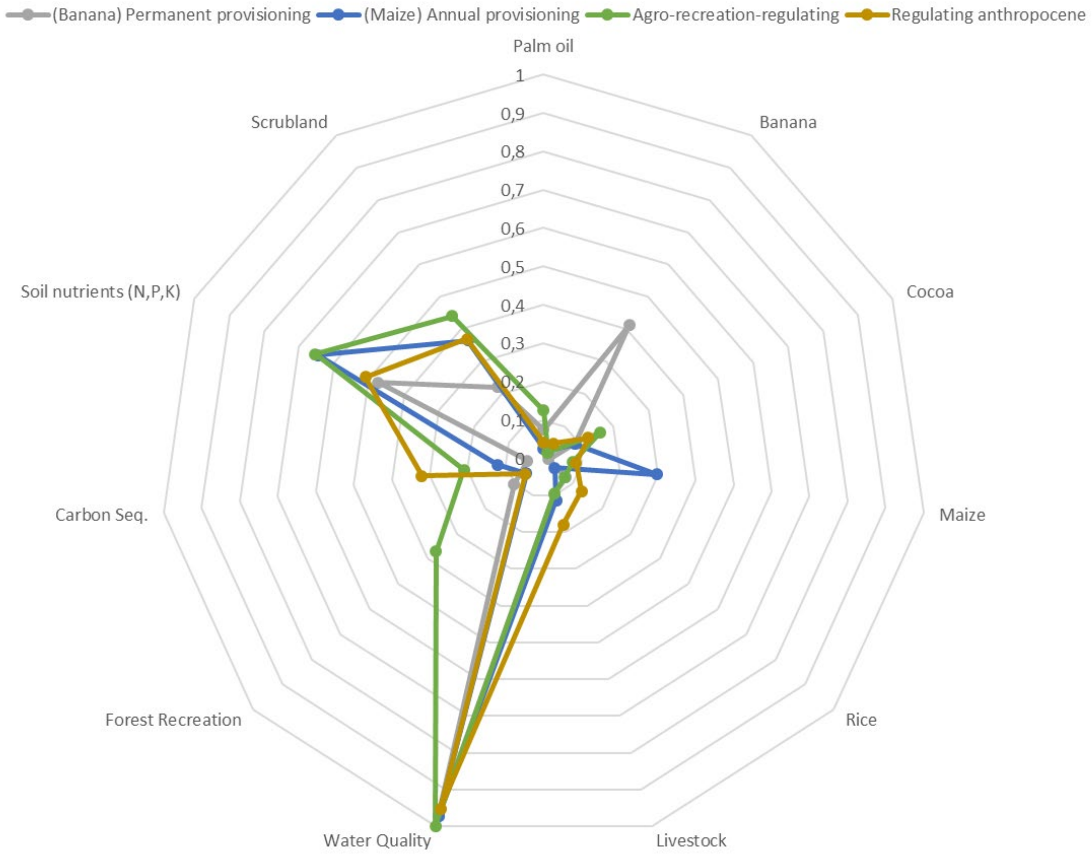

Fig. 4.10 ES bundle types for the year 2018. Values represent the average ES found within each cluster.

- **The year 2018 with fragmentation (Fig. 4.11)**. When trends in fragmentation are included in the year 2018, cluster analysis examining the provision of all 11 ES grouped the 91 municipalities into three data clusters. Significantly, carbon sequestration has been reduced and no clear regulating ES bundle type can be detected. Similar names can be used for the remaining three types.
    - **(Banana) Permanent provisioning (*N* = 13)**. No remarkable changes detected.
    - **(Maize) Annual provisioning (*N* = 59)**. This type keeps on increasing the number of *recintos* included in it. Apart from this, no remarkable changes can be detected**.**
    - **Agro-recreation-regulating (*N* = 19)**. It includes now the highest values for regulating (i.e., scrubland, soil nutrients, and carbon sequestration) and cultural (i.e., forest recreation) ES, and very low values for agricultural ones.

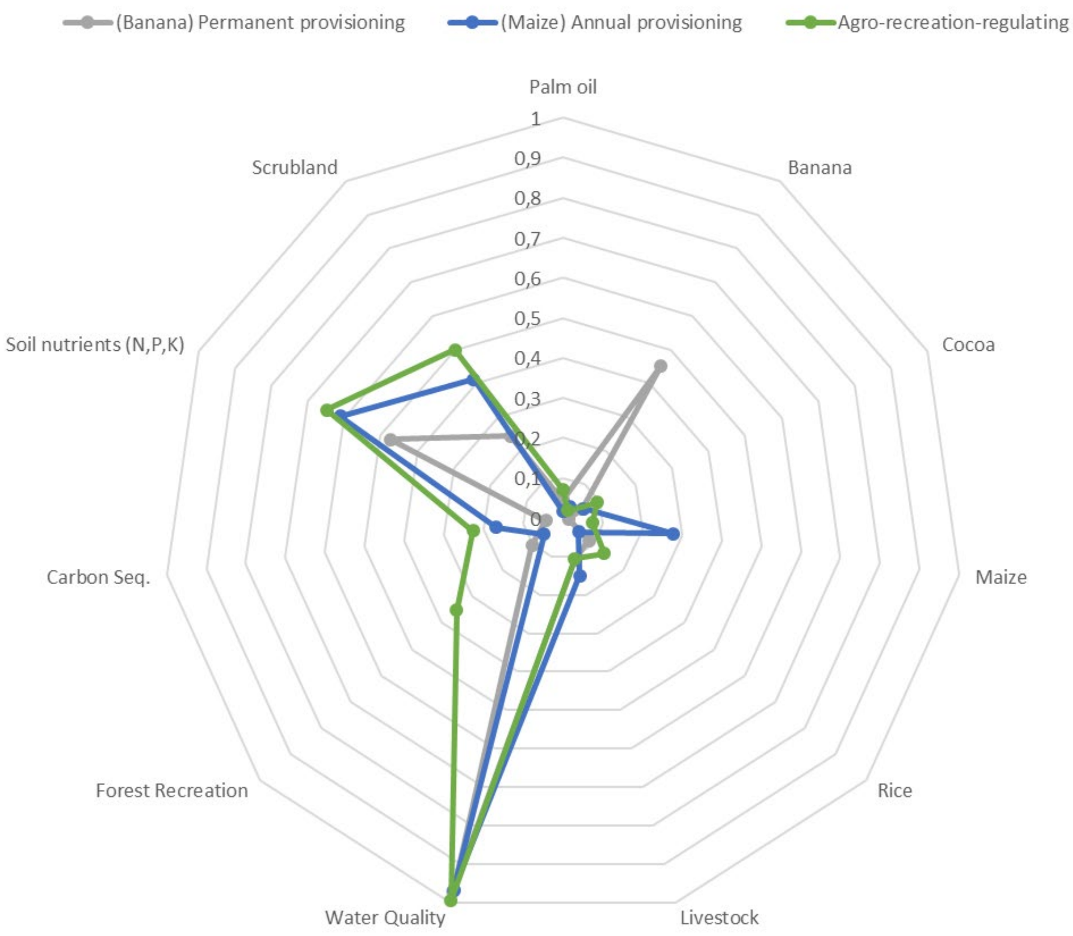

Fig. 4.11 ES bundle types for the year 2018 and considering fragmentation. Values represent the average ES found within each cluster.

4.2 Main points in the review

- In this chapter, we present empirical identification of ES and ES bundles across the AdM wetland territory. Our results present empirical evidence of significant trade-offs between provisioning and both regulating and cultural ES in this (essentially) agricultural (and protected) landscape. Significant differences can be observed between the years 2000 and 2018, mostly counteracting the correlation effect of annual and permanent crops. These can be explained by means of socio-economic reasons, but other drivers of change can be also at play. Knowing where these trade-offs are occurring and at scales relevant to social processes and decision making, such as the municipality level, makes their management possible. In these cases, knowledge of all trade-offs associated with different constructions of social-ecological systems could lead to more informed societal choices about landscape planning and management, as we will present in the next Chapter.
- Concerning types (i.e., bundles), four to three types of ecosystem service bundles were identified in two different time steps, the year 2000 and 2018, and including the impact of fragmentation in the year 2018. This framework of analysis is used to disentangle a complex social-ecological system, not easy to understand. The simplified landscape generated by the ecosystem service-bundle analysis captures essential patterns in the current provision of ES driven by ecological and social dynamics. We observe two fundamental dynamical trends in terms of types that seem (a) to lead to a 'monoculturalization' of the landscape, with unique provisioning ES (i.e., banana and maize), and (b) to include the anthropogenic impact to regulating ES. This human impact need not be problematic as seems to become integrated into cultural and recreational ES. We must bear in mind though, that, as RAMSAR site, the AdM is obliged to maintain its ecological conditions as a wetland and to promote its rational use. Thus, establishing a resilient balance in this agricultural landscape must be a priority for the region and the country. In this sense, our temporal analysis allows investigating how tightly ES is bundled, both in space and time, assuming social and economic conditions that can influence how ES in AdM are bundled.
- The impact of fragmentation is remarkable, both at ES and ES types levels. At the ES level, we observe no changes in correlations but more significant correlation coefficients. The fact that fragmentation implies homogenization of the probability distribution of areas dedicated to crops, might explain this trend. At the ES bundling level, fragmentation induces a reduction un type, suggesting also a consequence of the homogenization process. At this point, a parametric analysis would be needed to check if this outcome depends on our particular implementation of the fragmentation index (equation 4.2) or on the inner dynamics of the social and ecological system itself.

- Finally, it is fundamental to understand social and ecological drivers, feedbacks, and management schemes, which might allow for the prediction and modeling of ecosystem service bundles and thus, critical ecosystem service trade-offs and synergies on the landscape. Territories with higher values for regulating ES have more chances for the future, both for agriculture and other land uses because this category of services underlies the production of other types of services.

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4.4 Annexes

4.4.1 Quantification of ES

- **Crops: palm oil, banana, cocoa, maize and rice (Percentage of land dedicated to each crop production)**. Crop production was estimated using LULC thematic maps of the AdM wetland territory from the years 2000, 2010 and 2018. Every crop patch was classified and then accounted in numbers of ha per every Voronoi diagram related to every 90 recintos, within the AdM boundaries. The remote sensed information was collected by LANDSAT 7 ETM+ and Sentinel 2 satellites and processed using ArcGis and SNAP geographic software.
- **Livestock (Percentage of land dedicated to pasture)**. Livestock ES was calculated based on the natural pastures class identified in the using LULC thematic maps of the AdM wetland territory from the years 2000, 2010 and 2018. Natural pastures class was the only LULC type identified related to livestock activities. Other classes (i.e. cultivated pastures, forests, etc) were no classified because of its low significance in terms of the MMU. In the definition per se of each thematic legend, those units that are lower than the MMU were not incorporated, is for the 1: 25,000 scale an area of 0.3 ha and for 1: 50,000 of 1.25 ha. Considering the classes with surfaces tending to 0% due to their low representativeness in the study area, and finally, the categories that present associations were not considered in order to obtain a greater benefit when making the digital classifications. The percentage of land dedicated to pasture was calculated for each of the 90 Voronoi's diagram related to each of the same amounts of recintos, within the AdM boundaries.
- **Water quality (Water Quality Index - WQI).** The indexes were obtained from the AdM Wetland Management Plan report (Freire *et al.*, 2012), where 120 water samplings were taken from the same amount of stations. The WQI has been developed by "The National Sanitation Foundation, NSF"[3]. The importance of these parameters (dissolved oxygen, fecal coliforms, pH, BOD5, nitrates, phosphates, temperature, turbidity, and total solids), was expressed graphically by functional curves. Weights were then adjusted to each percentage of land of each of the 90 Voronoi diagrams, determining the importance of each parameter in water quality, according to the averages of the reported values.
- **Forest recreation (Percentage of sustainable, public and cultural sites contained within each *recinto*).** In order to protect and restore the richness of flora, fauna and to develop a sustainable Management between the inhabitants and

[3] http://www.nsf.org/es

nature of the fragile ecosystems at the AdM wetland, a proposal for the AdM wetland zoning has been made in 2012. Forest recreation ES was calculated based on the AdM inventory of sites located at the 3 different zonings: "Sustainable Conservation", "Public Use" and "Historic-Cultural" along with the AdM wetland territory. All the forest recreation sites were in a specific recinto. Then, each site was weighted and adjusted to each Voronoi diagram percentage of land-owning one or more sites.

- **Carbon sequestration ($kgCO_2/Ha$)**. Carbon sequestration ES was calculated using two outputs: Ecuadorian ecosystems at the continental territory map and the data available from the national average carbon sequestration capacity maps. The Ecuadorian ecosystems at the continental territory map represent the characterization, location, and distribution of the ecosystems of Continental Ecuador by the Ministry of Environment[4] in 2012. It was prepared at a scale of 1: 100 000 from biophysical modeling, interpretation of satellite images (2010-2012) and field validation. It is a basic input to explain the state of biodiversity through different types of analysis and a tool to facilitate the management and creation of policies consistent with the proper use and management of natural resources. On the other hand, the average carbon map of Ecuador consists of national SOC maps, developed as 1 km soil grids, covering a depth of 0-30 cm. The average ($kgCO_2/Ha$) includes the following variables: apparent density ($g.cm^{-3}$), organic matter (%) and / or organic carbon (%), thick fragments (%) and textural class. Both maps were treated in ArcGIS in order to calculate the area of ecosystem type founded within the AdM wetland boundaries and the carbon sequestration indicator ($kgCO_2/Ha$) of each of them.
- **Soil nutrients (% of N, P, K values)**. The values were obtained from the AdM Wetland Management Plan report (Freire *et al.*, 2012). We have chosen N, P and K among seven soil quality indicators, because these three soil components are the main soil quality references, and at least one of them radically decreases when monocultures are the majority at the agricultural landscape. Each N, P and K values were assigned to a recinto where the samples were taken. Those recintos without sampling data, an average value for N, P, K was calculated according to the upper administrative boundary average N, P, K value (districts of Puebloviejo, Baba, Mocache, Vinces, and Ventanas).
- **Scrubland (% of land in natural vegetation)**. Scrubland is considered a regulating ES because is part of the herbaceous and shrub vegetation land cover level which use is considered for conservation and/or protection actions by the Ecuadorian Ministry of Environment. Scrubland was estimated using LULC thematic maps of the

[4] http://mapainteractivo.ambiente.gob.ec/

AdM wetland territory from the years 2000, 2010 and 2018. Every scrubland patch was classified and then accounted in numbers of ha per every Voronoi diagram related to every 90 recintos within the AdM boundaries. The remote sensed information was collected by LANDSAT 7 ETM+ and Sentinel 2 satellites and processed using ArcGIS and SNAP geographic software.

4.5 Appendices

4.5.1 Glossary of acronyms

AdM	*Abras de Mantequilla*
BOD	Biochemical oxygen demand
CBD	Convention on Biological Diversity
ES	Ecosystem service
ETM+	Enhanced Thematic Mapper Plus
FAO	Food and Agriculture Organization
GE	Guayas ecosystem
K	Potassium
LULC	Land-use and land-cover
MA	Millennium Ecosystem Assessment
MAGAP	*Ministerio de Agricultura, Ganadería, Acuicultura y Pesca*
MMU	Minimum mapping unit
N	Nitrogen
NSF	National Sanitation Foundation
P	Phosphorus
SNAP	Sentinel Application Platform
WQI	Water Quality Index

5

Towards a decision- support methodology to define ES in Ecuadorian ecosystems

As we already presented in previous chapters, concern for the degradation of ES and its consequences to sustainability and well-being for Ecuadorian people in general and Guayas and AdM wetland in particular, are justified both in terms of ecological, social and economic consequences. There are emerging not only local initiatives (i.e., peasant associations, municipal networks, rural projects) but also at a global level due to the current critical climatic concern, where all stakeholders, including policymakers and scientists, are trying to run new ways of understanding and managing the decision-making process on ES.

The environmental monitoring of ecosystem services and their translation into sustainable practices via policy and decision-making methodologies is usually linked to various assessments that permits to quantify, map and value the services provided by ecosystems that are important to society. In the matter of this issue, planning and policy decisions need to be based on reliable estimates of current and expected trends in ES supply and their economic values. Assessing the spatial distributions of those resources sustaining the ES of, in this case, the AdM wetland is not enough. There is a need for a structured but at the same time flexible decision-making framework where "collaborative and facilitated application of multiple objective decision making and group deliberation methods to environmental management and public policy problems" can be implemented and applied (Gregory et al., 2012). This last chapter is a tentative effort towards this last practical and fundamental objective.

5.1 Decision-support methodology approach

In order to develop a sound and robust decision-support methodology, the main framework that has been considered is that stated in de Groot *et al.*, (2010); and Braat and de Groot, (2012) proposal which is called "Cascade Framework for integrated assessment of ecosystem and landscape services". Additionally, we will consider Burkhard *et al.* (2014) and Martinez-Harms *et al.* (2015) approach, which will be combined with the "cascade" framework in order to have a suitable method for the AdM wetland. This is because of the heterogeneity of ecological systems like the wetland case. However, as stated by de Groot *et al.* (2010): "Empirical information on the quantitative relationship between LU and ecosystem management and the provision of ES at the local and regional scale is however still scarce". The referred conceptual framework and typology for describing, classifying and valuing ecosystem functions, goods, and services in a clear and consistent manner, is the framework basis for our "Making Decision" proposal.

In Fig. 5.1 we observe the complete process we have followed in order to assess ES in the AdM wetland. The diagram reflects the interlinkage between ecological structures and processes with defined and valued ES of the wetland. At the same time, it shows every ecosystem function is the outcome of all the interaction occurring among all the inputs an ecosystem owns (biotic and abiotic components). Then, these functions are translated into ecosystem services that help to sustain and fulfill human wellbeing, which englobes an ecological, socio-cultural and provider perspective.

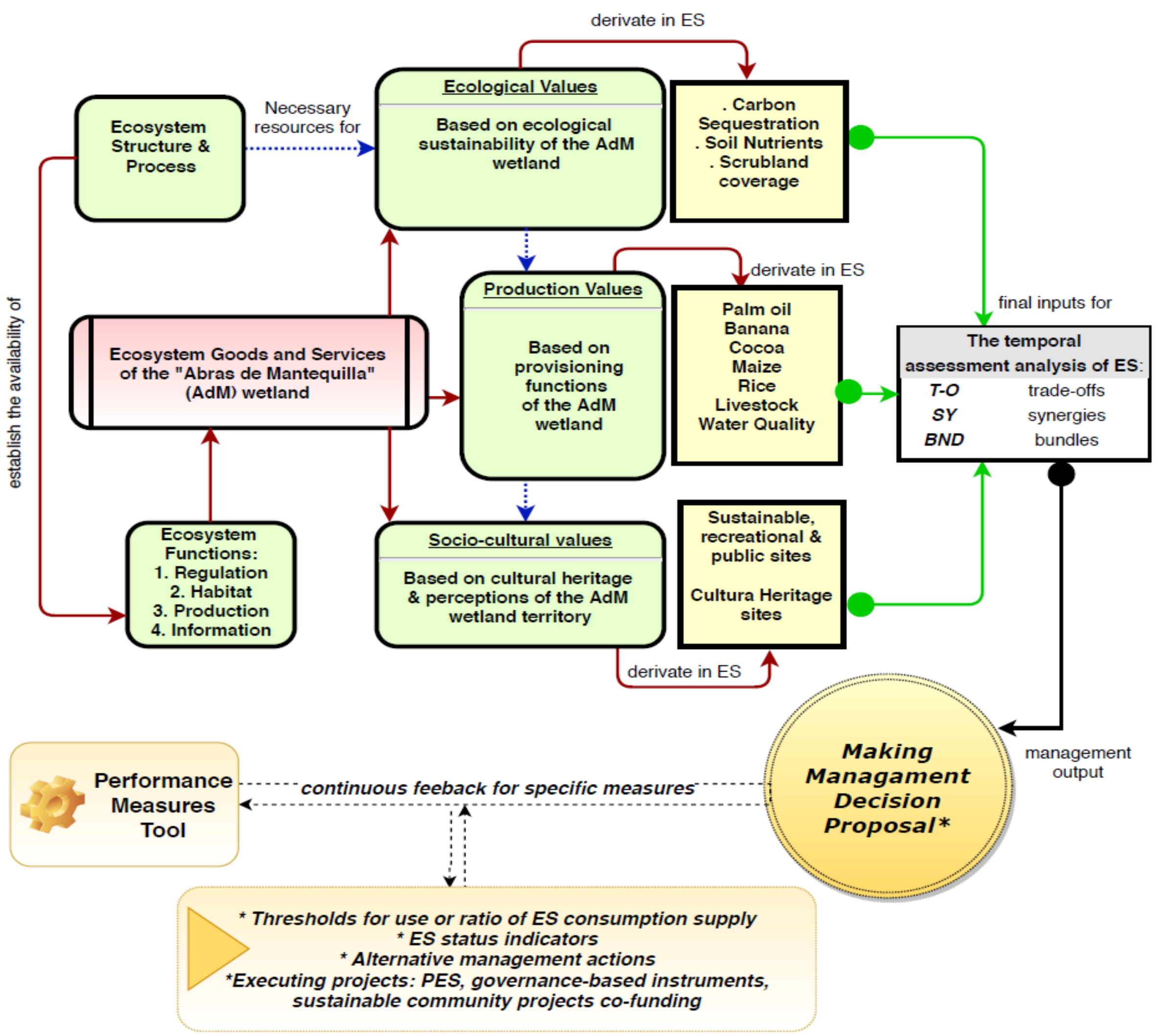

Fig. 5.1 "Making Management Decision" framework proposal for the management and assessment of the ES in AdM wetland. Adapted to our study site based on de Groot, Wilson and Boumans (2002).

Consequently, after developing an extended research scope through this work, we have identified some "must" phases in order to build a decision-making process for ES in our study site. We have fulfilled some of these steps during this research and adding some key phases proposed by different authors when it comes to design the monitoring and adaptive ES management framework (de Groot *et al.*, 2010; Maes *et al.*, 2012; Bagstad *et al.*, 2013).

5.2 "Making Management Decision" (MMD) proposal

Having previously analyzed trade-offs, synergies and ES bundles of the AdM wetland, we have reached the consensus that ES plays a crucial role to address many of the important policy and management-decision issues in our study site. When managing ES in a vulnerable area such as the AdM, several decisions must be taken at *recinto*, parish, district and province level. Some of these decisions are related to deciding when and where to restore ecosystems and where and how much to invest in sustainable programs/projects, in order to multiply services delivery.

In the proposal that follows, we try to describe every key step that includes all the practices and methods for defining, mapping and analyzing ES interactions, that we have applied in the AdM case. Every procedure applied has been subsequently justified in previous chapters and considered as a key-specific action in order to build this MMD proposal applied to the AdM case.

The MMD – AdM case is based on the MMD framework, which considers ecosystem structure, processes, and functions linked with the delivery and supply of ES at the wetland level. The final inputs attained from the 11 ES considered have permitted us to reach to a temporal assessment analysis of ES trade-offs, synergies, and bundles. From here, we synthesize every identified phase of the MMD below, with each of their guiding questions to help stakeholders to discuss, agree on and identify the policies and/or specific activities/actions to be implemented. For every phase, there must be a set of guiding questions, standards and policy actions that must be formulated in order to correctly direct the community efforts. The MMD-AdM case can be applied to deliver results, on the request of biodiversity and sectorial policies, at different administrative scales within the limits of the wetland.

1. **Identification of the problem.**
    a. *Guiding questions.*
        i. Are there any conflicts between human activities and natural resources quality in the area?
        ii. What is the current public understanding of ecosystem services and the benefits they provide?
    b. *Standards to be considered for Ph_ES identification*
        i. Main identified problems recognized and addressed in a specific area of interest or study site.
    c. *Policy and/or specific activities/actions*
        i. Territorial planning and development documents that are available in the study site.
        ii. Awareness and educative strategy plan.
        iii. Quantification and mapping of ES.
        iv. Assessment of threats of ES.
        v. Trade-offs assessment between ES.
2. **Social-Ecological assessment**
    a. *Guiding questions.*
        i. What is the current status of ecosystems and the services they provide to society?
        ii. What are the drivers causing changes in the different ecosystems and their services?
    b. *Standards to be considered for Ph_ES identification*
        i. Biophysical mapping of ecosystem services using data and models.
    c. *Policy and/or specific activities/actions*
        i. Spatial scale selection: local (100 - 1000 km^2), regional (1000 - 100,000 km^2), other.
        ii. ES selection types and indicators settlement.
        iii. Natural processes and social context analysis:
            1. LULC taxonomy.
            2. Social (i.e., social fabric mapping, stakeholder's interviews/meetings, etc.)
            3. Abiotic (i.e., soil and water quality, topography, etc.)
            4. Ecological (i.e., ecosystem status, habitats, protected areas, types of natural vegetation, etc.
            5. Economic (i.e., agricultural production analysis in the local and national economy, export data, commercialization mapping assessment, etc.).

3. **Assessment of trade-offs, synergies and ES bundles**
    a. *Guiding questions.*
        i. Are ES trade-offs and synergies identified and measured?
        ii. Are these trade-offs provoking bundle patterns in a specific area?
        iii. How to fit ES bundles into our framework (i.e., how to explicitly capture multiple functions, services, and benefits)?
        iv. How to integrate ES bundles into assessments and tools?
        v. How power asymmetries among institutions might influence multifunctionality and ES bundles?
    b. *Standards to be considered for Ph_ES identification*
        i. Assessment of trade-offs and synergies
        ii. Sound methodologies to assess trade-offs and synergies.
        iii. Statistical and spatial pattern methods to identify ES bundles.
    c. *Policy and/or specific activities/actions*
        i. Correlation between ES, p-value and other statistical analysis of tradeoffs/synergies of ES.
        ii. LULC fragmentation analysis and its linkage as a negative/positive driver of ES supply.
4. **Specification of objectives and ES performance monitoring**
    a. *Guiding questions.*
        i. Are the objectives achieved after a consensual process with local actors?
        ii. How have we advanced our understanding of links between ecosystems, ecosystem functions, and ES?
        iii. What is the direct influence of ES on medium-term local stakeholder's well-being?
        iv. Are ES performance monitored?
    b. *Standards to be considered for Ph_ES identification*
        i. Setting and using an analytical framework for ecosystem assessment
        ii. Promoting consistency in the typology of ecosystems and ecosystem services
    c. *Policy and/or specific activities/actions*
        i. General and specific objectives setting with stakeholders' participation.
        ii. Performance measures: thresholds and ratio of consumption/supply.
        iii. ES Performance monitoring indicators: ES supply and delivery status. (ES should be monitored as the biophysical supply or the number of services delivered to a specific community at local, regional or/and national scale).
5. **Making Management Decision Proposal**
    a. *Guiding questions.*
        i. What are the economic implications of different plausible futures?

ii. How do ecosystem services affect human well-being, who and where are the beneficiaries, and how does this affect how they are valued and managed?
iii. How might ecosystems and their services change under plausible future scenarios, including the development of scenarios and options for implementing some % restoration target?
iv. What would be needed in terms of a review of financing instruments?
v. How can we secure and improve the continued delivery of ecosystem services?
vi. Can we set priorities for ecosystem restoration within a strategic framework at a local and regional level?
vii. Can we design prioritization criteria for restoration and at which scale to get significant benefits in a cost-effective way?
viii. Can we define where to strategically deploy sustainable initiatives in urban and rural areas to improve ecosystem resilience and habitat connectivity and to enhance the delivery of ecosystem services?
ix. How to foster synergies between existing and planned initiatives at local, regional or national levels?

b. *Standards to be considered for Ph_ES identification*
i. Monetary and non-monetary valuation of ecosystem services.
ii. Mapping and valuation of ecosystem services as part of an integrated and stakeholder-based approach to sustainable land management and use of natural resources.

c. *Policy and/or specific activities/actions*
i. Thresholds setting for use or ratio of ES consumption supply.
ii. ES status indicators.
iii. Alternative management actions based on legitimized governance including local stakeholders (e.g. conservation planning, multi-objective optimization planning, multi-criteria analysis, cost-benefit analysis).
iv. Executing specific projects including financial incentives (e.g., payment for ES), governance-based instruments (e.g., enforcement of existing legislation, capacity-building, etc.) and sustainable community programs directed to co-fund projects at local and regional levels.

Additionally, some projects prospects have been listed in Fig. 5.2, focusing on the MMD key phases, that would help to achieve more specific actions when trade-offs between ES are occurring in the AdM wetland and, at the same time, to promote planning for the management of ES, allocating investments in ES management and evaluating alternative policy options.

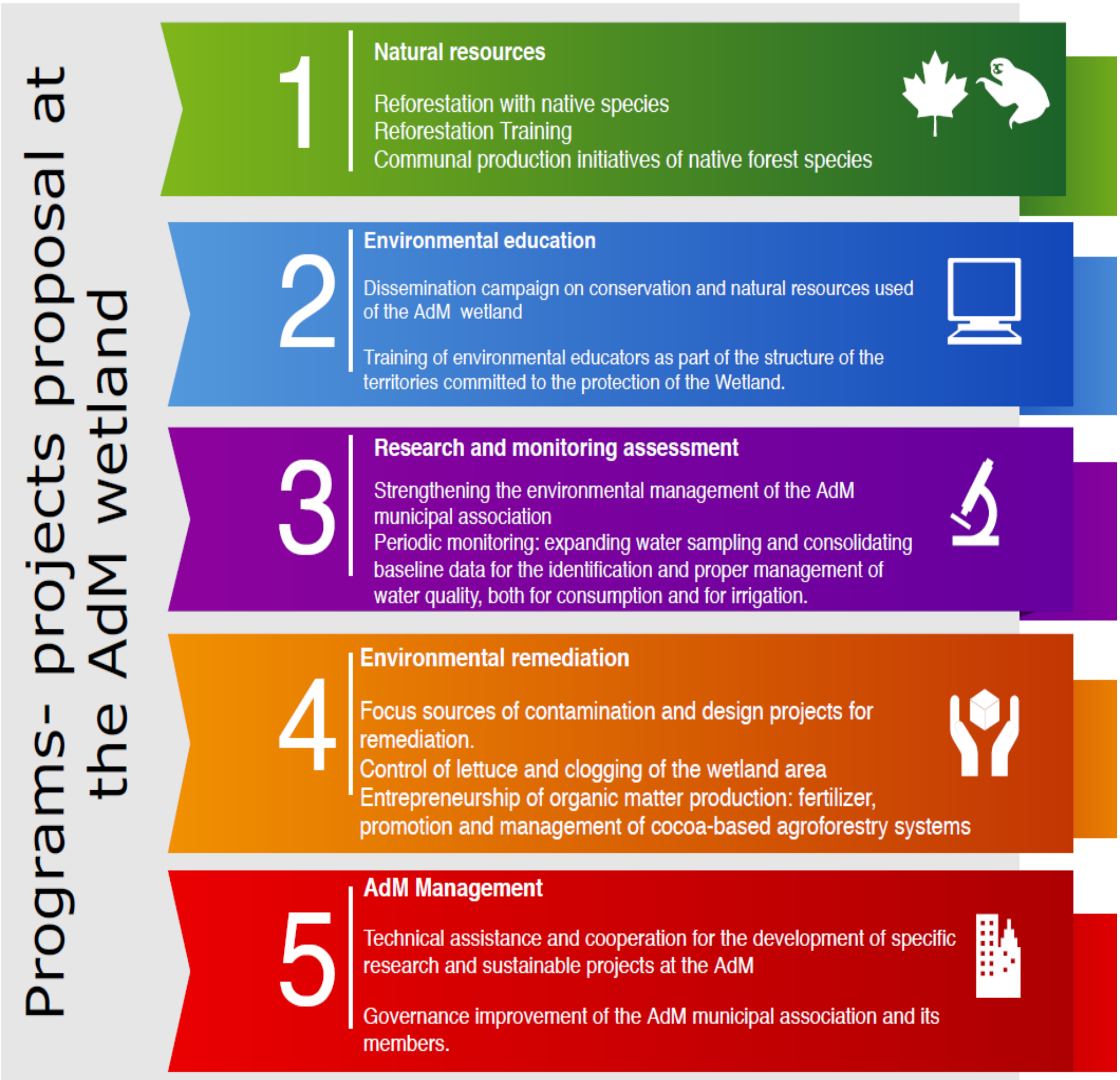

Fig. 5.2 Programs – projects proposal at the AdM wetland from the implementation of the MMD. Elaborated by the author.

An appropriately applied MMD in the area of influence of the AdM wetland plays an important role in the identification of management ES problems for their supply and delivery in this fragile ecosystem.

Moreover, we have incorporated diverse types of data (e.g. ecological, abiotic, remote sensing, land use, and land cover data). From the social data, we have had several interviews and meetings with local peasants' leaders that are in-situ participating in rural programs financed by the AdM municipal association, local and national institutions. Their feedback was a key factor to confirm the supervised classification mapping we made at the AdM. This was necessary due to the difficulty to gather imagery data of good quality, due to the atmospheric and geographical conditions of our study site.

Nevertheless, a more profound social-context analysis related to the supply and delivery of ES in the AdM is required, so stakeholder's preferences can be identified and mapped onto the different types of services, their potential beneficiaries, the accessibility of the different social actors to capital and technology assets, the political and institutional scenario and the evaluation of governance capacity of the local institutions.

This thesis has been focused on the assessment of ES bundles, trade-offs and synergies of the AdM wetland. But this work can be replicated in cases where temporal information scarcity gaps, non-favorable atmospheric conditions, and non-reliable public data are the main obstacles for the evaluation of the services provided by nature to society. Additionally, ES management actions and the application of a MMD is essential in a region susceptible to constant constraints of climate change. For example, the last phenomenon "El Nino" (2015-2016) impacts unveiled the existing problems regarding territorial planning and management, as well as the weak flow of information for decision making.

Finally, the "Commonwealth of Municipalities for the Sustainable Management of the AdM wetland" faces an important challenge in order to properly manage this RAMSAR site of interest, which requires the decisive participation of the population, local institutions and other stakeholders that inhabit it. For these reasons, it is urgent to have a reliable MMMD, that allows promoting the actions of conservation of natural resources, especially in the area of influence of the wetland, and thus support self-management for local development and initiate a process of decontamination and protection of water and bio-regulating sources.

5.3 Future work and reflections

From a management outlook, the concept of ES is gaining more attention because it is an opportunity for rural communities to guarantee the sustainable supply and delivery of their natural capital for future generations. This research has compiled enough evidence that ES at the Adm territory is somehow compromised, if not at risk. Therefore, we identify important activities/programs/projects for future research and practice, including, the identification of performance measures, and the deliberation of alternative actions. MMD for ecosystem services should be reinforced by the best available science methods in order to energize and give feedback to management decisions.

Furthermore, it is also suggested to incorporate the Sustainable Development Goals (SDGs) and their 169 targets under the Agenda 2030 of the United Nations. The inclusion of the SDGs on regional and local monitoring-projects-approach, like the AdM wetland, is a requirement when the land-use analysis is closely linked to food/fiber production, biodiversity, water resource management, and landscape resilience capacity. We highly recommend introducing SDGs indicators in the MMD proposal, especially the indexes linked to the SDGs 2,6,13 and 15 which are directly related to land-sector sustainability (Gao and Bryan, 2017). We describe the SDGs, some selected targets and indicators´ examples that should be considered to be included in MMD method at the AdM wetland territory level.

SDG	Selected SDG targets	Indicators at the AdM wetland territory level
Economic returns		
SDG 2 End hunger, achieve food security and improved nutrition and promote sustainable agriculture.	**Target 2.3.** By 2030, double the agricultural productivity and incomes of small-scale food producers, in particular women, indigenous peoples, family farmers, pastoralists and fishers, including through secure and equal access to land, other productive resources and inputs, knowledge, financial services, markets and opportunities for value addition and non-farm employment.	- Total net economic returns to all land-uses - The number of families benefiting from rural projects has increased their income by at least 30%, in a sustainable way. - Number of learning networks for small farmers in operation - Number of organizations strengthened in the management of support services for agroecological production, transformation, and commercialization - Number of people (50% women, 50% young, 25% indigenous) with improved knowledge in production, marketing, and associativity - Number of organizations that have adopted at least 2 best practices in production, entrepreneurship, marketing, and associativity - Number of producers with agroecological practices access to national and international certified markets - Number of families benefit from irrigation systems, collection centers, and other infrastructure for product processing
Food/fiber production		
SDG 2 End hunger, achieve food security and improved nutrition and promote sustainable agriculture.	**Target 2.1.** By 2030, end hunger and ensure access by all people, in particular, the poor and people in vulnerable situations, including infants, to safe, nutritious and sufficient food all year round	-The total value of agricultural Production - The number of families has made the transition to agroecological production systems. - The number of producers has adopted agroecological practices in their plots.
Water resource use		

SDG 6 Ensure availability and sustainable management of water and sanitation for all.	**Target 6.4.** By 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity. **Target 6.5**. By 2030, implement integrated water resources management at all levels, including through transboundary cooperation as appropriate. **Target 6.6**. By 2020, protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers, and lakes	-Water resource use in water-stressed catchments -Number of farms with the implementation and design of plot irrigation systems -Control and monitoring of water quality, and met accepted levels of WQI: minimum level "GOOD" and maximum levels of organochlorine and organophosphorus -At least 150 km of protection strips (main river areas) -At least 25% of homes must have sewer coverage and 100% waste disposal system coverage. -Number of improved water plants meeting quality standards -Revision of 76 km in the sub-basin of the Vinces river, 78km in the wetland and 56km in the eastern fringe of the commonwealth. Channeling and dredging according to the required areas
Emissions abatement		
SDG 13 Take urgent action to combat climate change and its impacts.	**Target 13.2.** Integrate climate change measures into national policies, strategies, and planning.	-Emissions abatement (metric tons of CO_2 yr^{-1}) -Number of critical areas of the wetland reforested at the head of the Chojampe estuary (one of the wetland's water suppliers) - The number of established protected areas of at least 3,000 ha per each 50,000 ha, reaching 198,000 ha in ten years (6% of the total). The objective is to return to the number of ha of the year 2000 (198,000 ha).
Biodiversity and land degradation		
SDG 15 Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss**.**	**Target 15.1.** By 2020, ensure the conservation, restoration and sustainable use of terrestrial and inland freshwater ecosystems and their services, in particular forests, wetlands, mountains, and drylands, in line with obligations under international agreements. **Target 15.3.** By 2030, combat desertification, restore degraded land and soil, including land affected by	-Biodiversity services (percentage of maximum) - The number of ha with an application of ecosystem restoration and similar forestry, in production and management of peasant orchard species (nurseries, pruning, integrated pest control, soil management), post-harvest practices and cocoa transformation. -Number of critical areas of the wetland with conservation

	desertification, drought, and floods, and strive to achieve a land degradation neutral world. **Target 15.5**. Take urgent and significant action to reduce the degradation of natural habitats, halt the loss of biodiversity and, by 2020, protect and prevent the extinction of threatened species.	and/or reforestation practices -Number of areas located, registered and legislated for environmental compensation, according to the Agreement of the Ministry of Environment for the control of environmental protected areas -Joint system of conservation areas, with investment and monitoring projects -At least 5% of the investment budget for the execution of environmental protection and flora and fauna recovery projects in the joint territory

Table. 5.1 Description of SDGs, linked targets and related indicators to the AdM wetland territory case.

From a complexity outlook, in recent years, the complexity of many coupled social-ecological systems have been successfully modeled (Janssen, 2002; Lansing and Cox, 2019), and even very simple models have provided major insight into these dynamics (Lansing and Kremer, 1993; Anderies, Janssen and Walker, 2002; Janssen and Scheffer, 2004), where simulating the effects of decisions about, for example, irrigation, land use or pest's treatment, generate local variations in harvests which, at the same time, influence future decisions by the farmers, creating a coupled social-ecological system governed by feedback from the environment. The development of equation- and/or agent-based computational models to account for the values and preferences of stakeholders, stablished through participatory methods, can enable and empower management decisions and highlight the opportunities and constraints for a true operative management process according to the local context. We see these as key ingredients for the ecosystem services paradigm to gain traction in science and policy perspectives.

From a general scope, the development of an agent-model applied to the AdM wetland context will be feasible in future research, due to the following states:

- From a systems perspective, the temporal analysis of possible changes of the implied values in the AdM wetland system considering their social, ecological and land-use variables interactions.
- A model that comprises social structure in the AdM agricultural landscape will permit to analyze if there is an influence in average harvested yields, improvement in terms of sustainability (e.g. socio-organizational peasants' capability to manage ecological and climate-change perturbations).

- Taking into account how farmers and peasants organizations lead their communities' decisions in terms of previous yearly-field-crop productivity numbers, which agricultural systems (e.g. agroforestry, agroecology, monoculture) will define every yearly-future-seasonal cycle (e.g. dry and rainfall seasons) and other socio-ecological matters. Bearing in mind the social context in our case study is a must when several rural projects have been financed in the wetland territory. These projects were part of the "Rural Good Living Program" of the Ecuadorian Ministry of Agriculture since 2003 and its main objective has been promoting the transition from monocultures towards diverse production yields which include agroforestry plots (cocoa, fruit trees and short-cycle crops). This change of paradigm will recover the characteristic of the traditional-peasant-farm and all its advantages in terms of food security, peasants´ family income, and sustainable environmental practices. Sin 2003, the mentioned program has co-financed 26 projects in which they have involved around 45 peasant organizations and 1,150 farm families who implemented and / or improved their diversified orchards located in the AdM wetland territory.

Besides, from a specific approach, the model can consider the follow socio-ecological, organizational and agricultural insights at the ADM wetland system have been occurring in the last years:

- The influence of the peasant school project in the wetland area (2015-2017). This project aimed to strengthen the organizational, social and productive structure of the peasants who inhabit the environment of influence of the wetland. 33 peasant organizations participated in the joint territory of the AdM wetland: Palenque, Mocache, Baba, Vinces, Puebloviejo, Ventanas and Echeandía.
- Understand the role of peasant family farming as an alternative for the conservation of natural resources, the production of healthy food in the face of climate change.
- Analyze the use of agroecological practices appropriate to the local culture (integrated pest management, crop diversification, and rotation) which favor the restoration of ecological balance in response to the complex socio-environmental and productive problems derived from conventional agriculture in the AdM wetland.
- Analyze the use of agroecological practices appropriate to the local culture (integrated pest management, crop diversification, and rotation) which favor the restoration of ecological balance in response to the complex socio-environmental and productive problems derived from conventional agriculture in the AdM wetland.

For future research work, the AdM wetland could be a case to analyze if this complex system has had and will have an adaptive pattern behavior facing more stress related to climate change impacts in the region. Landscape patterns and their criticality threshold could differ if agricultural "traditional" systems of resource management exist in fragile ecosystems like the AdM wetland.

From an ecological perspective, the AdM wetland needs the impulse on projects addressing the recovery of its biophysical and ecological landscape. It is essential because it will allow the restoration of the provision of environmental, recreational and regulating services to the communities located in the area of influence and the fulfillment of its ecological functions. It is also important to keep generating and gathering reliable data of vulnerable systems in poor and developing regions, so that the interventions in the wetland are designed based on detailed information, with the appropriate scale and with precise information, adjusted to its conditions. It is remarkable that only 11% of ES literature deal with low-income economies, such as the study case we have presented here. There is a need for a consensual effort in order to start ES assessments in fragile and vulnerable ecosystems in developing countries.

On the other hand, refining the quality of the water entering the wetland is a breaking point for promoting the morphological and water flow conditions that guarantee the biophysical sustainability of the wetland in the long term. In this sense, it is necessary to understand and model these coupled social-ecological dynamics to promote initiatives that restore the structure and function of the aquatic and terrestrial ecosystems of the wetland, as well as the conditions to achieve ecological connectivity with other remaining forest-land elements of its main ecological structure.

From an agricultural and economic viewpoint, in the case of the joint territory of the wetland, its intervention strategies should point towards the change of the monoculture production model, that despite the social and environmental problems they generate, has become traditional in the area, towards an agroforestry production model (e.g. national cocoa, fruit plantations and short cycle crops). This change of paradigm will recover the characteristic of the traditional peasant farm and all the advantages for the local community in terms of food security, better incomes and a significant resilience of the AdM wetland ecosystem services.

From a personal point of view, I will be happy if I could see someday that all this effort can be finally applied to increase the well-being of Ecuadorian people, especially those who inhabit the area of influence of the AdM. For several years, I worked as a consultant in the province of "Los Ríos", hand by hand, with women associations, farmers' communities, and peasants' organizations. It was probably the best experience I ever had because knowing the rural reality from the local actors gives you a different perspective of what landscape and agriculture is about. All the agricultural products we daily consume have many life stories behind, and most of them occur in a poor context where farmers fight for having fair incomes, better access to education and health services, or for just simply having access to safe water, nutritional food products and a better quality of life for them and their future generations. These are the contradictions of the Ecuadorian rural reality. But there is also hope when there positive initiatives like the peasant school that worked for two years, training leaders in organizational strengthening, administrative capacity development and better agricultural practices to finally achieve the transition of the AdM wetland, from being a region where the agricultural border has been extended in the last 20 years, to be an environment where agroforestry, wetland, and its landscapes and rural life coexist in a sustainable way.

5.4 References

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5.5 Appendices

5.5.1 Glossary of Acronyms

ES	Ecosystem services
AdM	*Abras de Mantequilla*
BND	Bundles
MMD	Making Management Decision
PH-ES	Phase of ecosystem service
RAMSAR	Ramsar Convention on Wetlands of International Importance especially as Waterfowl Habitat
SDG	Sustainable Development Goals
SY	Synergies
T-O	Trade-offs
WQI	Water Quality Index