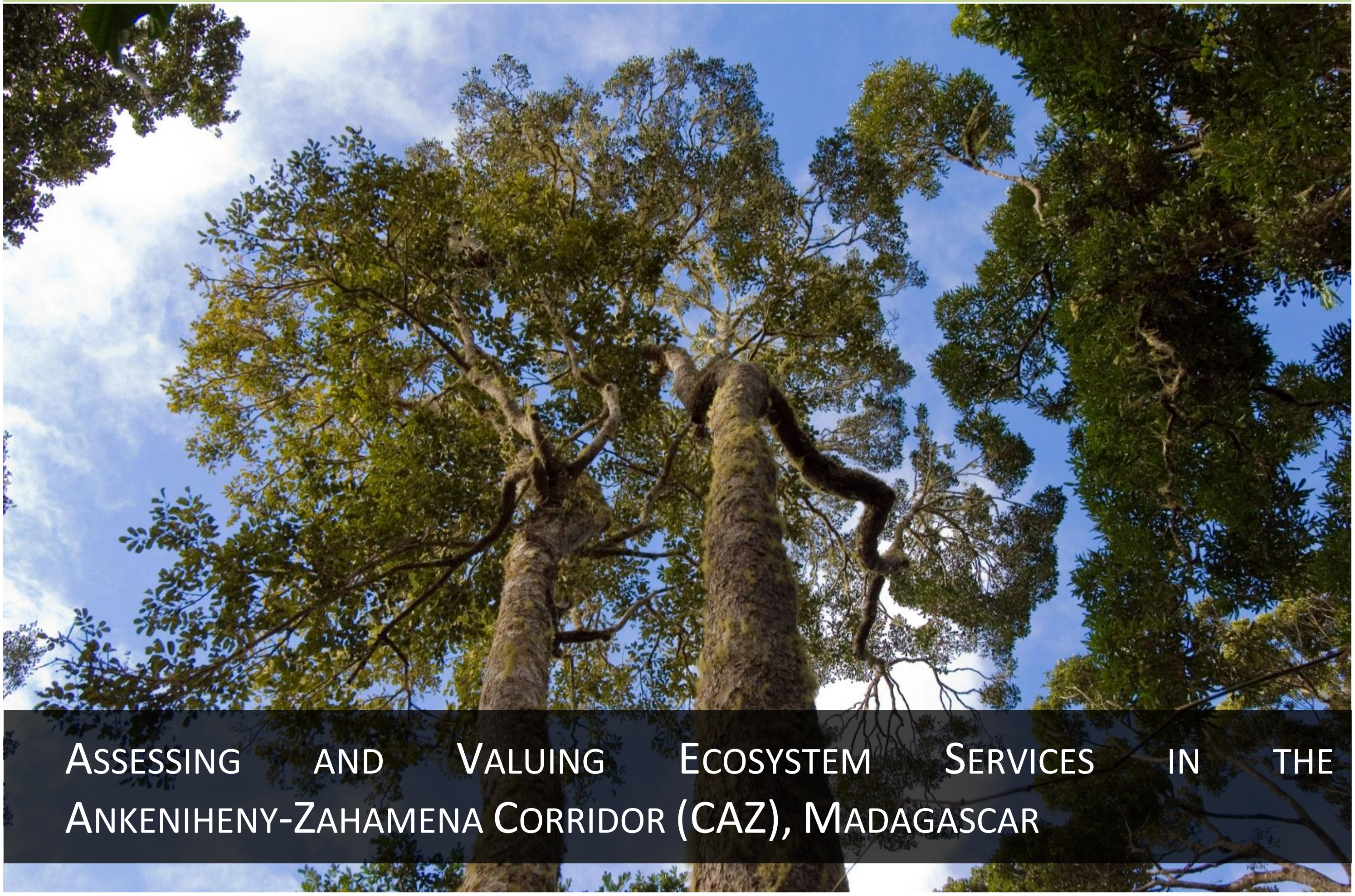

ASSESSING AND VALUING ECOSYSTEM SERVICES IN THE ANKENIHENY-ZAHAMENA CORRIDOR (CAZ), MADAGASCAR

A DEMONSTRATION CASE STUDY FOR THE WEALTH ACCOUNTING AND THE VALUATION OF ECOSYSTEM SERVICES (WAVES) GLOBAL PARTNERSHIP

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Cover photo: Mantadia National Park (Conservation International / Sterling Zumbrunn)

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ACRONYMS AND ABBREVIATIONS

ANDEA	Autorité Nationale de l'Eau et de l'Assainissement (National Water and Sanitation Board)
ARIES	Artificial Intelligence for Ecosystem Services
CAZ	Ankeniheny–Zahamena Corridor
CCBA	Climate, Community & Biodiversity Standards
CDM	Clean Development Mechanism
CI	Conservation International
CSS	Carbon storage and sequestration
DECC	Department for Energy and Climate Change
EC	European Commission
ES	Ecosystem services
EU	European Union
FAD	Fonds Africain de Développement (African Development Fund)
FAO	Food and Agriculture Organization of the United Nations
GCF	Gestion Contractualisée des Forêts (Contractualised Forest Management)
GDP	Gross domestic product
IAM	Integrated assessment model
INSTAT	Institut Nationale de la Statistique (National Statistics Institute of Madagascar)
JIRAMA	Jiro sy rano Malagasy (Malagasy national water company)
MODIS	Moderate Resolution Imaging Spectroradiometer
NASA	National Aeronautics and Space Administration
NPP	Net primary production
REDD+	Reducing Emissions from Deforestation and Forest Degradation + conservation
RUSLE	Revised Universal Soil Loss Equation
SCC	Social Cost of Carbon
SEDMOD	Spatially Explicit Delivery Model
SRTM	Shuttle Radar Topography Mission
TAMS	Tetik' Asa Mampody Savoka (Return the Fallows to Forest) project
TRS	Technical rate of substitution
UNDP	United Nations Development Program
UNEP	United Nations Environment Program
USAID	United States Agency for International Development
USD	United States Dollars
USLE	Universal Soil Loss Equation
VCS	Voluntary Carbon Standard
VOI	Vondron'olona ifotony (basic local communities)
WAVES	Wealth Accounting and the Valuation of Ecosystem Services
WB	World Bank
WCS	Wildlife Conservation Society
WTO	World Trade Organization

EXECUTIVE SUMMARY

Natural capital is commonly defined as the extension of the economic notion of capital to environmental goods and services. In addition to representing a primary factor of economic production, natural capital represents the supporting goods and environmental functions that enable life on the planet. Despite its enormous significance, the contribution of natural capital to national economies has been systematically ignored. That results in the exclusion of nature's value from policy analyses and precludes the development of management alternatives that recognize the importance of natural capital to national economic development. The Wealth Accounting and the Valuation of Ecosystem Services (WAVES) is a World Bank-led initiative that aims to integrate natural capital values into national account systems, and thereby encourage better, more efficient decision-making and planning.

Conducted as a demonstration case study for WAVES in Madagascar, this analysis provides an in-depth assessment of the contribution of key ecosystem services from the Ankeniheny-Zahamena Forestry Corridor (CAZ), the largest remaining contiguous patch of humid forest in eastern Madagascar. The analysis entails three related components: 1) a biophysical analysis, with an assessment and mapping of physical flows of selected ecosystem services; 2) an economic analysis, where an economic valuation of the services was performed; and 3) a policy analysis, where results of the biophysical and economic analysis were synthesized and discussed.

This analysis focused on three ecosystem services considered critically important for human well-being: (1) carbon storage and sequestration, (2) water supply, and (3) sediment retention. State-of-the-art methods were used to address the complex nature of ecosystem service provision as well as different uses of ecosystem services as inputs to economic sectors such as agriculture, mining, tourism and hydroelectricity. Although this research involved complex, multidisciplinary methods, it was designed and implemented strictly as a pilot study. As such, it is only a preliminary effort to identify some of the links between the ecological and economic systems in CAZ, and to demonstrate methodologies for assessing the critical contribution of natural capital to local people and economies.

Our results show that CAZ provides important benefits in terms of water supply and sediment regulation, upon which a variety of economic sectors are highly dependent, and is also an important carbon sink. Here are some of the highlights:

Water supply and sediment regulation: While current levels of water demand are essentially met in both the CAZ (i.e. forested) and non-CAZ (non-forested) sites where comparative analyses were conducted, the CAZ site clearly demonstrated the potential to sustain much greater water demand than did the non-CAZ site, which already faces critical levels of water demand. In addition, water quality, measured as reduced sediment load, was estimated to be significantly better in CAZ than in a non-conservation area. These results clearly highlight the role of forested areas such as CAZ in retaining precipitation in the form of usable water and in preventing sediment contamination of the water supply. The economic analysis of water, in turn, showed water use efficiency to be greater in the region's agricultural and tourism sectors, though the marginal value of water as a production input (an estimate of the economic value per unit of output of the production sector) was greater in the mining and hydroelectricity sectors.

Climate regulation: Carbon sequestration values are very high in CAZ, suggesting that the area has high value as a continued carbon pool and sink. However, results also showed the potential for high releases of carbon if the area is managed unsustainably. Livelihoods in this region are often based on unsustainable natural resource management practices, such as *tavy* (slash and burn) agriculture and illegal logging, both of which are associated with deforestation in CAZ. This could tip the balance and quickly turn the area into a significant source of carbon emissions. The high economic value of carbon sequestration – estimated as the marginal benefit accrued to the society in association with the sequestration of one ton of carbon (or emission reduction) – highlights the importance of valuing ecosystem services from protected areas and forest ecosystems and signals the potential increased welfare that this service may bring to the Madagascar's society.

These results are particularly relevant given the ongoing discussion on the need for the development of regional and national integrated water resources management planning and policy in Madagascar. Informing water policy is a priority of WAVES in the country. Such policies, by definition, must address the individual and competing needs of different sectors (i.e. agricultural, industrial, energy, tourism, mining, and others). Policies must also address the industrial efficiency and profitability of a given operation; its impact on water flows and sediments; and equity in the distribution of resources. Many, if not all of these issues can be informed by wealth accounting and valuation of ecosystem services, as proposed by WAVES.

The high economic values of carbon sequestration estimated for the region highlights the importance of valuing ecosystem services from protected areas and forest ecosystems. This is another important goal for WAVES in Madagascar. If realized – through engagement in carbon markets, such as through Reducing Emissions from Deforestation and Forest Degradation (REDD+) and the Clean Development Mechanism (CDM) – these values could represent a significant increase in welfare. They can also contribute to measures toward the sustainable financing of the national protected area network, and provide momentum for the design of an improved forest sector policy. This is particularly important for Madagascar since the country's protected area network has not achieved financial autonomy and relies heavily on external aid for its operation.

Key Messages:

To date, there have been few analyses that assess both biophysical and economic values of ecosystem services in a common framework. This is also one of the biggest challenges for WAVES: to enhance understanding of the contribution of ecosystem services through the use of robust and credible methods. This preliminary analysis – a rapid ecosystem services assessment – is an effort to demonstrate the feasibility of techniques to model and value ecosystem services in a data scarce environment, and the utility of such an approach in identifying the relative importance of different areas, such as forest and non-forest areas, or protected and non-protected areas. Collectively, results produced by the biophysical and economic analyses can help to inform prioritization exercises and the design of management alternatives.

An important outcome of this analysis was the identification and development of methods to quantify four key dimensions of ecosystem services, each with a different relevance for policy assessments: input productivity, economic value, sustainability of supply, and quality of supply. While these four dimensions are interrelated, in the absence of quantitative models it is possible to imagine a policy framework that considers all of them in a multiple criteria analysis. Such an analysis could be used to rank the opportunity value of each prospective policy instrument in regards to the policy context to which it would apply. This analysis can inform the design of policy interventions by allowing comparisons among different sites, highlighting important trade-offs between competing alternatives, and ultimately guiding decision-making based on locally determined priorities.

This study demonstrates the ability to quantify the contribution of natural capital to a regional economy, a first step towards the incorporation of natural capital into a national accounting framework, and provides a foundation for additional studies. Better understanding of the magnitude of nature's contributions can help to demonstrate the trade-offs between natural resource exploitation and degradation, and the potential benefits of more sustainable management of natural resources. Understanding trade-offs is key to policies and management decisions to appreciate economic benefits of protected areas, ensure the distribution of revenues from key economic sectors, and resolve management of conflicts over resource use. This is especially important in Madagascar given the global and regional significance of the country as one of the world's ten most threatened forested hotspots, and the need for significant effort to protect its natural capital.

In this study, we also demonstrated the relevance of methodologies for the assessment of economic dimensions of ecosystem services and their benefits, as well the detailed, spatially-explicit and dynamic methodology for ecosystem services – provided, for example, by the Artificial Intelligence for Ecosystem Services (ARIES) tool. The use of production technology to estimate both efficiency and marginal value of production for which water is an input, were combined with biophysical estimates of water availability and sediment regulation, resulting in contextual outputs for the four dimensions described above.

Further research should focus on the determination of monetary values of services for incorporation into national accounting, which should then be fully integrated with the biophysical analysis such that the value of the CAZ for water supply/sediment control to the intended users can be determined. We also recommend modeling experiments to pinpoint precise thresholds in the extent and quality of the natural environment that supports critical services. Lastly, we recommend the replication of additional pilot studies to develop a protocol that reduces the inaccuracies inherent in any national accounting based on partial assessments, and to facilitate scaling up.

1. INTRODUCTION AND OBJECTIVES

Natural capital is commonly defined as the extension of the economic notion of capital to environmental goods and services. In addition to representing a primary factor of economic production, natural capital represents the supporting goods and environmental functions that enable life on the planet. Worldwide, there is a systematic lack of assessment of the contribution of natural capital to national economies. The failure to estimate the magnitude of this contribution results in the exclusion of nature's value from policy analyses and precludes the development of management alternatives that recognize the importance of ecosystem services to human well-being. Wealth Accounting and the Valuation of Ecosystem Services (WAVES) is a World Bank-led initiative that aims to integrate natural capital values into national account systems, and thereby encourage better, more efficient decision-making and planning. WAVES's main goal is to promote sustainable development worldwide through the implementation of comprehensive wealth accounting that focuses on the value of natural capital and the integration of 'green accounting' into more conventional development planning analyses.

WAVES is a Global Partnership currently being implemented in five partner pilot countries. Developing countries such as Botswana, Colombia, Costa Rica, Madagascar, and the Philippines are working to establish environmental accounts in practice. Australia, Japan, Norway, the United Kingdom, and Canada are developed countries in which efforts towards environmental accounting is taking place and are, as a result, important WAVES partners. Other important partners include international organizations such as United Nations agencies (UNEP, UNDP, and the UN Statistical Commission), as well many supporting research and non-governmental organizations. WAVES seeks to foster the implementation of natural capital accounting with the ultimate goal of incorporation in policy analysis and development planning, while supporting the development of internationally agreed-upon guidelines for ecosystem accounting.

In Madagascar, WAVES activities will be carried out in two phases:

(i) Phase 1 (February to December 2011): Preparation phase during which time two technical case studies for presentation to the Rio+20 United Nations Conference on Sustainable Development and country-specific Feasibility and Planning studies will be prepared.
(ii) Phase 2 (2012 – 2015): Implementation phase during which technical project activities will be implemented.

1.1 PROJECT OVERVIEW AND SCOPE OF THE STUDY

As part of the Phase 1 activities in Madagascar a technical case study was proposed for an assessment of ecosystem services in the Ankeniheny-Zahamena Forestry Corridor (CAZ) in eastern Madagascar. The objectives of this case study are to:

(i) Demonstrate the utility of state-of-the-art analytical and modeling methodologies to advance knowledge on the understanding of the role of natural capital and its contribution to the provision of ecosystem services in Madagascar.
(ii) Investigate how the results of such analyses could be used to improve the integration of ecosystem services into local, regional and national policy development.
(iii) Investigate the feasibility of scaling up the methodology applied in this case study to other regions in Madagascar and to assist the Government and national stakeholders to identify future priority zones.

This analysis entailed three related components: 1) a biophysical analysis, with an assessment and mapping of physical flows of selected ecosystem services; 2) an economic analysis, where an economic valuation of such services was performed; and 3) a policy analysis, where results of the biophysical and economic analysis were synthesized and discussed, and implications of alternative management scenarios of CAZ addressed. This report presents a description of methods and summarizes the main findings of the CAZ technical case study.

1.2 CONSTRAINTS AND SCIENTIFIC CONTEXT

It is important to highlight the context of the analysis presented in this report, as well as the constraints under which it was implemented.

1) Although this research involves complex and transdisciplinary issues, it is important to keep in mind that it was designed and implemented as a pilot study. As such, this study is a preliminary effort to address linkages between ecological and economic systems in CAZ, and to demonstrate the application of methodologies to assess the critical contribution of natural capital to local people and its significance to their economy.
2) The analysis was done under significant data scarcity, a common problem in developing countries, and in Madagascar in particular. In an ideal scenario, this kind of analysis would require extensive data collection, including field work to supplement existing data. The latter has proved impossible within the time and resources constrains under which this assessment was done.
3) Ecosystem service analysis, in all its current incarnations, is a rapid assessment technique that cannot be expected to be based on fully detailed biophysical and economic models. This is particularly important to remark here, as the work we present goes into significantly higher physical detail than all other common ES assessment methodologies. The models used to characterize flows and budgets of carbon, water and sediment are developed specifically for the purpose of rapid ES assessment, and are therefore tuned to operate under the resources available for that kind of analysis. As such, they cannot be expected to produce results that are applicable outside of the context of this analysis.

In light of these considerations, this study must not be interpreted as anything more comprehensive than a preliminary assessment of the specific issues addressed in the analysis. It is designed to shed light on the feasibility and replicability of the proposed approach, and on ways to enhance future and more comprehensive assessments.

1.3 STRUCTURE OF THE REPORT

This report is organized as follows: Section 2 provides an overview of Madagascar and of the Ankeniheny-Zahamena Corridor (CAZ) – the site where the analysis takes place – providing the context and introducing issues of concern. Section 3 explains the empirical strategies for both the biophysical and economic analyses, which are described in terms of ecosystems services in the case of the former and economic sectors in the latter. Section 4 presents results from both analyses, and Section 5 provides a discussion focusing on the value of specific indicators, the utility of the methods, the potential for scaling-up the analysis to other regions, and the policy implications of the analysis. The conclusion in Section 6 synthesizes key messages with respect to the overarching objectives of the case study. The report finishes with a discussion on the limitations of this study and recommendations for future work.

2. CONTEXT AND ISSUES

2.1 OVERVIEW OF MADAGASCAR

Madagascar, the fourth largest island in the world, is located in the Indian Ocean off the southeastern coast of Africa. With an area of less than half a percent of the earth's landmass, it harbors nearly 5 percent of global biodiversity (World Bank, 2012). A mega-diversity hotspot, Madagascar's forests harbor a multitude of endemic species of lemurs, centipedes, orchids, and chameleons – just to name a few taxa.

Madagascar is also one of the poorest countries in the world, and one where 77% of households live under the poverty threshold, the highest rate in Africa (World Bank, 2011). With a population estimated at 19.6 million (World Bank, 2011)[1], Madagascar's Human Development Indicator of 0.43 is ranked 135th globally (UNCTAD, 2011). The country's GDP of USD 8,721 billion[2] (UNCTAD, 2011) had an average annual growth of 3.6 percent in the last decade[3] (World Bank, 2011), the result of a fragile economy where services is a leading sector (55%), followed by agriculture (29%), industry (16%) and manufacturing (14%)[4]. The country has suffered from chronic levels of political instability and is highly dependent on official aid. Such aid comprises 40% of the government budget and 75% of the public investment program.

Madagascar's national governance regime is characterized as a semi-presidential representative democratic republic. The elected president (head of state) chooses a prime minister (head of government), who in turn, recommends nominees for his cabinet of ministries. The two main constitutional powers are executive – represented by the government, and legislative – represented by the ministerial cabinet, senate and national assembly. Madagascar operates on five different administrative levels: 6 autonomous provinces (*faritany mizakatena*); 22 regions (*farita*); 116 districts (*fivondronana*); 1,548 communes (*kaominina*); and 16,969 *fokontany*.

Due to high historical rates of deforestation, Madagascar is considered one of the world's 10 most threatened forested hotspots (Conservation International, 2012). Though ultimately the result of complex and disparate drivers in different parts of the county, deforestation in Madagascar is generally attributed to an increasing need for agricultural land due to high population growth rates, and to unsustainable land use practices such as *tavy* (slash and burn) agriculture and illegal logging (Wendland *et al.*, 2010). Deforestation rates were estimated at 8.5% annually between 1990 and 2000, and only 15% of the island's area is thought to currently remain in primary forest (Harper *et al.*, 2007). High levels of deforestation threaten not only the unique biodiversity of the country, but the livelihoods of a large population who face environmental degradation primarily in the form of water resource scarcity and soil loss.

2.2 OVERVIEW OF THE ANKENIHENY-ZAHAMENA CORRIDOR (CAZ)

The Ankeniheny-Zahamena Corridor (CAZ) is a newly-designated protected area in the eastern escarpment of Madagascar, in the province of Toamasina and the districts of Ambatondrazaka,

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[1] Estimated in 2009
[2] 2010 estimate.
[3] Estimated for 2000-2009
[4] Based on 2009 GDP

Moramanga, Ampasimanolotra, and Toamasina Rural. It is situated amidst a mosaic of land uses including agriculture, forest plantations, community-managed zones, and villages, as well as five government-managed national parks and reserves (Zahamena National Park, Zahamena Reserve, Andasibe-Mantadia National Park, Mangerivola Reserve, and Analmazoatra Reserve). The CAZ has a surface area of 381,000 ha, and its forests, wetlands, and rivers are home to over two thousand species of plants, many endemic to the region, as well as a great number of species of mammals (including many species of lemurs), amphibians and birds. Figures 1 and 2 show maps of CAZ and its main uses.

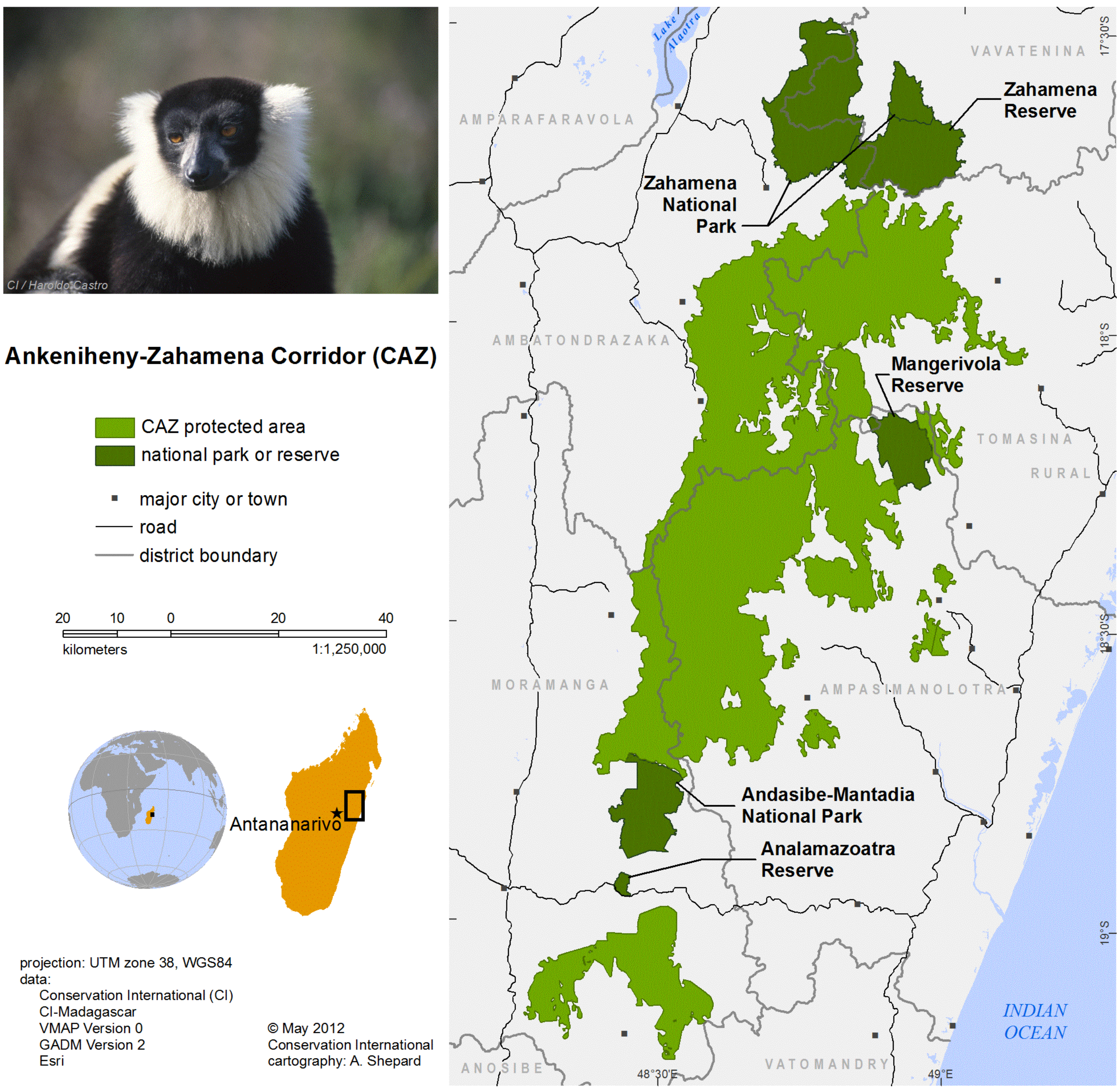

Figure 1. Overview of the Ankeniheny-Zahamena Corridor (CAZ).

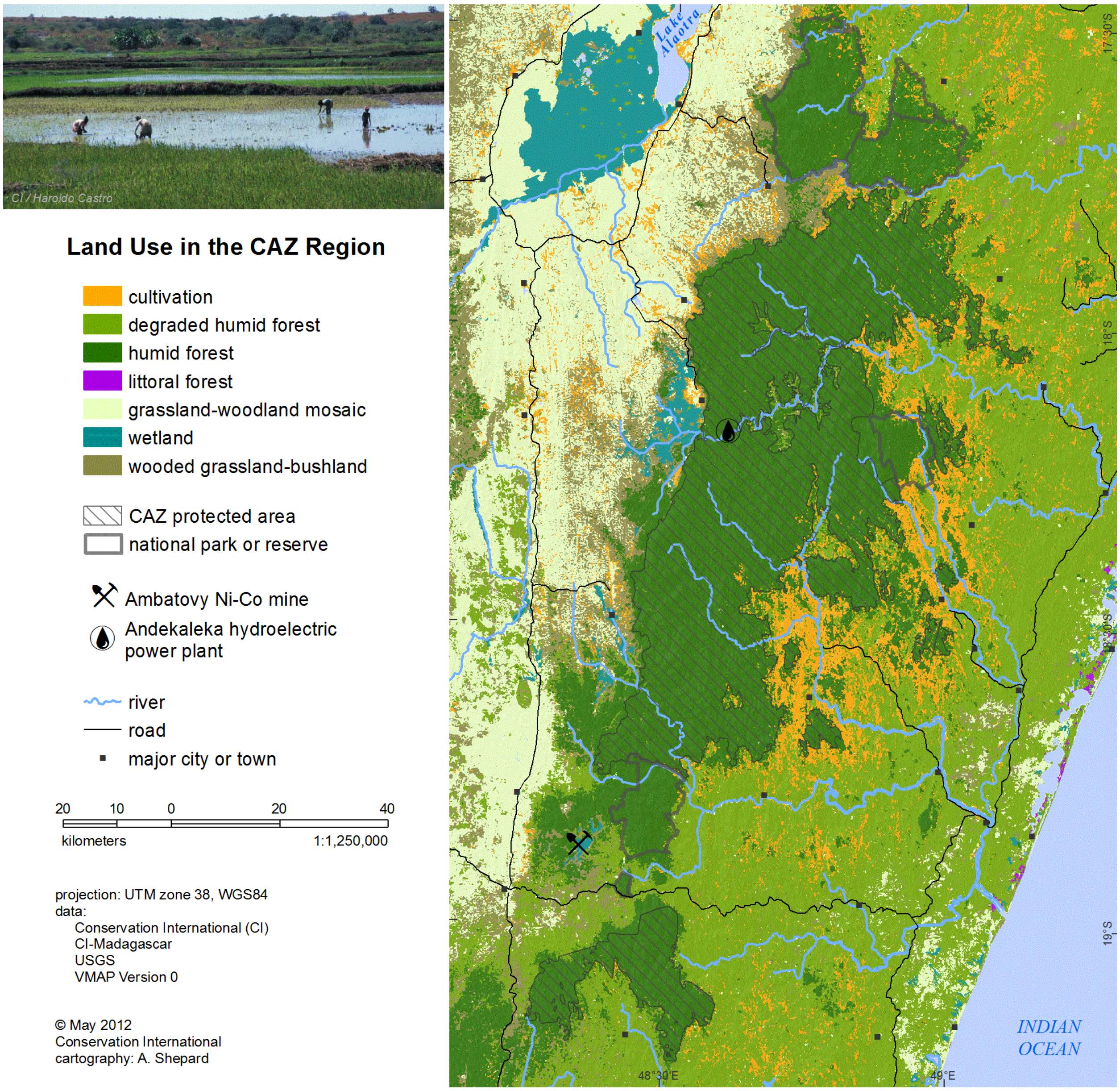

Figure 2. Land use in the CAZ.

CAZ is also home to nearly 350,000 people, mostly rural communities who practice a mix of subsistence agriculture and cash crop production as a basis for their livelihoods. Key revenue sources in CAZ include rice, coffee, bananas, manioc, lychee, poultry, and charcoal. In this mosaic of land uses, deforestation – primarily as a result of *tavy* agriculture – as well other unsustainable and illegal uses such as small scale illegal mining, illegal logging and hunting (USAID, 2007), threaten both the area's biodiversity and livelihoods of the communities that depend on the region's natural resources for their subsistence.

Significant investments have been made in the region over the past few years giving CAZ a strong capacity and foundation for governance and partnership. These investments, made through a variety of funding mechanisms, have allowed communities better stewardship of their natural resources, and have provided livelihood alternatives to unsustainable activities. These include the implementation of a participatory process for designating new protected areas, as well as the establishment of community forest management transfers (GCFs), which has granted certain rights and responsibilities of forest management to community associations in the region. Successful initiatives like these have paved the way and have provided momentum for other regional investments such as the TAMS (Tetik' Asa

Mampody Savoka) and CAZ REDD+ forest carbon projects, the Node Small Grants program, various smaller-scale conservation agreements, and development of the ecotourism sector. Additionally, the CAZ region continues to experience substantial efforts for biological inventory, socio-economic study and cartographic work.

2.3 OVERVIEW OF ECOSYSTEM SERVICES

For this study, we elected to analyze three ecosystem services: (1) carbon storage and sequestration (CSS), (2) water supply, and (3) sediment regulation. The latter was only considered for its effects on water quality (reduced turbidity), ignoring other related services such as beneficial sediment deposition for agriculture, which is less relevant in the selected study areas. Following is a description of the context for the analysis in Madagascar and in CAZ.

2.3.1 CARBON STORAGE AND SEQUESTRATION

Aerial photographs indicate that in 1950, approximately 27% of Madagascar's land area was forested (159,959 km^2). Analyses show that by 2000, total forest cover in Madagascar had been reduced to only 15%, a loss of over 70,000 km^2 (Harper *et al.*, 2007). This alarming deforestation is largely due to anthropogenic activities such as fuelwood cutting and *tavy* (slash and burn) agriculture. The past decade however, has seen a decrease in annual deforestation rates and an increase in awareness of the ecosystem service values that preservation of these forests can provide. Currently, there are at least seven forest carbon initiative projects in operation and under development in Madagascar (Forest Trends, 2012). These are spearheaded and funded by a combination of national and international government agencies and non-profit organizations, and all aim at restoring and preserving Malagasy forests for carbon and biodiversity ecosystem service values.

CAZ is considered one of Madagascar's top conservation priorities, and has received much attention as to the potential provider of forest carbon resources. Like the rest of the country, however CAZ has not been immune to deforestation (Figure 3). It is estimated that one hectare of deforestation in the CAZ results in an average of 270 tons of CO_2 released into the atmosphere (Conservation International, 2010).

Two leading forest carbon projects are currently underway within the CAZ:

The Tetik' Asa Mampody Savoka ("Return the Fallows to Forest") project, or TAMS, is a reforestation initiative that is focused on restoring degraded agricultural land back to its natural state in order to re-create forest corridors between existing protected areas. The initiative is designed to generate CDM (Clean Development Mechanism) certified emissions reduction credits, and it has been included in the portfolio of the World Bank's BioCarbon Fund. This project is under the leadership of the Malagasy government and is supported by Conservation International, and since its inception in 2005 has restored over 300 ha of both public and private fallow agricultural lands (Harvey *et al.*, 2010). Additionally, more than 200 jobs have been created by this initiative, providing direct stimulation to the local economy (Conservation International, 2010).

CAZ is also the site of the "Ankeniheny–Zahamena–Mantadia Biodiversity Conservation Corridor Project," one of the first officially recognized REDD+ projects in Africa (World Bank, 2012b). The goals of this initiative are to reduce deforestation and enhance the capacity of the communities to manage natural resources, while protecting biodiversity and water resources important for downstream production (Conservation International, 2010). This REDD+ initiative, taking place on more than 425,000 ha of rainforest, is one of the key elements that, in 2005, led to the designation of the CAZ as an official protected area. The CAZ REDD+ initiative is certified against the Voluntary Carbon Standard (VCS) and the Climate, Community & Biodiversity Standards (CCBA) (Harvey *et al.*, 2010), and revenues from the marketing of carbon emissions reductions are expected to be among the financing mechanisms responsible for supporting its long-term protection and management. This initiative is under the leadership of the Malagasy government and is supported by Conservation International, and was the first REDD+ project to receive the support of the World Bank's BioCarbon Fund (Harvey *et al.*, 2010).

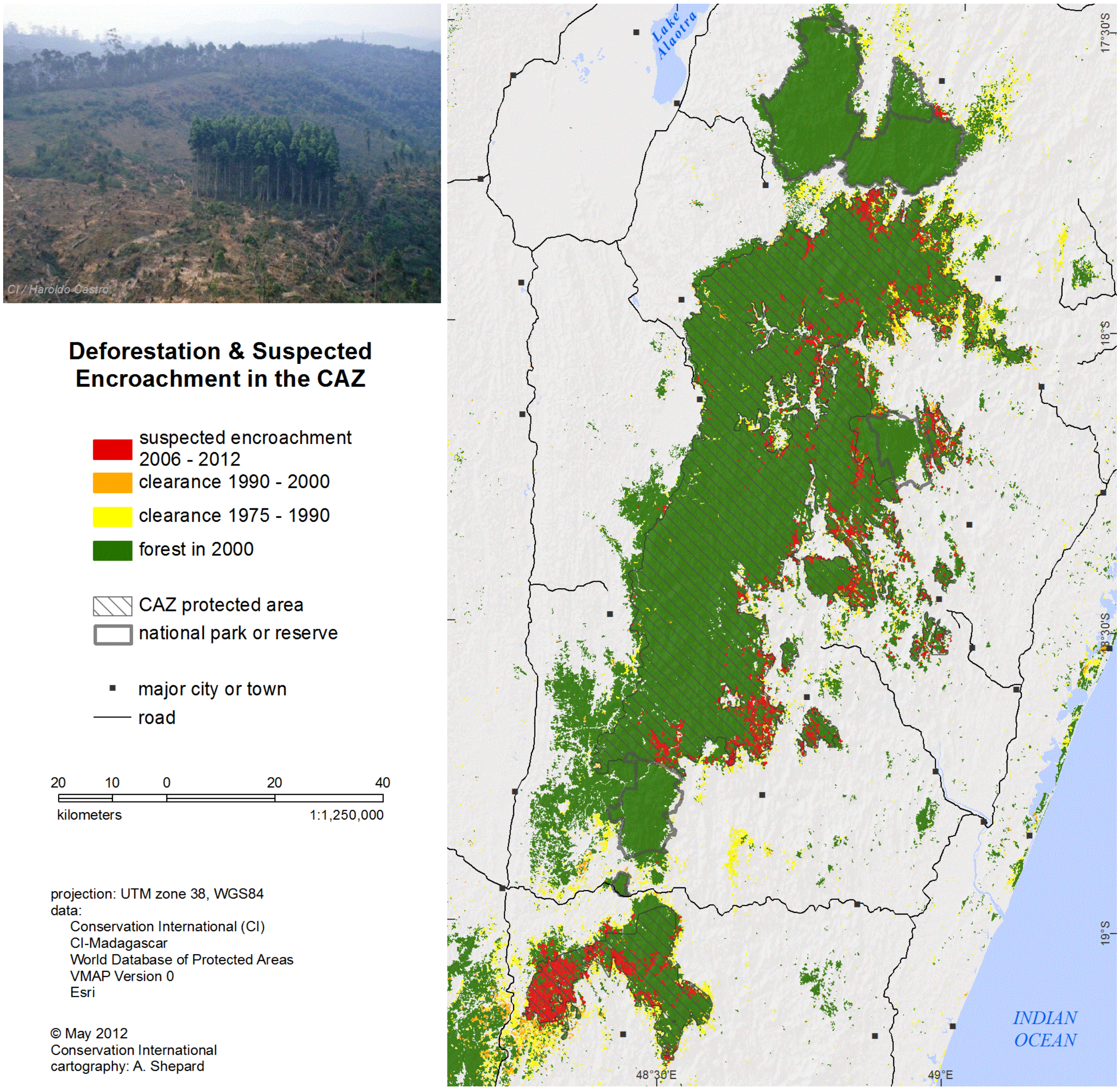

Figure 3. Deforestation in the CAZ

2.3.2 WATER SUPPLY

Madagascar is a country of relatively abundant renewable water resources[5], which are distributed among five main drainage basins: the slopes of the Montagne d'Ambre (north), the Tsaratanana, the eastern slope, the western and north-west slopes, and the southern slope. However, due to large variations in climate (FAD, 2005), these water resources are unevenly distributed throughout the

[5] Long-term average annual precipitation is 1,513 mm/yr. Total renewable water resources, (those that after exploitation will return to natural levels), are estimated at 337 km^3/yr – about 17,600 m^3 per person (FAO, 2012).

country. Water resources are abundant in the northern and central regions and become scarcer in the more drought-prone east and south (Health, 2010). The country's main rivers rise in the north-central highlands and flow west, south and east (FAD, 2005).

The three main uses of water resources in Madagascar are domestic, industrial and agricultural. Agriculture is responsible for 99.98 percent of the total freshwater withdrawals in the country – 14.31 km^3 of water per year – compared to 0.30 km^3 and 0.16 km^3 for municipal and industrial uses, respectively (FAO, 2012)[6]. In terms of annual renewable water resources, these freshwater withdraws account for roughly 4.36 percent of the country's total water budget, 4.25 percent of which is solely for agricultural use. Surface water is the primary source for all of these freshwater withdrawals.

Irrigation in Madagascar is largely gravity fed, and used primarily for micro irrigation (less than 200 ha) and family plots (less than 10 ha), which combined, account for 73 percent of the irrigated land in the country. About 98% of irrigated land is used for growing rice (Health, 2010). Though irrigation represents a significant portion of withdrawals, there are no official estimates on total volumes of water required by irrigated areas (UNDP, 2011). The majority of irrigation infrastructure in Madagascar is highly vulnerable to flooding and siltation, and often requires repair at the beginning of each season (UNDP, 2011).

Annual rainfall in the Ankeniheny-Zahamena Corridor (CAZ) is estimated to be in the range of 2,500-4,000 mm/yr (USAID, 2007). The topography of CAZ is rugged and is characterized by steep slopes and narrow valleys that feed the eight major rivers whose headwaters are located in the corridor: the Faritany Toamasina, Simianona, Marimboha, Manatsatrana, Maningory, Onibe, Sahatavy, and Fanandrahana Ivondro (Miray, 2003). These rivers provide water directly to an estimated 350,000 residents within the corridor, as well as to residents of the provincial capital Toamasina via a network of dams and aquifers (Satoyama Initiative, 2012). There are no official estimates for domestic consumption of water in the CAZ region, or for agricultural or industrial uses.

2.3.3 SEDIMENT REGULATION

Erosion and sedimentation are major global problems that impose a high cost on the functioning of ecosystems and ecosystem service delivery (Yang *et al.*, 2003). Excessive erosion and sedimentation have negative impacts on agriculture, water supply, electric power generation, and navigation, as well as on coastal and near-shore marine ecosystems and the services they provide. While some of these impacts can be positive, such as the provision of rich alluvium for floodplain agriculture, sediments in waterways tend to have adverse impacts on settlements (flooding and landslides) and infrastructure (dams and irrigation) (World Bank, 2011b). For example, reduced sediment delivery to deltas can lead to loss of coastal wetlands and the critical services they provide (Costanza *et al.*, 2006, Day *et al.*, 2007).

Approximately 70% of Madagascar, by area, is covered by soils which, due to the topography on which they are located and their physical structure, are highly prone to erosion (World Bank, 2011b). One study shows that between 1993 and 2003, 48% of hillsides in the east of the country had suffered loss of soil quality (World Bank, 2011b). While anthropogenic activities certainly contribute to increased levels of soil erosion in Madagascar, data on erosion rates is highly variable and recently there has been increasing acceptance that the island's soils were predisposed to erosion long before human settlement (World Bank, 2011b).

Erosion and nutrient leaching in CAZ are important problems in the region, where both *lavaka*[7] gullying (Kull, 2000) and sheet erosion can be found. The significance of *lavaka*, which to a great extent is part of

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[6] Data for municipal are from 2000, while for agricultural and industrial use are from 2005.

[7] *Lavaka* are vertical-walled gullies in lateritic substrate that can reach 300 m long and 70 m wide.

a natural process, is much smaller than that of sheet erosion (Kull, 2000). Deforestation and natural geologic and soil conditions in Madagascar are known to produce top soil loss and land degradation by gullying and sheet erosion, which leads to excessive water turbidity and to ecological impact from deposition in rivers and lakes. Clay and silt from erosion are also carriers of adsorbed chemicals which are then transported to aquatic systems. It is estimated that about 70 percent of the county is subject to soil erosion.

Consequences of erosion can be locally quite severe. Sedimentation of channels, for example, which tends to increase in plots further away from forested areas, leads to a lack of water in irrigated areas and to economic losses both due to lower productivity and needed repairs (Rakotoarison, 2003). Significant deposits of sand can also damage the turbines of hydroelectric power plants – an important source of electricity in Madagascar. The impacts of sedimentation are an accepted burden for hydropower operations in terms of the perpetual need to flush sand deposits from dams, but these impacts are more severe and result in higher economic losses during low water flows when they can significantly reduce electricity production. Erosion in Madagascar has also led to extensive silting of estuaries, and of mangroves, and to declines in coral reefs and coastal fisheries.

The CAZ is located primarily atop an escarpment, and thus provides substantial services in the provision of water and control of sediment flow to a large surrounding area, including the agricultural plains on both the east and west sides of the corridor, and to the two hydroelectric power plants that supply electricity for Madagascar’s two largest cities (World Bank, 2011b).

2.4 ECONOMICS OF ECOSYSTEM SERVICES

Ecosystem services (ES) are often used as inputs in production system (e.g. timber is used to build furniture; plants are used in the pharmaceutical and textile sectors; water is needed for producing many goods and services). It is important to investigate and measure the “impact” of ecosystem services on the production of different goods and services which are traded in markets.

Economists are interested in a particular measure of production efficiency: the marginal productivity of production inputs. That is, economists wonder, what will happen to the total output when we vary the use of a (marginal) unit of a selected input? Marginal productivity of the input is therefore a measure of the effects on total output of a small variation (increase) of the input. When the input (marginal) increase generates a more than proportional increase in the output, the production technology is characterized by increasing returns. When the input (marginal) increase generates a less than proportional increase in the output, the production technology is characterized by decreasing returns. When the input (marginal) increase generates a proportional increase in the output, the production technology is characterized by constant returns.

A production system is more efficient when returns are increasing, less efficient when returns are decreasing. This means that an additional unit of input will produces proportionally more output when the production technology presents increasing returns. By the same note, decreasing returns imply that total production costs are increasing faster than production. This might cause a loss to society not only because of lower profits and dividend distribution, but other social benefits such as higher prices and worse environmental protection. Therefore, efficient use of resources implies, among other things, a minimization of social costs of industrial production.

Water productivity, for example, conveys important information for environmental policy design, because understanding the impact of the marginal unit of input (water) on the output production and assessing the technological characteristics of production will allow the analysts/policy makers to better assess trade-offs, e.g. the same amount of water can be used more efficiently in sector A rather than in sector B. This in turn can have significant impacts in terms of natural resource conservation and management from a sustainable economic growth perspective.

A selected ecosystem service (water supply), is herein interpreted as fundamental production inputs (like all other market inputs, e.g. labor, capital, machineries) for the economic, market based performance of four different sectors in the CAZ area: (1) mining, (2) agriculture, (3) tourism, and (4) hydroelectric generation. (Figure 4).

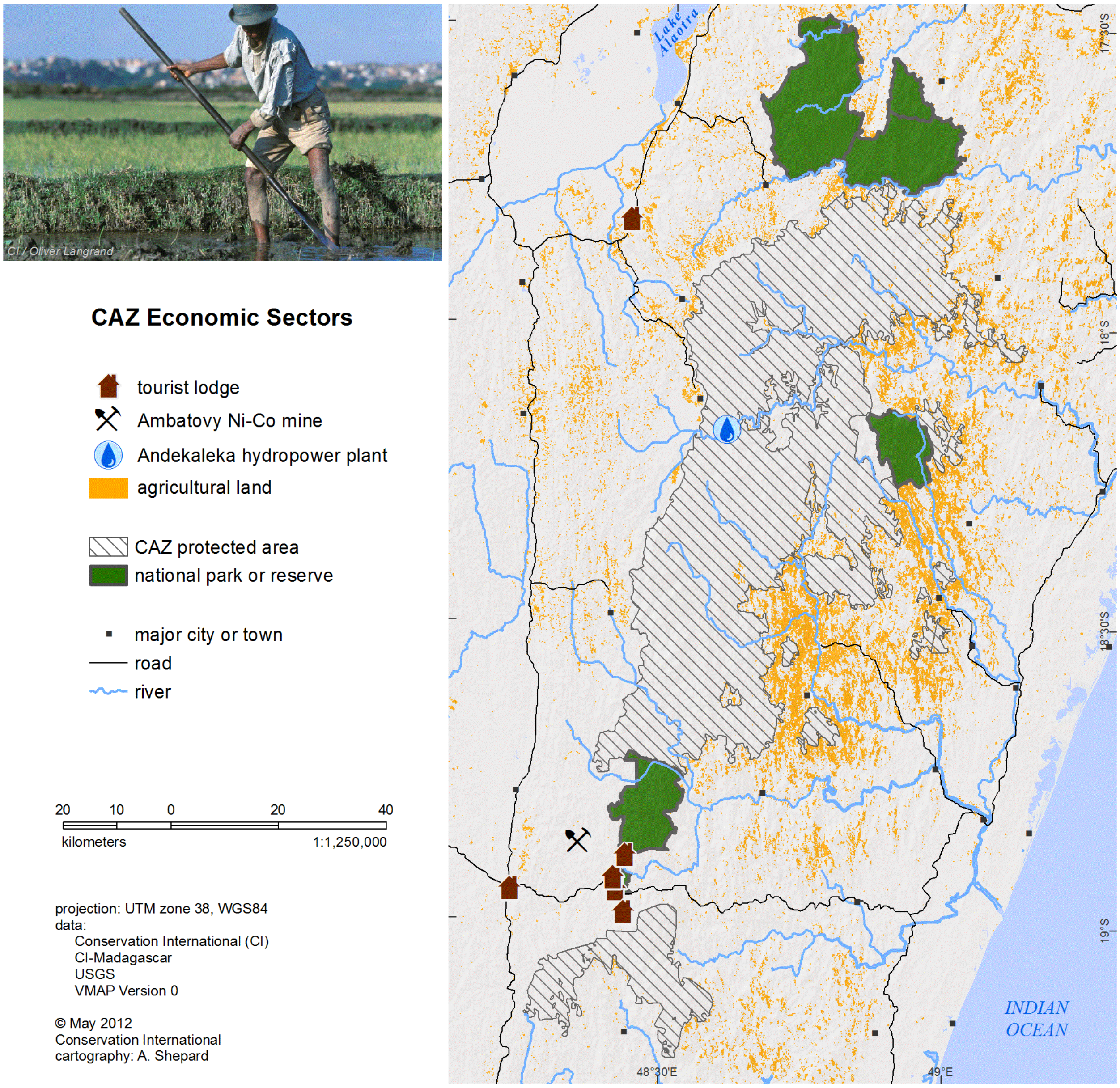

FIGURE 4. CAZ ECONOMIC SECTORS.

3. METHODS

While several ecosystem services studies have already been carried out in Madagascar (Wendland *et al.*, 2010), and in the CAZ region in particular, the uniqueness of the analysis we provide here is two-fold. First, it is performed with a benefits-centered framework for ecosystem services, using state-of-the-art technology to assess biophysical estimates of ecosystem service provision, use, and flow. This technology ultimately links supply and demand, and can greatly assist in decision-making. Second, our analysis makes explicit the spatial interdependency of economies and natural systems, particularly with respect to the determination of the impact of selected ecosystem services on human activities and choices, and the potential for thresholds in the supply of critical ecosystem services. In this section, we describe in detail the methods used to address the biophysical and socio-economic aspects of ecosystem service flows in the CAZ region.

3.1 BIOPHYSICAL ANALYSIS: THE ARTIFICIAL INTELLIGENCE FOR ECOSYSTEM SERVICES

Spatial maps of the biophysical distribution of ecosystem services (ES) have been used for many years. More recently, ES-specific computing tools have emerged to systematize their mapping and economic valuation with the final purpose of assisting policy decisions. Most tools attempt to convert qualitative information, chiefly land use type, into estimates of biophysical value of services. The ARIES (Artificial Intelligence for Ecosystem Services) methodology aims for a more realistic view of ES that accounts for the complex dynamics of ES and allows a more precise and spatially explicit quantification of the benefits provided. Ecosystem services are seen in ARIES as the result of the flow of a beneficial or detrimental carrier of the amounts transmitted from ecosystems to humans. The nature and mode of the flow of benefits may be very different for each ecosystem service. Each service will be carried by different media, which may range from physical (e.g. water, CO_2) to energetic or informational (e.g. culturally mediated services, aesthetic views, proximity to valuable destinations). In all cases, ARIES will choose the appropriate model and quantify the actual benefits accrued by society by linking them to precise amounts and locations where the carrier has flowed or accumulated. Figure 5 depicts the various components of a hypothetical service analysis to help clarify the notion of ecosystem services adopted in ARIES. In this conceptual model, the green area is the natural source of a service carrier, which flows to societal beneficiaries (in blue) along flow paths (black) that depend on the type of carrier and on the landscape. During the process, the carrier may encounter sinks (in orange) where the carrier is intercepted or depleted (in quantity or quality) so that it cannot reach the user anymore. The final amount of carrier that reaches the beneficiaries will be linked to the amount of value obtained, directly for beneficial services (such as water for drinking or irrigation) and inversely for preventive services (such as protection from floodwater or river siltation). Rival users of ES compete for the benefit (e.g. the water that irrigates one crop is not available for others located downstream), while non-rival users do not (e.g. aesthetic views can be enjoyed regardless of how many people are there to watch). If the carrier flow concentrates in specific areas, those areas are critical to the delivery of the service and policy decisions need to ensure that they are protected. Only this kind of dynamic analysis can fully highlight the consequences of policy decisions on ES delivery.

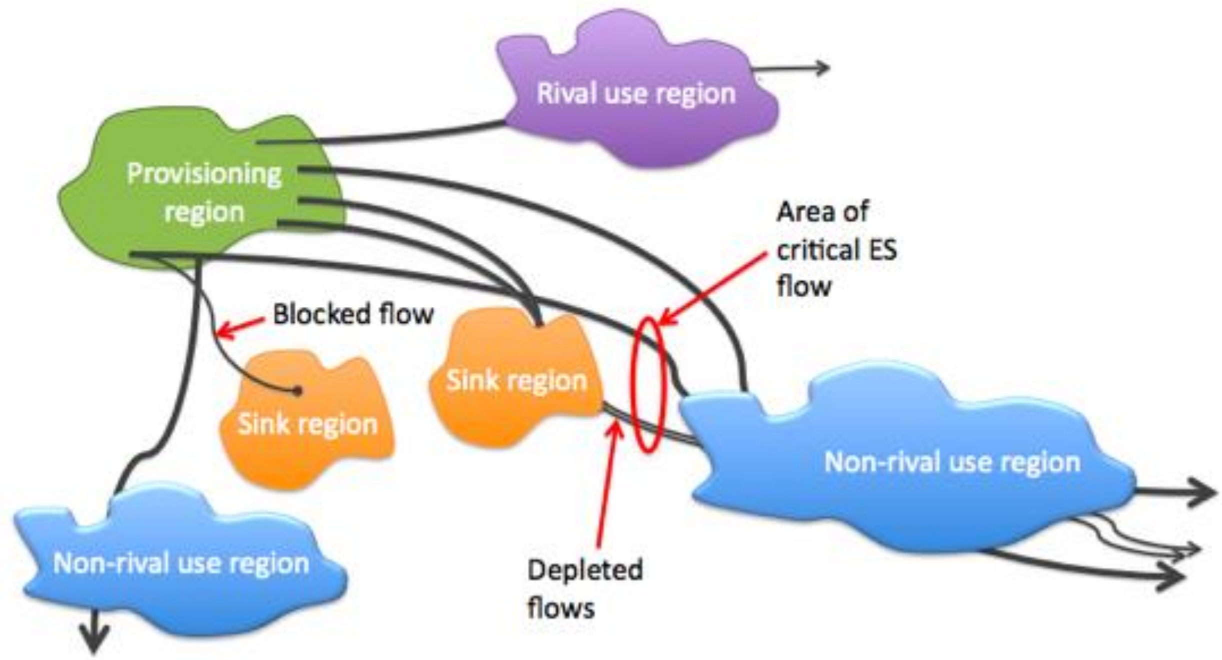

FIGURE 5. CONCEPTUAL MODEL OF ECOSYSTEM SERVICES UNDERLYING AN ARIES MODEL.

Recognizing that each situation is unique and that an accurate adherence to the local priorities is necessary for effective decision-making, ARIES does not use a predefined model for any service. Rather, the existing data on the selected region suggest which individual model "pieces" are most appropriate, and these are automatically assembled into a final model which is precisely tailored to the situation under study. Such choices are made automatically by the artificial intelligence algorithms in ARIES, on the basis of a constantly updated knowledge base compiled from literature and expert opinion (Villa, 2009).

Emphasis on spatial physical flows to actual beneficiaries

ARIES can produce a full account of winners and losers and potential vs. actual provision for each ecosystem service. Because of its emphasis on actual spatial flows, ARIES can compute results that highlight the efficiency of delivery as well as the evenness of its distribution, allowing decision makers to plan interventions and policy in a very precise way. After ARIES has finished computing the model for a service, the results will contain not only how much value has been accrued by beneficiaries, but also how much is produced that cannot get to them, and which social groups remain in need because of the uneven spatial distribution of service provision.

Because of the emphasis on actual physical flows to explicitly characterized beneficiaries, ARIES is immune from commonly cited problems of ES analysis, particularly from "double counting" of values: ES benefits are only accounted for when the beneficiaries are actually impacted, and each benefit is modeled separately and accounted for in the proportion that has actually been accrued by explicit beneficiaries. Although the ecological factors implied in service provision and routing may be in common between different benefits, each benefit is independently modeled and quantified and can safely be added to the full value of each natural feature implied in its provision. Compounding of values, such as the synergic benefit of water supply and water purification, is a different matter that ARIES only addresses when the beneficiary models have enough detail to allow it. All values are provided as input to the economic analysis so that they can each be given proper consideration in case their effect on economic value is not additive.

Results of an ARIES session

ARIES synthesizes the ES flow results into different groups of spatial maps. The first group helps one understand how much service value is available and how much room is there for improvement. Theoretical supply maps will show the amount of value that could be produced in ideal situations, assuming that all the service can get to people. Potential supply maps show the amount that can get to beneficiaries but may be wasted due to policy-affected factors, e.g., downstream pollution. Actual supply maps show the value that actually gets to the users in a useful form in the current situation. Comparison of these maps helps one understand the efficiency of ES service delivery in the area: if the potential supply is much higher than the actual supply, there usually is room for policy-driven improvements in delivery and/or equity.

These source maps quantify the actual stocks of natural capital that provide a given ecosystem service, and they depict the direct source of any economic value resulting from the corresponding ecosystem services in the area. ARIES can differentiate this value into theoretical, potential and actual, providing unprecedented insights in the efficiency of provision and the potential for improvement. This approach is vastly superior to the more conventional land-use driven approaches, which do not perform any assessment of beneficiaries and are limited – with a great degree of inaccuracy due to not considering dynamic physical flows – to coarse assessment of theoretical values.

Other ARIES-generated maps link supply and demand in ways that may be used to spot problem areas in need for intervention. The blocked supply map shows the value that is produced by the ecosystem but cannot get to humans, because of policy-controlled issues such as pollution or diversion from infrastructure. Inaccessible supply maps show the value that is produced by the ecosystem but cannot be accessed by humans because of the inherent features of the landscape. The first can be used to spot areas where intervention may help restore service delivery; the second to highlight those areas where service production may not be utilized. All such scenarios can be simulated in ARIES and their relative tradeoffs illustrated by comparing the resulting outputs with the baseline.

3.2 BIOPHYSICAL ANALYSIS: METHODOLOGICAL APPROACH FOR THE CAZ STUDY

The preliminary CAZ biophysical study has concentrated on three ecosystem services: (1) carbon storage and sequestration, (2) water supply, and (3) sediment retention as it pertains to water quality. Following is a description of the most important aspects of the models employed in the analysis of these three services. Full detail on the methods which were adopted for this study is given in Bagstad *et al.* (2011), Villa *et al.* (2011) and Johnson *et al.* (2010). In particular, the reader is referred to the ARIES modeling guide, available online at www.ariesonline.org/toolkit. In the guide is a full description of the models, their assumptions, data needs and conditions of application.

Due to the preliminary character of this study, only a subset of the ARIES service typologies has been investigated in this work. The scales of the study have also been limited to those that were practical for the data and resources available. Therefore, please note of the following caveats:

1. The three services have their only link point in the connection between the sediment model and the water model (sediment flows are intersected with water flows in order to assess the benefit of sediment regulation to the same users that benefit from water supply). Also, rival uses of water have been properly accounted for by using the result of each independently modeled use of water as an input to compute the available supply to other uses. Other link points, such as the feedbacks of each different use on the demand for other services, or the potential tradeoffs between water quantity and quality in situations of resource limitation, have not been explored.

It must be mentioned, however, that no such tradeoffs are explored in any of the currently available methodologies for ES assessment.

2. Due to limitations in data availability, the water and sediment models use annual precipitation data; all water use and supply figures are therefore expressed annually. While water use has important annual fluctuations, the patterns of flow do not change significantly from season to season, and comparative results of CAZ vs. non-CAZ areas remain representative of the added values provided by the natural features of CAZ even if seasonal dynamics is not addressed in the physical models.
3. Despite the above limitation, the values accounted for by the biophysical analysis are independently expressed in terms of input to explicit beneficiaries, not in terms of output from the same natural features. They can therefore be considered additive from the point of view of the biophysical analysis, and used as independent inputs for their economic valuation.

The complexity of the transport models for water and sediments, and the requirement to run them at fine spatial resolution in order to obtain sufficient realism even for a preliminary analysis, prevents investigation of remote effects such as the role of water supply and sediment regulation in affecting hydropower production located outside CAZ, but dependent on it for the supply of upstream water resources. Such analysis requires data and computational resources that are unavailable in a study of this scale.

3.2.1 CARBON STORAGE AND REGULATION

Carbon sequestration and storage help to provide a more stable global climate by taking up greenhouse gases and keeping them out of the atmosphere. Different portions of the natural landscape store and release carbon at different capacities and rates. In ARIES, the areas where vegetation and soils have sequestered carbon are designated as *sources* of the ecosystem service. In Madagascar, sequestration rate is seen as a function of soil C:N ratio and the difference between mean summer high and winter low temperatures, land cover, vegetation type, and actual evapotranspiration, percent tree canopy cover and forest degradation status. In ARIES parlance, the areas where stored carbon may potentially be released due to fire, land use change, deforestation, or other vegetation and soil disturbances are designated as *sinks* of the ecosystem service[8]. Soil carbon storage in Madagascar is influenced by slope, soil pH, soil oxygen conditions (i.e., greater storage in wetlands where anaerobic conditions inhibit respiration), vegetation density (an intermediate variable incorporating tree canopy cover and degradation status), and soil C:N ratio. By subtracting the potential stored carbon release from carbon sequestration in a region of interest, we compute the carbon available to offset anthropogenic emissions. By mapping levels of carbon sequestration, stored carbon release, and anthropogenic emissions in a common unit (tons C/yr), we can fully describe regional carbon balances – the level of a region's net release or uptake of atmospheric CO_2. Such values are computed probabilistically and spatially, so that maps of the output variables can be computed along with the relative uncertainties, and then aggregated to region-wide carbon budgets. While the ARIES carbon models do include a use component and a flow component (e.g. carbon emitters who can offset their emissions) the value of carbon in Madagascar is largely dependent on global carbon markets so this component has been omitted from this study.

[8] Our use of the term *sinks* is different from the typically used term in the carbon literature; our use follows the generalized ARIES ecosystem services terminology used to identify the spatial dynamics of services. The designation of areas of carbon sequestration as *sources* of the service and areas of potential stored carbon release as *sinks* reflects the designation of carbon sequestration and storage as a *provisioning service*.

3.2.2 WATER SUPPLY

Freshwater supply in the form of both surface and groundwater plays a critical role in supporting human well-being. To better quantify amounts generated by ecosystem water supply and regulation, ARIES simulates surface and groundwater flow to connect human beneficiaries (e.g. agriculture, industry, domestic use) with their upstream water sources and sinks. Once these ecosystem dependencies are identified, the various landscape effects on water quality and quantity along these flow paths can be estimated, and the final water value to users can be assessed under different land management scenarios. In ARIES, water quantity is largely a function of topographically-based hydrologic simulation. Water supply is a complex ecosystem service to spatially model, given (i) that groundwater and surface water are closely connected but move based on different controlling factors, (ii) that these influences on hydrology and hydrologic models differ greatly based on the spatial and temporal scale and the region of the world considered, and (iii) that available spatial data can rarely support modeling at both high spatial and temporal resolutions. Given these limitations, our current water supply models operate at an annual scale (which is matched by available spatial data for important variables including precipitation, infiltration, snowmelt, and evapotranspiration). We currently consider only flows of surface water, though we do model the infiltration of surface water into groundwater and groundwater extraction from wells when data are available. We also use a set of generalized models to represent sources of surface water (precipitation, snowmelt, springs, baseflow to rivers, and incoming inter-basin water transfers), sinks of surface water (evapotranspiration, infiltration), and the flow of surface water across the landscape (routed using SRTM elevation data).

For the purposes of this study, water use has been modeled for three different classes of usage, in order to best connect with the economic analysis.

1. Irrigation use for rice fields. The water needs of rice fields in the area were computed according to the FAO irrigation manual (Brouwer *et al.*, 1985), using the Blaney-Criddle method for evapotranspiration, growing season length estimated by latitude, and assuming two harvests per year from transplanted rice. Data were checked for consistency with information provided by the Lac Alaotra authorities (neighboring but not located in CAZ) and corrected for annual rainfall (from global data).
2. Use by tourists in CAZ lodges. Such usage data were provided by the lodges and extrapolated to other lodges in the area. Spatial mapping was done manually by tracing the outlines of the lodges in Google Earth.
3. Use for industrial mining was modeled in a similar way as the tourist usage using data provided by the Extractive Industry Transparency Initiative for the nickel-cobalt mine in Ambatovy.

As the usage of water is rival (any user will impact the supply for the users downstream) models for residential usage, livestock, and irrigation for cultures other than rice have also been developed, based on global population density and livestock data corrected for available information provided by Madagascar authorities. To simplify the analysis these have been made part of the sink model, so that rival use is properly considered but no ES flow analysis is done for these.

3.2.3 SEDIMENT REGULATION

For the scope of this preliminary study, only the sediment affecting water quality has been modeled, allowing us to quantify the benefits provided by the CAZ natural features in protecting the water sources from excessive turbidity due to dissolved sediment. We model sources of waterborne sediment, sink regions where sediment deposition occurs, and users who either value or are harmed by the delivery of sediment or the presence of excessively turbid waterways. Sediment regulation can thus be classified as either a provisioning or preventive service whose benefits are rival and are measured (in tons of sediment) at the watershed scale. Running the sediment flow model allows the mapping of spatial connections between sources of sediment, areas that promote sediment deposition, and users that benefit from or are harmed by sediment delivery. In Madagascar, high rates of deforestation (Harper *et al.*, 2007) and low natural rates of succession have led to high levels of erosion (Wendland *et al.*, 2010). Excess sedimentation can be particularly damaging to rice fields (Carret and Loyer, 2003). Most of CAZ is not located in a floodplain so the dissolved fraction of sediment is more of an issue than in other areas. For this reason, and because the economic analysis concentrates on water, the flow paths of water computed by the water models described above have been set as the recipient (use model) of sediment flow, allowing us to estimate the spatial location and amount of sediment that is likely to contaminate the water sources in each point of the study area.

Spatial modeling of sedimentation has frequently relied on source models derived from the Universal Soil Loss Equation (USLE, Wischmeier and Smith, 1978; RUSLE, Renard *et al.*, 1996; SEDMOD, Fraser, 1999) that use five factors – rainfall runoff erosivity, soil erodibility, slope steepness and length, cover management, and conservation practice – to estimate soil loss over a given spatial and temporal extent (e.g., tons sediment/ha-yr). Spatial data for soil loss and RUSLE factors are available globally as a 0.5x0.5 degree raster dataset (Yang *et al.*, 2003). However, such models apply only to sheet erosion in moderately hilly landscapes with similar physical and ecological characteristics as the central United States. Thus, their application is hard to justify in other parts of the world. The ARIES internal rule base selects the appropriate models on a point-by-point basis using the data as a guide (Villa *et al.*, 2011), and in Madagascar it will most often adopt an ad-hoc probabilistic model calibrated to data rather than the “canonical” but hardly justifiable USLE approach (see Bagstad *et al.*, 2010 for more details). Erosion sinks are areas where sediment accumulates as it flows through a watershed. The source and sink models estimate the annual quantity (in tons or kg of sediment per hectare) of sediment that erode from one part of the landscape (in the source model) and are deposited elsewhere (in the sink model). On the basis of that, a flow model computes the amount of beneficial or detrimental sediment delivered or the amount of sediment carried in flowing water (i.e., turbidity). Since we do not model wind-based erosion, sediment flows are modeled using a relatively simple hydrologic model. We use hydrography and SRTM elevation data to derive flow direction to route water across the landscape and through waterways. This simple approach has the benefit of being applicable at relatively coarse spatial scales and at any location on Earth, and is therefore best suited to ES analysis when sophisticated hydrological models would add little to the precision of the study but much to its cost in time and research.

3.3 ECONOMIC ANALYSIS: METHODOLOGICAL APPROACH FOR THE CAZ STUDY

The methodology for the economic element of the CAZ case study was based on two distinct approaches: The first focused on climate regulation and used market-based values for carbon which were then multiplied by the carbon sequestration estimates resulting from biophysical values. The second approach focused on water supply. This approach identified the impacts and the values of water supply as an ecosystem service in the CAZ market productive system on four different economically productive activities: agriculture, tourism, mining and hydroelectric generation (Figure 4). Working from an industrial economics perspective, we assess the contribution of the environment to economic activities, rather than assessing the impact of economic activities on the environment. As such, this analysis does not focus on non-market valuation of negative externalities (e.g. pollution, environmental depletion assessment). However, the analysis is unprecedented in its inclusion of ecosystem services into market dynamics and its attempts to empirically estimate and quantify the contribution of ecosystem services in the performance of economic activities.

The ‘rapid assessment’ nature of this analysis precluded us from being able to perform an in-depth industrial economic analysis of each sector. Following is a description of the analytical framework that was adopted for water supply given the time and data limitations that this study faced.

3.3.1 INPUT PRODUCTIVITY AND VALUE OF MARKET PRODUCTIVITY

The simplest and most common way to describe the production technology within a sector is via a production function[9]. A production function mathematically describes the relationship that links the sector's various inputs and outputs (Varian, 1992), for example, the relationship between irrigation water input and surplus rice output. Having the production technology expressed in a functional form allows us to mathematically investigate the marginal effects of inputs on outputs. For example, if we consider the ecosystem service an important input for the production of a good or service, we are interested in knowing how total production (in terms of total quantity of produced output) is effected when we add an extra, marginal unit of input. In technical terms, we want to measure the marginal productivity of the ecosystem service input on the production of selected goods and services that are produced in the CAZ area.

The marginal productivity of the input (e.g. water) provides information about the economic and technological efficiency of the production process, but does not convey any information about economic value. Therefore, in order to measure the economic value of a production-input ecosystem service, we employ an additional methodological tool provided by microeconomic theory: the value of marginal productivity. The value of marginal productivity is a measure of how much marginal revenues (obtained by the sale of an additional output unit) increase with the use of each additional (marginal) unit of input. This indicator is computed by multiplying the input marginal productivity times the output market price. The value of the input marginal productivity can also be interpreted as an opportunity cost – e.g. the cost of a forgone unit of water destined to an allocation different from the one currently considered. The value of the marginal productivity of water provides a monetary measure that bridges the technological characteristics of production (where water is an input) to the economic profitability of production.

However, there are some caveats to these methods. In order to calculate the value of the marginal productivity we used data on the (final) output prices. (An explanation of the methods used to gather this data can be found in the technical appendix). Input and output price formation is an important element in the derivation of marginal productivity value, but given limited time and resources we were unable to focus in detail on that particular element. In addition, we do not take into consideration the water market structure in CAZ, because, to our understanding, it is still under development. Nonetheless, our analysis and theoretical framework allow us to derive solid economic values, in spite of neglecting this important feature. When we compute the value of the marginal revenues using a scaling-up method (i.e. multiplying the value of marginal productivity per unit, times the total produced/sold/exchanged output) we can better assess the economic value of the considered production sector and trace it in national accountability.

In this study, we empirically assess the market productivity and the value of the market productivity of an important production input, water, in the performance of four economic activities in CAZ. We assess how (and how much) the selected ecosystem service affects the production of market goods and services. Our objective is neither to assess the overall production efficiency of the four economic sectors, nor to estimate the frontier of productive possibilities in the CAZ area. Our objective is to provide an economic assessment of how marginal variations of an ecosystem service input can affect

[9] It is important here to clarify the difference between ecological and economic production functions. Ecosystem function is the capacity for natural processes and components to provide goods and services that satisfy human needs. In particular, ecological production functions describe the processes that combine and change organic and inorganic substances into goods that can be directly used by humans (Hawkins, 2003). In our valuation framework, when ecosystem services are not directly used, but instead become inputs in a production system carried on in markets, we switch from the ecological production functions to the economic production functions, where ecosystem services are production inputs.

market production in different economic sectors within the same geographical area. Our analytical framework makes use of concepts and instruments that are solidly anchored in mainstream market economic theory. This framework is robust in the context of data scarcity and it produces values that are easily comparable for policy scenario design. Finally, we intend that this exercise is easily replicable.

3.3.2 TESTING PRODUCTION FUNCTIONS

The next step of the analysis looks at the organization of production within these economic sectors (mining, agriculture, tourism, and energy), and examines how (and how much of) the ecosystem service is used in the production, specifically, of nickel, cobalt, rice, tourist arrivals, and hydropower.

In order to compute water productivity, we need to assess the impact of the input water on the production of total outputs. We need, therefore, to empirically estimate production functions that mathematically describe the technical relationships linking water to the above-state production outputs.

Our methodology, therefore, aims to define/model a particular production function, for each considered sector. A general formulation of the production function is shown in Equation 1:

$$(1)\ Q = q(L;K;N,Z)$$

where ***Q*** is the total output of some good (cobalt, rice, etc.), ***L*** is the input of human capital (e.g. labor); ***K*** is the input of financial capital (e.g. infrastructures and machineries); ***Z*** represents other inputs (e.g. land) and ***N*** denotes the input of natural capital (e.g. water). This very simple, general representation of the production function can be interpreted as follows: in order to get an amount of output ***Q*** the production technology is based on the use of work, capital, water and other inputs. Once these variables are selected, it is important to understand how they are interlinked and each affect total production. This is accomplished through a study of the economic sectors' characteristics, and through the definition of the functional form (e.g. the mathematical relationships that link the inputs) of the production functions.

We have modeled unique production functions for each of the principle economic sectors in the CAZ region in order to get a realistic representation of how production inputs, including water, are functionally linked in the production of cobalt and nickel (mining sector); rice (agriculture); tourist arrivals (tourism) and hydroelectricity (energy). Estimation of the production functions occurred in two stages: (1) assigning a numerical value to the model variables; (2) testing with data whether or not the model is a correct approximation of the economic and mathematical relationships between inputs and outputs we are trying to describe. The (estimated) marginal productivity values of water in the four selected economic sectors were then used to compute the value of the marginal productivity of water for each sector.

For this analysis, our research largely focused on gathering the necessary data in order to assign a legitimate numerical value to the impact of water in the production of different market goods. Data for the analysis were collected by teams from the Madagascar World Bank and Madagascar Conservation International in the period November-December 2011.

Enough data were available to estimate marginal productivity of water in the mining and agricultural sectors, but not for the tourism and energy sectors. For the latter sectors, we relied on information about water productivity found in the industrial economic literature and through experts' interview.

The technical appendix of this document contains a detailed description of the models, the data, the estimation techniques and empirical diagnostics adopted to produce the found in this report.

3.3.3 EMPIRICAL ANALYSIS: MINING SECTOR

Cobalt and nickel are extracted by Ambatovy, a multinational, large-tonnage, long-life mining enterprise located near the town of Moramanga (Figures 2 and 4). At a construction cost of approximately USD 5.5 billion, Ambatovy is the largest-ever foreign investment in the country – and one of the biggest in sub-Saharan Africa and the Indian Ocean region. It will soon rank among the largest lateritic nickel mining entities in the world.

Data for the mining sector analysis were gathered from different sources of information, including Ambatovy's internet site, technical documents, reports and expert interviews. These data include:

- Output measures: quantity in tons of produced nickel, cobalt and ammonium sulphate per year, assuming a mine life-span of 30 years.
- Input measures: labor (measured in number or workers), machinery (measured in capital investment), water (measured in cubic meters), land (measured in hectares), raw material (quantity of used tons of limestone, sulphur, ammonia, coal), and energy (measured in kilowatts).

After creating the dataset, we estimated two different Cobb-Douglas production functions (for nickel and cobalt), using the ordinary least squares[10] estimation method, and considering the temporal dimension of production to be a mine life-span of about 30 years. Please see the technical appendix for more detail.

3.3.4 EMPIRICAL ANALYSIS: CARBON

In order to value the carbon sequestration services of CAZ area's forest in monetary terms, a range of carbon prices are applied to reflect the damages caused by different degrees of climate change impacts. In the present report, a number of well recognized EU studies (EC, 2008; DECC, 2009 and Centre d'analyse stratégique, 2009) have been looked at to choose the most suitable value for carbon prices, taking into account the 2020 emission reduction target for Europe as well as the estimated social costs of carbon. By definition, the Social Cost of Carbon (SCC) is the net present value of the impact over the next 100 years (or longer) of one additional ton of carbon emitted to the atmosphere today (Watkiss *et al.*, 2005). The present estimates of SCC might/should influence our efforts to stabilize CO_2-equivalent concentration, and reduce emissions. The underlying statistical magnitudes are the outcome of Integrated Assessment Models, which translate climate damages into monetary costs to a society – see Appendix II for more information. For this reason, the SCC also is referred to the marginal global damage cost of carbon and its magnitude is used for a proxy of the market price of carbon. It is important to note that a range of estimates of carbon prices are used here in order to account for uncertainties of climate change damages. In this context, we have chosen to use the European Commission estimates (EC, 2008 and DECC, 2009) as the lower bound values and the French study estimates (Centre d'analyse stratégique, 2009) as the higher bound values for carbon values – see Table 1.

The upper- and lower- bounds of carbon value in 2010 are applied to the estimates of total carbon flow in the CAZ (section 4.1.2) in order to estimate the total carbon value provided by CAZ area and to reflect other co-benefits that conservation and forestry provide.

[10] The model was estimated with IV estimation methods.

TABLE 1. CARBON VALUES[11] USED IN THIS STUDY (USD/T, 2010)

Unit	Range	2010	2020
Carbon (C) or C-equivalent	*Low*	83.6[a]	189.6[b]
	High	155.6[c]	272.3[c]

Source: a. DECC (2009), b. EC (2008), and c. Centre d'analyse stratégique (2009).

Note : Note: the conversion between Euro/tCO_2eq and Euro/tC is based on the conversion to CO_2 from C using the ratio of molecular weights (44/12).

3.3.5 EMPIRICAL ANALYSIS: AGRICULTURAL SECTOR

Agriculture and farming are important economic activities throughout Madagascar. In the CAZ area, most local households cultivate rice and manioc, but also potatoes, corn, coffee, pepper, sugarcane and different fruit types (bananas, lychee, citrus, and pineapples). Rice cultivation in Madagascar (and in the CAZ area) follows two main techniques: (a) irrigation and (b) *tavy*[12]. CAZ households practice both techniques on a 50:50 proportion.

Data were gathered from a variety of sources: ministerial (Ministry for Agriculture, Farming and Fishery) surveys and censuses of the agricultural sectors and households; the National Statistical Bureau (INSTAT); the national water company (JIRAMA); Rice Observatory; regional development plans; and information from local authorities. These data include:

- Output measures: quantity in tons of produced rice and manioc, number of households' farm animals in selected administrative areas within the CAZ in 2009.
- Input measures: labor (measured in number or workers), tools (measured in number of most-commonly used hand-tools), water (measured in cubic meters), land (measured in hectares), and type of machinery used.

Since the agricultural sector in the region is primarily subsistence-driven, we estimated a system of Cobb-Douglas production functions assuming that there are economies of scope between the activities of rice and manioc cultivation and the management of household-scale livestock (poultry). Three Cobb-Douglas production functions were estimated: a) one where the quantity of produced rice is the dependent variable; b) one where the quantity of produced manioc is the dependent variable; and finally, one where the quantity of managed farm animals is the dependent variable. The system is estimated by the three stage least squares estimation method. Again, see the technical appendix for more detail.

3.3.6 LITERATURE AND EXPERTS ANALYSIS: TOURISM SECTOR

Tourism is a leading economic sector in Madagascar. Eco-tourism particularly significant, given that the island holds 70 species and sub-species of the charismatic lemurs, 190 types of amphibians, 346 types of reptiles, over 1000 varieties of orchids, and more than one hundred cultural sites located in protected areas. However, the number of annual tourist arrivals in Madagascar is much lower than the other prime Indian Ocean destinations. For instance in 2008, 300,000 international tourists arrived in Madagascar, while in the same period Mauritius reported more than one million international arrivals (UNPD, 2011).

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[11] In a Cost-Benefit Analysis, or any project regarding the economic valuation of the carbon sequestration services from a given natural ecosystem, the SCC can be interpreted as the value of avoided climate damages, always measured at the margin. In other words, the marginal benefit accrued to the society in association with the sequestration of one ton of carbon (or emission reduction).

[12] Irrigation: the rice water comes from terrestrial watersheds (canals, lakes, rivers, and so on). Tavy: the rice water comes from pluvial water gathering.

The principal tourist attraction site in the CAZ area is Andasibe-Mantadia National Park, home to hindri lemurs and many endemic species of flora and fauna. At the time of this study, the touristic receptive infrastructure in CAZ consisted of 19 hotels and lodges, of varying categories, for a total of 279 rooms.

Data on the tourism sector were gathered from a variety of sources: UNPD reports, experts meetings, Moramanga Tourism Office, Regional Development Plans; interviews of hotel managers; interviews of staff at Mantadia National Park and other parks and protected areas. These data, however, are not sufficient to econometrically estimate a production function for the tourism sector, especially given that estimates of annual international and domestic arrivals in the CAZ area were not available. Making use of World Trade Organization (WTO) data, which provide an average value of the number of beds per room (1.63) at a national level, we were able to use our lodging data to estimate the number of beds in CAZ, and therefore the number of tourists per day. Following this logic we could then get an estimate for the annual water consumption per tourist in the CAZ area. See the technical appendix for more detail.

TABLE 2. WATER CONSUMPTION IN THE CAZ AREA IN THE TOURISM SECTOR

Hotels and lodges located in the CAZ area	
Number of rooms	279
Number of beds	454
Occupancy rate (over 360 days)	87.8%
Overnight stay (average number of days of a tourist)	4.6
Average water consumption per tourist (m^3 per day)	90 - 120
Lower and upper estimates of total annual water (m^3)	12,934 – 17,245
Total Annual Water per tourist (m^3)	15,089

Source: Own elaboration (based on data from Vakona Forest Lodge, the UNDP report and World Tourism Organization data for Madagascar)

3.3.7 LITERATURE AND EXPERTS ANALYSIS: ENERGY SECTOR

The Andekaleka hydroelectric power plant is located in the heart of the CAZ protected area. In 2011 this plant produced about 25 million kWh of electricity. It provides power for many regions throughout the country, including the capital city Antananarivo and the provincial capital Toamasina. Hydroelectric power plants use water as a sole input in the generation of electricity, and represent the single largest consumer of water (albeit non-rival) of any industrial, governmental or residential activity in Madagascar.

For the energy sector, we were unable to retrieve input data (labor, capital, energy, machinery and water) about hydropower production that could be easily represented by a Cobb-Douglas function as with the other sectors. The estimates for the value of marginal and average productivity were provided by the national water company (JIRAMA) via e-mail.

4 RESULTS

4.1 BIOPHYSICAL ANALYSIS

The ARIES models were used to compute source, sink, use and flow for three ecosystem services:

- Carbon storage and sequestration
- Water supply for the principal classes of users located in CAZ and around it;
- Sediment retention with explicit attention to the role of sediment in water contamination.

The total area of interest for the purposes of this modeling is the bounding box of the administrative districts intersecting CAZ, as provided by CI Madagascar, with the main region of interest chosen to be their convex hull amounting to a total area of 9065 km^2. The larger area around CAZ was simulated as necessary to correctly represent hydrological connection in services that depend on it (water and sediment). The analysis produced a large amount of data, only the most relevant of which are discussed in this report. Because of the different requirements in each type of model, and the constraints imposed by available data and resources, different strategies were chosen to characterize the contribution of CAZ to values resulting from carbon-related services (where spatial dynamics is trivial) and water-mediated services such as water supply and sediment regulation, where higher detail is required and computation is demanding.

4.1.1 CHOICE OF CONTEXT FOR THE ES ANALYSIS

The computation of carbon-related services doesn't present a challenge in terms of spatial dynamics, so the whole area of interest was used for the preliminary carbon assessment. A tentative carbon distribution and budget was computed for the region using Bayesian network models for vegetation and soil sequestration, storage and release (see Bagstad *et al.*, 2010 for full details on the models) trained on available global NPP data from MODIS observations developed by NASA.

Quantifying hydrologically mediated services such as water and sediment requires simulation of full spatial dynamics at fine resolutions, and is very demanding in an area as large as CAZ. In general, water services are not accounted for in ES analysis using detailed hydrologic modeling unless very long and deep studies are undertaken. In addition, uncertainties due to lack of data accumulate in large areas, making a full account of such services over the whole area much less reliable than smaller studies. In data-poor areas, it is normally impossible to produce full-scale hydrologic simulations, which require long-term data series, very complex calibration, and large investments in time and resources.

The ARIES paradigm mandates accounting for explicit beneficiaries and actual flows of ecosystem services, as opposed to the general accounting of potential provision done in most ES methods available at the time of this writing. For this reason, ARIES includes simplified hydrologic models that are meant to be used within the data and resource limitations typical of ES assessments, so that such services can be accounted for with the necessary attention to beneficiaries and flows even if at the expense of accuracy. A resulting consequence is that the best way to assess the ES value of specific natural features is to compare two different areas – one which clearly expresses the natural features of interest, and another which is in clear contrast to it – while maintaining the same environmental conditions as much as it is practical. The result of such comparative analysis are much more indicative of the true ES value than a quantitative accounting of physical flows would be, because the latter is bound to be less accurate than reality because of the limitations discussed.

For this reason, two smaller areas were chosen within the bounding box of CAZ and their full spatial dynamics were simulated in order to compare their aggregated values. One of the areas was chosen within the corridor, to represent the full range of natural features believed to be of value in CAZ. The other was chosen just outside the area, so that the environmental conditions remained comparable, but the natural features of interest were absent. Figure 6 shows the locations selected. The first area is well-connected to the natural CAZ environment and includes part of Andasibe-Mantadia National Park and areas of controlled development. The second is located at the north-west of CAZ and has a drier climate and more intensive agriculture, representing a good candidate for a comparison that can help assess the comparative value of the CAZ environment for service delivery.

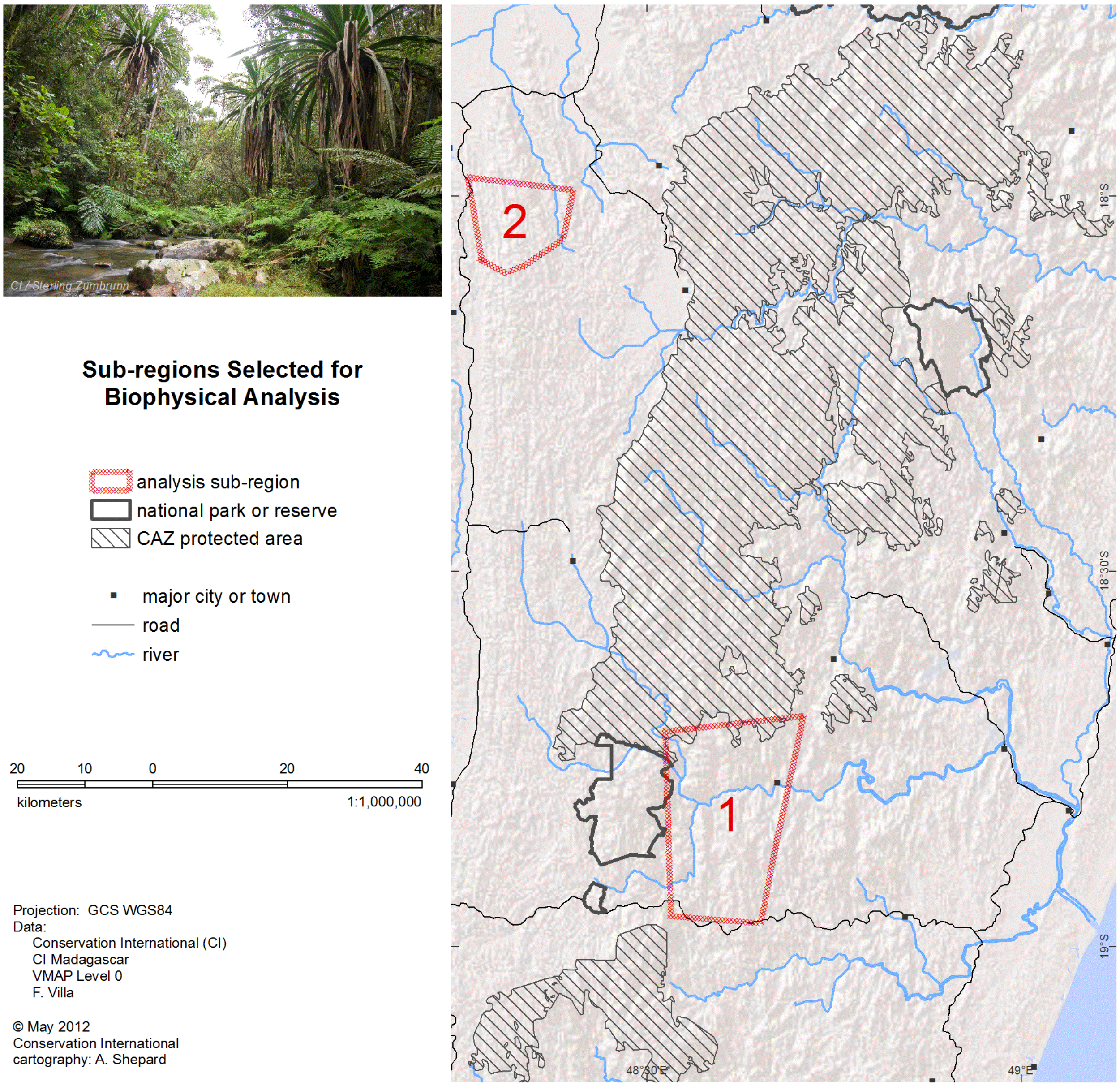

FIGURE 6. SUB-REGIONS SELECTED FOR BIOPHYSICAL ANALYSIS

4.1.2 CARBON SERVICES

Modeling of carbon was done using a Bayesian network model based on data of temperature, canopy cover, land use, vegetation type, soil C/N ratio, population density, soil pH, soil oxic conditions and forest degradation status. The model was calibrated using available MODIS NPP data for the components related to productivity. The carbon models produced estimates for carbon storage by soils and vegetation, carbon sequestration by above- and below-ground vegetation, and release of stored carbon. The latter represents a potential release, driven by deforestation and population density, and carries fairly high uncertainty due to: (i) the difficulty of predicting the probability of deforestation, (ii) to the compound uncertainties coming from using a high number of data sources, and (iii) to the lack of data for training. Uncertainties for all other variables are very small so the results are presented as means, except for C release, which is presented with upper and lower bounds. The model estimates yearly amounts and each estimate comes with corresponding uncertainty estimations.

TABLE 3. VALUES FOR CARBON SEQUESTRATION AND POTENTIAL RELEASE IN THE CAZ.

Variable	*Tons C / km^2 / year*	*Total in area*	*Uncertainty (coefficient of variation)*
C sequestration (above and below ground)	991	8,988,010	0.01
Potential C release (low and high boundaries)	587 – 4024	5,322,437 – 36,478,280	0.67
Variable	***Tons C / km^2***	***Total in area***	***Uncertainty (coefficient of variation)***
C storage in soils	7991	72,444,374	0.05
C storage in vegetation	20645	187,153,226	0.02

Estimated C sequestration values are very high, suggesting high value of CAZ as a carbon sink. The great uncertainty in estimating C release does not hide the fact that a potentially high release, joined with high amounts of C stored in vegetation, can tip the carbon balance towards negative values. The uncertainty in the C release model makes predictions difficult, but shows how the threshold between a positive and negative carbon budget can be crossed, suggesting that the high value stemming from C sequestration in CAZ should be considered fragile, with the potential for the area of switching from a carbon sink to a carbon source unless deforestation and other uses of the forest are controlled.

4.1.3 WATER SERVICES

The bulk of the ARIES modeling for this preliminary study consisted of establishing levels of demand for water services in a quantitative and spatially-explicit way, and simulating the dynamics of water delivery, taking into account water supply from precipitation, and water loss from evapotranspiration, runoff, groundwater exchange and rival use. A preliminary water budget was then computed for the two areas by aggregating the spatial results obtained.

4.1.4 DEMAND ANALYSIS

Water demand in the two areas studied was assumed to be split between demands for irrigation, livestock, residential and tourism industry, each of which was estimated separately and summed to obtain the total water demand (Figure 7). Other sources of water demand (such as industrial use) were assumed negligible and not included. At the same time, water uses that are not rival (e.g. for hydroelectric power generation) were not considered because non-rival use does not affect the results in their present form.

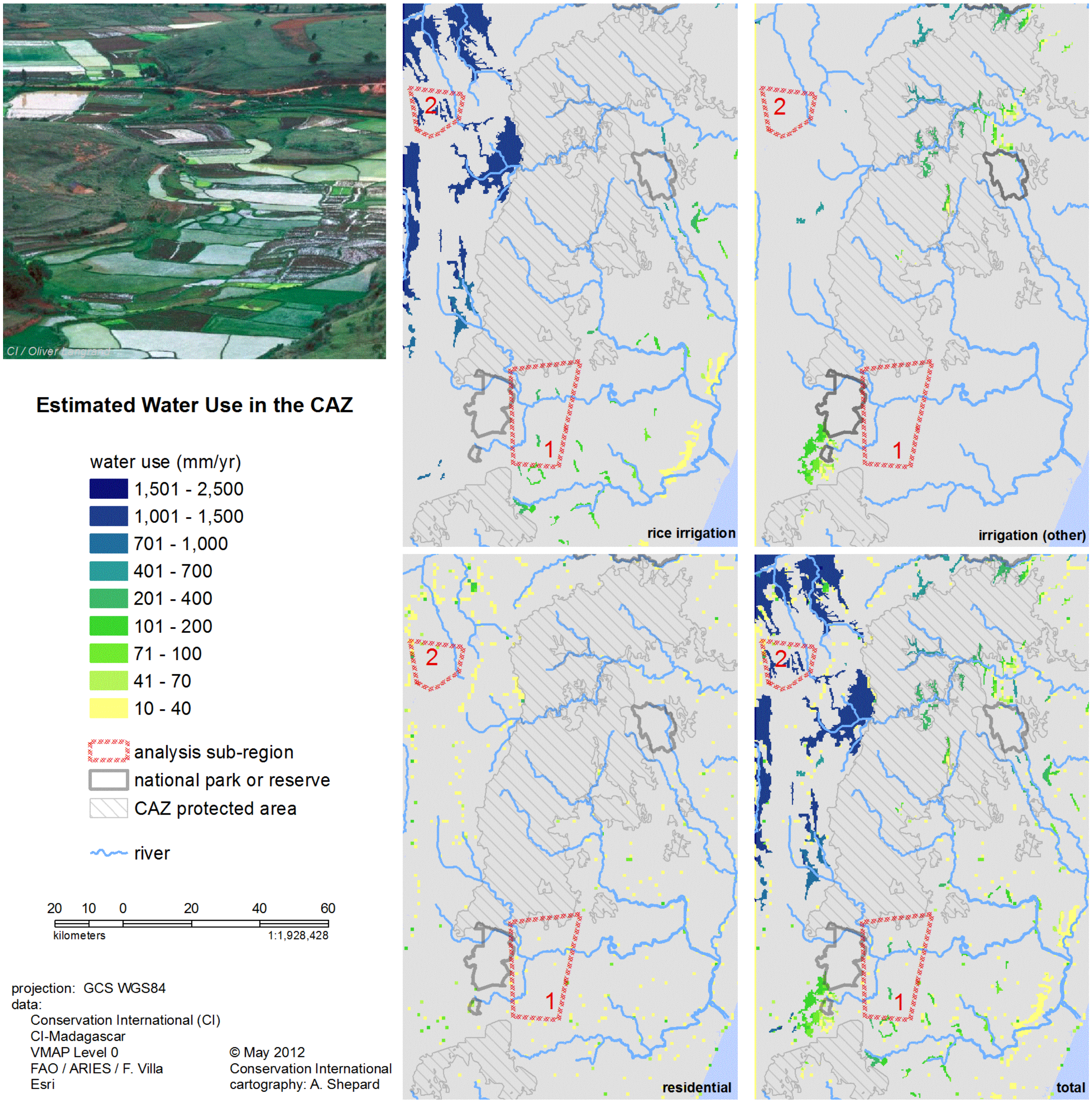

Figure 7. Estimated water use in the CAZ for four categories of beneficiaries.

Given the importance of rice crops in the area and the availability of better data regarding rice (including the location of rice fields as opposed to all other cultivations), the total irrigation demand was split into irrigation demand for rice and not for rice; independent models were developed for the two, and the supply/demand/flow analysis was focused on rice irrigation demand, using the remaining rival use from irrigation as part of the sink (water loss) model.

The irrigation demand of rice was estimated using guidelines published by FAO, adopting the Blaney-Criddle method for evapotranspiration (Brouwer *et al.*, 1985). The growing season length was estimated by latitude; two harvests per year from transplanted rice were assumed. As a result, the irrigation demand varied across the areas, with an annual average of 2263 mm. The annual rainfall at the rice paddy location was subtracted from the total demand, to yield the actual required water need from the watershed. This, with the necessary caution due to the inevitable low accuracy of the study, accounts for the relatively large proportion of rice fields in CAZ that only rely on rainfall – a fact that by itself hints to higher efficiencies of water use within CAZ, which the ARIES study helps to quantify with more precision.

Demand for irrigation relative to cultivations other than rice was estimated as an average based again on FAO rules and an inventory of cultivars in the area from verbal accounts. Due to the lack of data, this estimation was much less reliable than that for rice; uncertainty for non-rice irrigation demand estimation was assumed around 50%, while that for rice demand were assumed 15%. Because of the modeling choices made, such uncertainties affect the sink model and not the use model, which has a lesser effect on the final accuracy of the flow results.

Livestock demand, less crucial because the total demand from the sector is much less than irrigation, was estimated using FAO global livestock spatial data for sheep, goats, cattle and pigs to estimate the approximate population density of these species, applying water use coefficient conversions from literature independently for each species, and summing the result.

Residential use was computed based on probability distributions of water use computed from available data in relatively comparable, developing countries (chiefly rural areas of Mexico), and global 2006 population density data provided by LANDSCAN. This method was deemed ultimately more accurate than using the little information available for Madagascar. The same uncertainty related considerations made for the non-rice irrigation apply for this variable.

The water demand for tourism was estimated using data provided by the Vakona lodge in Andasibe-Mantadia National Park (see section 3.3.5) and extrapolated spatially to the other known lodges in the area. Models of tourism-related water use were run independently, considering the other water uses as sinks for the model. Because of the much smaller areas and low demand compared to agriculture, the rival use from tourism was negligible in the agricultural model.

4.1.5 SOURCE AND FLOW MODELING

The main source of water was assumed to be rainfall, estimated using WorldClim data representing current rainfall conditions computed with data from 1950 to 2000. The ARIES flow model moves the water across the landscape, computing flow direction from global, high-resolution elevation and slope data, then running it to the stream network and simulating stream flow. Water that intersects sinks and users is added to the water balance for these components. As evapotranspiration data for the area are not available, a probabilistic model was used to estimate it. ARIES runs probabilistic models and is therefore capable of estimating uncertainties for all its outputs[13]; the highest uncertainty estimated in all runs of the water supply model was in the order of 15% estimated as coefficient of variation. An example output map of the flow model, not discussed in this report, is shown in Figure 8. As explained in the introduction many other maps are produced by a run of ARIES; this report only describes those results that are most relevant to understanding the total value of the natural features in CAZ.

[13] Of course such uncertainties reflect only some of the sources of uncertainty in the data and models. Like in all modeling exercises, the uncertainty in the assumptions and methods themselves must also be considered.

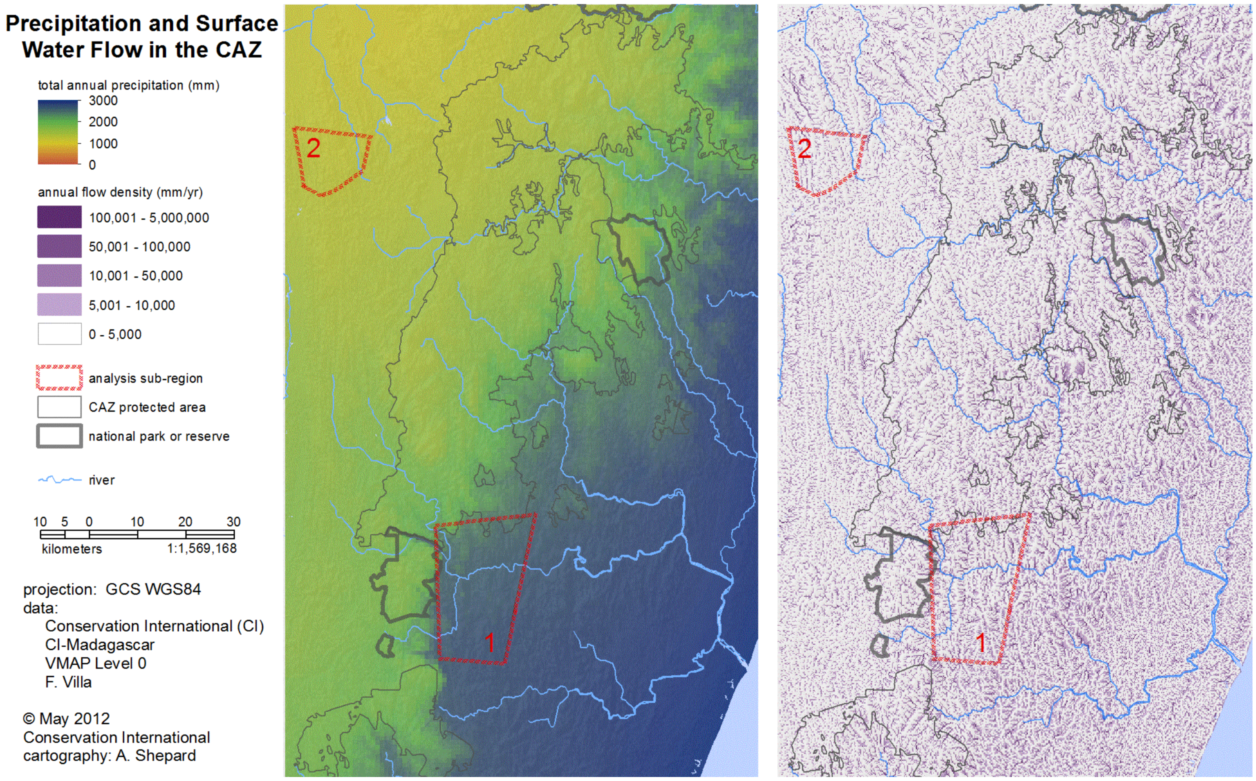

FIGURE 8. ANNUAL PRECIPITATION AND SIMULATED SURFACE WATER FLOW TO THE BENEFICIARIES[14].

ARIES models were run in both the designated areas (within and outside CAZ) to estimate demand, supply and flow of water to its beneficiaries in each. As explained, the use analysis was limited to rice irrigation due to better data and lower uncertainties in estimating the demand. Other rival uses of water were considered as part of the sink model instead of use. The results obtained for rice can be considered representative of the overall sustainability of water supply for other sectors as well (see below for further detail).

Spatial result maps were produced for both areas, and aggregated budgets were computed for each area. Table 4 shows the aggregated budgets, from which it is clear how the efficiency in turning the water supply into usable water is greater in the CAZ area. For example, the water lost to infiltration and evapotranspiration is 8.7% in CAZ, as opposed to 10.4% of the total precipitation outside it.

TABLE 4. TOTAL ESTIMATED WATER BUDGET (MM/YR) FOR SAMPLE AREAS INSIDE (1) AND OUTSIDE (2) CAZ.

	Total in CAZ	*Sample area 1*	*Sample area 2*
Rice irrigation	105,805,594	1,230,962	3,293,623
Non-rice irrigation	6,552,348	1,345,329	91,862
Livestock water use	141,401	11,255	42,563
Residential use	3,547,546	914,370	662,419
Annual precipitation	3,433,192,244	1,544,508,508	221,912,981
Infiltration and evapotranspiration	N/A (model not run)	161,185,511	19,306,823

Each flow model run estimates spatially and quantitatively the actual provision of water to the users vs. the demand, and is therefore suitable to understand the sustainability of the water resources. In order to obtain an approximate estimate of the sustainability, the flow models in each area were run repeatedly with incrementally inflated demand, which produced criticality profiles for water supply in both areas. The results of this analysis are summarized in Table 5, which shows how the current levels of

[14] As identified in Figure 7

demand are essentially met in both areas, but while the area in CAZ has potential to sustain much greater demand, the non-CAZ area is already at critical levels.

TABLE 5. RESULTS OF SUSTAINABILITY ANALYSIS FOR WATER SUPPLY (MM/YR) IN THE TWO AREAS.

	Sample area 1	*Sample area 2*
Current water need	1,230,962	3,293,623
Maximum potential	62,831,145	3,190,178
Ratio potential/need	5100%	96%
Percentage of total precipitation used for rice agriculture	4.068%	1.437%

It is important to note that such estimates have only relative value, and due to the many other factors that influence water supply and are not included in the model (not to mention the fact that the data are relatively old and global change has certainly impacted the area since), it is probably safe to consider such percentages as overestimates.

The last row of Table 5 shows the percentage of the total precipitation that the natural features in the two areas are capable of making available as usable water for irrigation. It is clear how the CAZ area is almost three times more efficient than the other in converting and retaining water received through precipitation. It should be noted that while these results refer to rice irrigation, there is no reason to assume that any other use of water would show significant differences; all factors having to do with water source, sink and flow do not depend on the use selected, so these results (with the caveats illustrated above) can be considered general.

4.1.6 FACTORS AFFECTING WATER QUALITY: SEDIMENT CONTAMINATION

Sediment release and buildup are major environmental factors in Madagascar, and no water analysis can be complete without accounting for the water quality issues related to sediment release and transport in the water supply. In order to establish the role of CAZ in regulating sediment that contaminates the water supply, a specialized ARIES sediment model was built to compute the intersection between sediment freed from erosion and the water flow paths. As explained above, the results of this model should only be considered comparatively and are not deemed accurate enough to establish actual levels of dissolved sediment for any other purposes. The models were run in the same two areas identified for water supply, in order to comparatively assess the role of the CAZ natural features in influencing water quality in the form of dissolved sediment. Data about the precise role of sediment contamination for all the uses considered were not available for this study, so no estimate of the actual value of the water supply for the intended uses was made; the comparative analysis does, however, highlight the physical amounts of sediment per cubic meter in each area, offering a good base for comparison and a base for a value analysis when data become available.

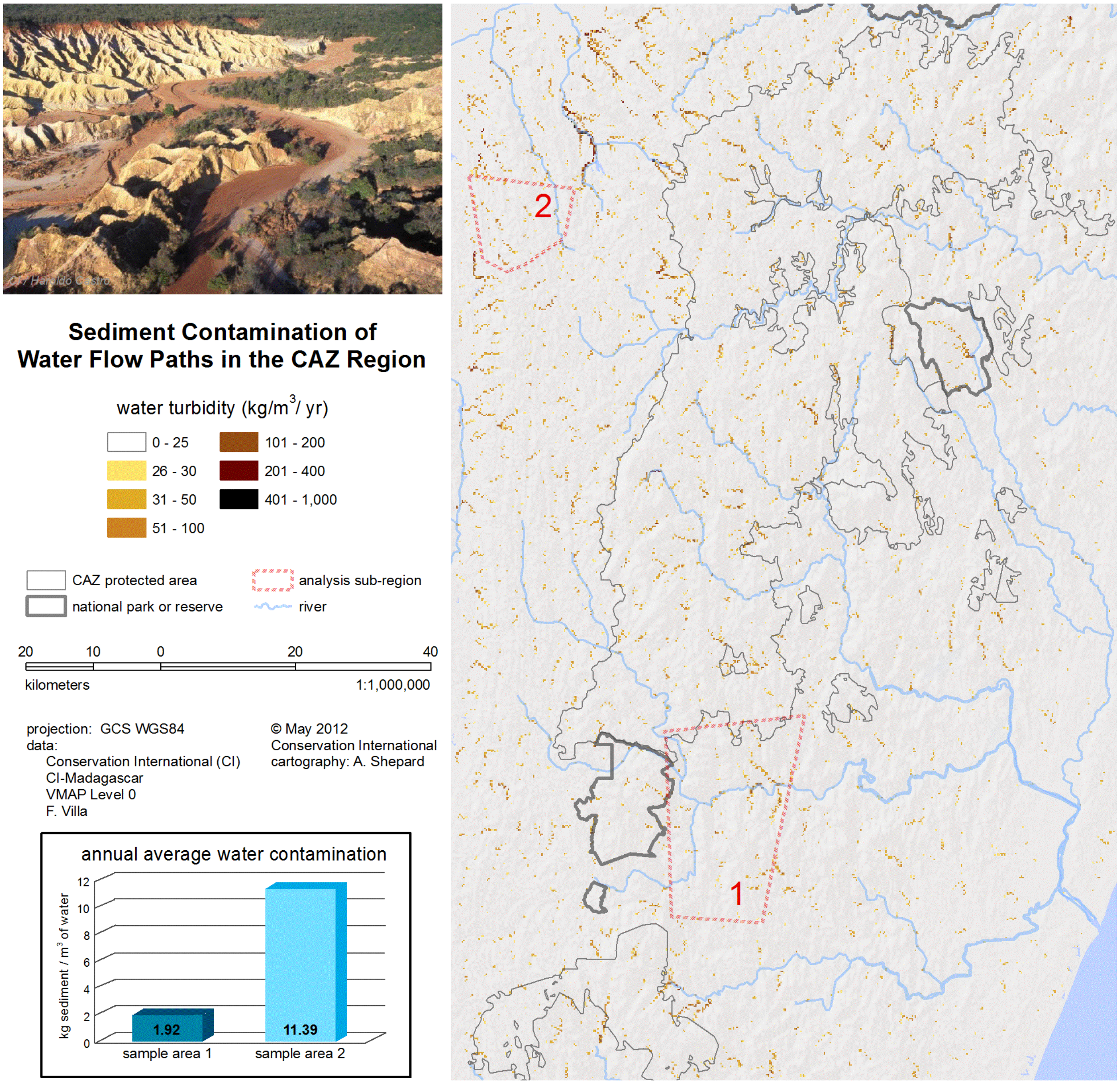

FIGURE 9. SEDIMENT CONTAMINATION OF THE WATER FLOW PATHS AFFECTING THE BENEFICIARIES[15].

Soil erosion was computed using a hybrid approach, adopting the RUSLE equations on low slopes and resorting to a probabilistic model considering precipitation, storm frequency, soil texture, slope and tree cover when the slope was too high for the RUSLE equation to be defensible. Sediment sinks are only relevant when the area is located in a floodplain, which none of the sample areas is. The flow model runs eroded sediment through the water transport system and establishes the total amount of sediment that is likely to contaminate the water flow in each point. The chart in Figure 9 clearly demonstrates how much less contamination occurs within the CAZ boundaries than outside.

The average amount of contamination of freshwater by sediment is approximately 6 times higher outside CAZ than inside. The specific effect on the water quality and economics of the region are more difficult to establish as more accurate data are required; it is, however, well known that sediment contamination is detrimental to different degrees for all water uses considered. As average values of >10kg/m^3 are quite high, the analysis clearly shows how sedimentation is a major factor in determining

[15] As identified in Figure 7

loss of productivity for the water supply and that the role of the natural features in CAZ is determinant in protecting water quality.

4.2 ECONOMIC ANALYSIS

The economic analyses for carbon and water used distinct approaches. While for carbon we were able to use market values, the economic assessment for water supply focused on two main aspects of that ecosystem service used in market production: the productivity of the resource and the value of the marginal productivity of the resource (or value of marginal revenues). Below is a brief discussion of these results.

4.2.1 CARBON

Based on results from the biophysical analysis of carbon in the CAZ, we know that the net flow of forest carbon in the CAZ area can range from negative values (e.g. forest loss and associated net carbon release) up to a maximum sequestration value of 3,665,573 tons of C/year (see section 4.1.2 – calculated as the difference between total C sequestration and potential release). Taking into account the annual productivity of the CAZ forest in terms of carbon sequestration and the social cost of one unit of carbon released to the atmosphere[16], we can infer that the total economic benefits of the forest ranges between USD (million) 306.4 and 570.4 per year – see Table 6.

TABLE 6. CARBON SEQUESTRATION BENEFITS IN THE CAZ REGION (IN MILLION USD).

Range	*2010*	*2020*
Low	306.4	695.0
High	570.4	998.1

Calculations based on Social Cost of Carbon values as reported by the European Commission (EC, 2008) and by the technical report to the Commission coordinated by Alain Quinet (Centre d'analyse stratégique, 2009).

If, instead, we refer to an alternative metric indicators , such as the market price values provided by the European Trading Scheme, which in July 2012 is reported as average 9.45 Usd (per tCO2e – see Euroactiv 2012)[17], then this economic benefit of the CAZ forest would be estimated in 2020 at 221.9 million USD. Alternatively, we can use market carbon values derived from voluntary agreements – see Table 7 for an overview[18]. In this context, we would be estimating this same economic benefit of the CAZ forest, and always for 2020, to range between 70.5 million USD (when using China as our reference) and 975.4 million USD (when using the Netherlands as our reference).

4.2.2 MINING SECTOR

From our analysis, we can infer that a 1% increase in the use of the ecosystem service (water) results in a 0.7% increase in the output of nickel and a 0.43% increase in the output of cobalt. This ecosystem service is an important variable in the production function for the mining sector in CAZ. The estimated coefficients for the ES input water present diminishing returns for mining production. In other words, all

[16] Social Cost of Carbon is the net present value of the impact over the next 100 years of one additional tonne of carbon emitted to the atmosphere today. It is the outcome of Integrated Assessment Models (IAM), which translate climate damages into monetary costs (or externality) to a society.
[17] Value reported as 7.15 Euro, which is well below the 20 Euro that the ETS started to operate in 2008. For more information see EurActiv (2012)
[18] For more information see Peters-Stanley 2012.

other inputs being held constant, an increase of water input yields a decrease in the marginal (per unit) output of nickel and cobalt. Please see the technical appendix for tables showing the coefficients and results of the Cobb-Douglas production functions modeled for this analysis.

TABLE 7. VOLUNTARY CARBON MARKETS (PRICE PER CREDIT/ CERTIFICATE IN USD PER TCO_2E)*

National or sub-national program	*Starting date*	*Price range*	*Volume transacted (2011)*
British Columbia, Carbon Neutral Government	2008 (r)	25	800,000
United Kingdom, Woodland Carbon Code	2011	7 to 24	200,000
The Netherlands, Bosklimaatfond	2011	32	design phase
Italy, CARBOMARK	2009	10 to 55	design phase
Oregon, Carbon Dioxide Standard	1997 (r)	6 to 9	73,225
California, Cap and Trade	2012 (r)	6 to 10.5	3,000,000
Oklahoma, Carbon Program	2008	3.5	26,100
Costa Rica, C-Neutral Standard	2011	design phase	design phase
Australia, National Carbon Offset Standard	2010	unknown	937,000
Japan, Japan Verified Emissions Reduction Program	2008	95 to 130	50,000
Korea, Korea Verified Emissions Reduction Program	2007	5	439,837
China, China Green Carbon Foundation	2007	3 to 5	148,000
Thailand, Thailand Verified Emissions Reduction Program	2013	design phase	design phase

**Reference date: January, 2012*
(r) Regulatory regime.

4.2.3 AGRICULTURE/FARMING SECTOR

For the agriculture and farming sector, our analysis demonstrates that 1% increase in the use of the ecosystem service (water) leads to a 0.91% increase in the production of rice; a 0.83% increase in the production of manioc, and a 0.93% increase in the production of poultry. Again, the selected ecosystem service is an important argument in the production function[19]. The coefficient estimates for the ES input water yield (almost) constant returns for the agriculture-farming economic sector. Again, see the technical appendix for tables showing the coefficients and results of the Cobb-Douglas production functions modeled for this analysis.

4.2.4 TOURISM SECTOR

Unfortunately, we were not able to find enough data about the technology for hotels management within the tourism sector in CAZ in order to produce empirical estimates of the marginal productivity of water. Through our literature review and expert interviews, we were able to get information on average daily water consumption per person for different segments of the tourist sector.

a) 0.48 cubic meters: luxury international tourism (source: Vakona Forest Lodge)
b) 0.12 cubic meters: international tourism (source: UNDP, 2011b)
c) 0.09 cubic meters: national tourism (source: UNDP, 2011b)

[19] It is important to highlight that in terms of rice production, canal vs. pluvial water are modelled as the same type of input. We did not have enough information on differences in the other inputs between the two types of rice production (e.g. hours of work per day for the two alternative techniques, differences in tools and so on) to model them as separate production functions.

These data can be interpreted as average productivity values for the ES-input water, representing three different market demand segments, and including tourist provenance. If we can credibly assume that the average productivity equals the marginal productivity of water[20] then we can also assume that the ES-input-water presents constant returns for the tourism production/sector. Please see the technical appendix for further discussion of the analysis done for the tourism sector.

4.2.5 ENERGY SECTOR

Our analysis of the hydroelectric energy sector was based on data from interviews with experts from JIRAMA (the Malagasy national energy company). These experts estimate that the Andekaleka hydroelectric power plant uses 0.5 cubic meters of water to make 1000 kWh of electricity. Based on the average annual production of electricity from Andekaleka, we can infer that the energy sector in CAZ uses 12.5 million cubic meters of water annually.

Reservoir size is an important factor when considering marginal productivity of water in hydroelectric power generation. There are likely to be fewer natural streams recharging the volume of a small reservoir than there would be for a large reservoir. It would be expected then that small reservoirs are slower to be recharged than are large reservoirs for each unit of water released from a dam. Recharge is important as it serves to maintain a constant level of water pressure as water is passed through the generators. We can therefore realistically assume diminishing returns to the water releases for dams at small reservoirs, where water release would not be recharged by inlets. Over a fairly short period of time these water releases will reduce the head of the dam, thereby reducing the amount of power that can be generated per unit of water.

For larger reservoirs that receive inflows of water on a more continual basis (or where daily releases have a small impact on reservoir levels), an assumption of constant returns to water releases appears to be more realistic (Campbell, 2010). The Andekaleka hydroelectric plant is adjacent to small reservoirs, and we can realistically assume diminishing returns to the water releases.

It is important to highlight that hydroelectric power plants of all sizes provide inexpensive electricity and produce no pollution. Unlike other energy sources such as fossil fuels, water is not destroyed during the production of electricity and can be reused for other purposes.

4.2.6 SYNTHESIS OF WATER PRODUCTIVITY

Our main findings with respect to the marginal productivity of water in different sectors are summarized in Table 7.

TABLE 8. WATER MARGINAL PRODUCTIVITY PER SECTOR IN THE CAZ AREA.

Economic Sector	*Marginal Returns*
Mining	Diminishing
Agriculture-Farming	Constant
Tourism	Constant
Energy/Hydropower generation	Diminishing

Table 8 synthesizes our estimates of the economic value of water supply to four economic sectors in the CAZ region.

[20] For instance, assuming that the per day per tourist average water consumption is totally used for showering (for instance), we can credibly infer that the same amount of water will be used by an additional (marginal) tourist for taking an additional (marginal) shower.

These results demonstrate that the economic value of water varies by sector. For example, water presents the highest productivity value when used in the mining sector. In this case, the value of the marginal return for one additional cubic meter of water used in the production of cobalt is USD 7,541, as derived from the sale of an additional unit of cobalt. Alternatively, we may read the results in terms of opportunity cost. In this case, if an additional unit of water is not used to produce cobalt, e.g. is allocated to an alternative production or it is simply no longer available, this would be interpreted as an economic loss that amounts to USD 7,541. It is beyond the scope of this study, but a proper economic assessment of the market price of water will provide guidance on the issue of ecosystem payments and pricing.

TABLE 9. ECONOMIC PRODUCTIVITY OF WATER.

Economic sector	***Estimated marginal productivity***	***Economic value of marginal productivity (2012 USD/output)***
Mining		
Cobalt	0.43	7,541
Nickel	0.70	11,906
Agriculture		
Rice	0.91	469
Tourism		
Luxury segment	0.48	50
Electricity		
Residential use	0.40	6,980
Industrial use	0.40	680

Note: Output of the Cobalt, Nickel and Agricultural sectors expressed in tons. Output of the Tourism sectors expressed in terms of number of tourists in the CAZ area. Output of the Electricity sector expressed in terms of megawatts.

5. DISCUSSION

In this section, we discuss the results of our analysis with respect to the main findings, their applications and possible limitations. In general, our results can be synthesized in terms of a set of indicators, as discussed below.

5.1 INDICATORS RESULTING FROM THIS ANALYSIS

5.1.1 INPUT PRODUCTIVITY

Productivity describes how well resources are being used by a given sector to produce outputs. In our analysis we showed that water productivity changed across sectors. This is evidence of differences in industrial organizational efficiency among the sectors under consideration. Greater technological efficiency in the organization of production (the use of inputs), will lower production costs, and as a result, lower social costs. A given sector may produce less than what is optimally required by the markets because it is not efficient (with respect to the use of the water input), and because its costs proportionally increase with output. However, theory suggests that even if technology is not efficient, firms' production can be very profitable, if, for example, the firm enjoys market power and can set a price higher than the marginal costs of production — having, as a result, no incentives or needs to keep marginal costs low. Usually, inefficient production is linked to oligopolistic/monopolistic markets, since the capability to 'set price' offsets, at the margin, the need to lower total costs of production by adapting a technological organization of production. Our empirical findings show the (marginal) impact of the input-water in the production of different market goods and services and provide guidance for sectors that can be improved, such as demonstrating that the technological efficiency of water is higher for the agricultural sector than for the mining sectors.

5.1.2 ECONOMIC VALUE

The profitability of an economic sector refers to the capability of the sector to produce economic profits. Economic profits are the total revenues, generated by the sales, minus the opportunity costs of production. Our results show that carbon values have the potential to represent enormous profits for the CAZ region. However, realizing those full profits within the context of the current global carbon market is unlikely. Water values in turn, measured as opportunity costs of production – with water as an input – are higher in the mining and hydroelectric sectors. In both cases, if an additional unit of water is not used to produce nickel/cobalt or electricity, and instead is allocated to an alternative production or is simply no longer available for that production, this will result in an associated economic loss that amounts to thousands of dollars.

5.1.3 SUSTAINABILITY

The sustainable use of a resource can be more broadly understood by combining both biophysical and economic analyses. In this context, the estimated economic value of the present use of the resource/ecosystem service is considered along with an understanding of the provision of that resource/ecosystem service and its spatial and temporal allocation to various sectors. This can help to inform one whether the economic benefit associated with the use of this resource is likely to persist across time, all things being equal. Our results show that the CAZ area has potential to sustain much greater demand than the non-CAZ area, which is already at critical levels.

5.1.4 QUALITY OF SUPPLY

Different land uses are known to have different impacts on water quality. Evidence has shown that forests, for example, are capable of preventing surface erosion (Bruijnzeel, 2004, Rakotoarison, 2003b) whereas other uses such as grazing may exacerbate it. Indeed, our results show that the quality of water from a conserved area, in terms of volume of sediments, is roughly six times that of a non-conservation area.

* * *

The next section focuses on the overarching objectives of the assessment, and as such, addresses: (i) the utility of the methodologies here employed; (ii) the integration of ecosystem services into policy development; and (iii) opportunities for scaling up to other regions. In doing so, we consider how the indicators we have produced in this analysis could inform policy priorities for WAVES Madagascar, while drawing key messages from the assessment.

5.2 UTILITY OF STATE-OF-THE-ART ANALYTICAL AND MODELING METHODOLOGIES

In this assessment, a dynamic and spatially-explicit modeling methodology was employed to map and quantify the physical flows of ecosystem services, both from the natural source and the human benefits perspectives. By doing so, we were able to pinpoint the location and extent of demand (met and unmet) for different users and to shed light on the important biophysical dimensions associated with the continuous provision of ecosystem services. The economic analysis, on the other hand, provided an estimate of the magnitude of the contribution of selected ecosystem services to specific sectors as well as on their marginal value as inputs, based respectively on efficiency and marginal productivity theory. Combined, the methods described above convey a clearer and more complete picture of the diverse array of values provided by CAZ, characterizing the links between physical benefits and crucial dimensions of their societal value.

5.3 USEFULNESS OF METHODOLOGIES FOR RANKING PURPOSES

It has already been pointed out that the approaches used to model and value ecosystem services in this analysis are better interpreted as a means to rank different areas/sites than as absolute statements of value. This is true for all rapid ES assessment methods, and stems from a number of reasons. First, the great data scarcity typical of ES assessments in developing countries implies a higher level of uncertainty. Our physical assessment is unique in ES practice because it actually attempts to quantify this uncertainty, so that decision-making can take account of the reliability of the results as well as their quantitative products. Second, no physical ES assessment will be quantitatively reliable in absolute terms unless deep and costly studies are made to understand the peculiar model structures necessary to reflect poorly understood local conditions. Comparative studies such as ours, made between areas that are similar in everything except the natural environments that provide the source of the ES values under study, are therefore better at providing useful information on ES values than are studies which focus on absolute value of a single area.

As a result, the findings of this analysis should be used only as a means to inform the relevance of certain areas, such as demonstrating the significance of forested versus non forest areas (or protected versus non protected areas) specifically with respect to different levels demand for the services. For example, our findings show a 4-fold change in quality and a 10-fold change in sustainability of supply in protected areas versus non-protected. That is even more relevant when combined with the economic analysis findings which show how the very same (marginal) unit of an ecosystem service can affect market production differently for different economic sectors within the same geographical area. For instance, our analysis showed that water efficiency was higher for agriculture than for other sectors, but productivity value of water was highest in the mining sector. Combined, estimates produced by both the biophysical and economic analysis can help to inform prioritization exercises and management alternatives.

5.4 MULTIDISCIPLINARITY OF THE ANALYSIS

In this analysis we demonstrated ways to quantify four key dimensions of ecosystem service that have different relevance for a policy assessment. These are: (i) input productivity; (ii) economic value; (iii) sustainability of supply; and (iv) quality of supply. Potential policy implications of these dimensions are more thoroughly discussed in the policy section below. It is however, important to note that while all the dimensions above are interrelated, in absence of quantitative models of such interrelationships, it is defensible to imagine a policy framework that considers all of them in a multiple criteria analysis, which could be used to rank the opportunity value of each prospective policy instrument in the policy context it will apply to. One of the strengths of such types of analysis is the ease with which heterogeneous information can be combined together, where quantitative measures can be used along with semi-quantitative information and ranks. In such cases, the different dimensions of the assessment provide observations that can be ranked according to their importance for the policy context in question. Different scenarios corresponding to the application of specific policy instruments for the same region can be also developed and used to assess the overall value of the instrument in that policy context.

5.5 REPLICABILITY OF THE ANALYSIS

One important aspect of this case study is that it has the potential to be consistently replicated at other areas/sites. This is true for a number of reasons. First, our research was systematically implemented, and our methods were specifically chosen in order to be replicable in data poor environments; second, our assumptions are explicit and well-documented throughout the analysis and report; and last, but perhaps most importantly, the multidimensionality of indicators that our results presented allow for an improved understanding of the role of specific services in issues as tightly connected as efficiency, productivity and sustainability. These dimensions, as previously discussed, allow for comparisons among different sites and can support and, among other things, inform important trade-offs given competing alternatives.

5.6 INTEGRATION OF ECOSYSTEM SERVICES INTO POLICY DEVELOPMENT

The implications of our results for WAVES-related policies are discussed next. As a background for this discussion we look at a set of selected policies that were identified as priority for WAVES phase 2, and which were the subject of extensive consultation and endorsement by the WAVES Steering Committee in the country. In a nutshell, these priority policies encompass the overarching goals in the development of macro-economic indicators, as well as sub-goals that focus on the mining sector, management of watershed and water resources, value of protected areas and forest ecosystems, and coastal zone management. Given the limited nature of ecosystem services assessed in this analysis, we will focus our discussion on priority policies associated with water resources and management of protected areas and forests.

5.6.1 MANAGING WATERSHEDS AND WATER RESOURCES

The policy goal here is to generate information on the value of water resources with the purpose of contributing to regional and national integrated water resources management planning. This is a critical priority goal and its significance for Madagascar cannot be overstated. Indeed, according to the System of Environmental-Economic Accounting (2012), integrated water resources management planning can play an important role in: (i) the improvement of water supply and sanitation services; (ii) the management of water supply and demand; (iii) the improvement of the state of the environment and water resources; and (iv) adaptation to extreme hydrological events.

We argue that the four key dimensions of ecosystem services described in this analysis – input productivity, value, sustainability and quality of supply – can provide insight into the relevance of water services to economies and livelihoods, supporting the development of regional and water resource accounts, and ultimately informing policies toward improved management of the water resources sector. This can be particularly relevant where data is relatively scarce.

To illustrate this point, let's consider a policy intervention aimed at the development of a national master plan for regional and integrated management of water resources[21]. This policy intervention has the specific goal of maximizing access to water for select economic activities and ultimately increasing income opportunities for local populations. Such a policy would necessarily need to consider, among other things, the individual and competing needs of different sectors (i.e. agriculture, energy, industry, tourism, mining, etc.); the industrial efficiency and profitability of a given operation; its impact on water flows and sediments; and equity in the distribution of resources. The dimensions of ecosystem services that we quantified in this analysis can inform such a policy intervention, and ultimately guide decision-making ranking given locally determined priorities.

From the perspective of input productivity, for example, policy and decision-makers can consider the relevance of efficiency to the ultimate goal of sound water management, given other competing criteria, and rank it accordingly in a multi-criteria context. This type of exercise can help in determining how critical efficiency may be for the desired policy intervention, such as policy concessions. Policy and decision-makers can also take into account the overall importance of value – measured as opportunity cost – when considering policy interventions that may benefit from high profitability of sectors, such as adjustment and implementation of differentiated tariffs for water consumption, implementation of payment schemes for water, etc. The quality of supply can, in turn, be critical for policy and decision-makers as it highlights the importance of prioritizing a resource allocation scenario that provides a longer life insurance in terms of the contribution of the ES to human well-being. This information gives an important signal to the level of the use/extraction of the resource, which in turn affects the overall supply conditions of the resource (i.e. current versus potential supply in biophysical terms). Ultimately, this points to the need to carefully consider the role of conservation in ensuring continuous, sustainable provision of ecosystem services, and for enhanced support of innovative measures and incentives toward that goal.

Lastly, policy and decision-makers can consider the overall importance of water-related ecosystem service benefits, such as those of sediment retention. Water-born sediments can have pervasive biological and socio-economic impacts and can lead to production and revenue losses, both locally and regionally. Ultimately, they can pose a threat to food and health security. As with the sustainability criteria, the benefits of sediment retention highlight the relevance of protected forests and the critical services they provide, the need to better understand and monitor the impacts of deforestation, and the

[21] Proposed point of entry for WAVES Madagascar, as described in the Feasibility Study, to inform the development of a work plan for Phase II WAVES.

need to further invest in initiatives that focus on conservation as it relates to development and human well-being.

5.6.2 VALUE OF PROTECTED AREAS AND FOREST ECOSYSTEMS

This policy goal refers to the valuation of additional ecosystem services (carbon, timber, hydrological, erosion control and other services) in priority protected areas and forest sectors. The global and regional significance of Madagascar as one of the world's ten most threatened forested hotspots, demands significant effort for the protection of its biodiversity, and the services that the country's unique ecosystems provide. While protecting areas has been widely used as a means to achieve biodiversity conservation targets, tapping the economic benefits of these areas can be a critical tool toward successful protection, not only because it can be more cost-effective, but because financial resources can then be used to ensure continuous provision of multiple benefits lo local people and to provide alternative livelihoods. In that sense, valuation of additional ecosystem services can indeed be used to identify means to support the financing of protected areas, while highlighting the importance and effectiveness of conservation measures, and extending support to the development and implementation of similar forest conservation measures elsewhere in the region.

Our results clearly demonstrate that CAZ's forestry resources play an important role not only in terms of water and sediment regulation, but most remarkably in terms of carbon sequestration and associated benefits for climate stability. This potential benefit is estimated to range up to one billion US dollars in 2020, when measured at current prices. Such a highly significant welfare magnitude signals the potential profits that this service may bring to Madagascar's society. Moreover, the monetary estimate of the value of the forest carbon sequestration can contribute to measures toward the sustainable financing of the national protected area network, and provide momentum for the design of an improved forest sector policy. This is particularly important for Madagascar since the country's protected area network, whose current annual operating cost of the network is roughly USD 14 million, has not achieved financial autonomy and relies heavily on external aid for its operation. The protected area network represents a largely untapped source of economic benefits that, if converted into financial returns, could be used both to improve its own financial sustainability, as well as that of the natural resources sector more generally. Capturing the market of this economic benefit is therefore essential.

The carbon sequestration values of CAZ forest point to the need for the country to engage in carbon markets, such as Reducing Emissions from Deforestation and Forest Degradation (REDD+) and the Clean Development Mechanism (CDM). It also points to the need for broader measures to protect and manage forested areas, such as economic incentives for forest conservation and sustainable management. This is critical not only because of the risk that forests could become a source of emissions, but also due to the additional benefits forests have for local economies, such as the provision of freshwater. Although Madagascar's high deforestation rates and low forest cover clearly justify investments in both REDD+ and CDM –indeed several pilot initiatives are ongoing, including two in CAZ – many barriers remain for for such projects to be more broadly implemented, and for benefits to be more widely distributed. These barriers include the need for land tenure rights reform, improved forest policy and management, capacity building, and the identification of alternative livelihood opportunities.

5.7 OPPORTUNITIES FOR SCALING-UP TO OTHER REGIONS

Economic valuation links ES input levels to economic output. Because such input depends on characteristics that are both physical (such as precipitation, slope, or soil type) and social (such as the level of need and the location of beneficiary groups), a biophysical modeling analysis done in the way exemplified in this work can connect the landscape and social data with ES physical outputs. Economic analysis can then use production function estimates based on existing data to produce values and complete the link between the landscape and the economy in a scaled-up context.

If biophysical modeling can provide estimates of ES outputs that can later be connected to an economic analysis, it could also be used to produce a national accounting for areas where economic estimates are not available, so long as enough information is available to compute ES physical budgets. Although methodologies like ARIES are specifically designed to make this exercise much less data-demanding and therefore more widely applicable than it has conventionally been, physical modeling remains a costly and difficult activity to perform on large arbitrary areas, due to the fact that each ES has a unique, local range of scales which constrain the ability to employ the same models everywhere. For example, water routing requires fairly high resolution data both at the physical and the social (beneficiaries) sides. It is tempting to try to circumvent this problem by statistically correlating the raw biophysical data to their likely ES outputs, based on results from our pilot study areas. Common ES valuation practice has conventionally adopted a simplified version of this approach: it assumes that a particular land cover type is likely to produce a set of services, and it correlate ES values to that land cover type, transferring values based on area. However, we have demonstrated in this study that even the direct use of more precise biophysical data to extrapolate value can be difficult, as evidenced by the following:

1) The source areas of particular ES can in most cases be mapped directly from biophysical data. However, most ES are non-local, i.e. they are used in locations that may be very far from where they are produced. It is therefore not generally justifiable to apply ES value transfer criteria to extrapolate value estimates without accounting for the beneficiaries and the way they are connected to their sources.
2) The connection between landscape characteristics and production of ES is in most cases through a set of complex, non-linear processes such as water flow and circulation. Due to the non-linearity of these phenomena, there is no monotonic relationship between the productivity of the source and the levels of benefit accrued. Also, sink areas need to be considered along the ES provision path. Therefore it is very difficult to justify a direct correlation approach between raw biophysical data and ES output in a way that can apply valuation and produce a national accounting.

This suggests that it would be very difficult to produce a scaled-up accounting for a large area based on a handful of accurate pilot studies. Application of an analysis, such as that demonstrated here, on carefully selected sample areas can greatly improve the accuracy of any national account in the following ways:

1) Biophysical analyses will highlight the dynamics of each ES in the pilot areas by illuminating the physical connections between source-sheds and benefit-sheds. This provides a direct demonstration of which specific physical characteristics are likely to influence ES outputs and by how much. Such sensitivity information can be analyzed by experts for applicability to wider contexts, providing rules of thumb for when ES extrapolation is justifiable, and possibly criteria for such extrapolation. This approach is vastly superior to assuming a generic link between land cover and ES value, as is done in conventional approaches.
2) Full biophysical analyses in sample areas can help identify when a direct correlation between raw data and ES output is possible and what the uncertainties involved may be. This can be done by measuring the discrepancy between results from a full biophysical study in a sample area, and a direct correlation of biophysical data to ES output. Causes of this discrepancy can also be connected back to the raw data, thereby producing predictors of the applicability of a correlation approach. If done in a sufficient number of pilot areas, this can illuminate the likely errors and ultimately help decide whether a correlation approach is justifiable, and how to estimate the unavoidable errors involved.

3) Biophysical analysis can provide rules of thumb for which factors are more or less likely to influence ES outputs. For example, the pilot study described in this document clarifies and quantifies the role of forest areas vs. non-forested areas in retaining precipitation in the form of usable water and in preventing sediment contamination of the water supply. While the direct connection with the beneficiaries remains complex and hard to generalize, local differences are going to have less influence when results are aggregated at a national scale, and the results of this analysis still provide useful information to improve any national accounting that was done without this information.

6. CONCLUSION

This study, limited in scope and resources, demonstrates the feasibility of approaches to model and value ecosystem services for the purposes of ranking different areas/sites. The assessment of ecosystem services in terms of resource use sustainability – combining results from the biophysical and economic analysis – requires understanding of the complex nature between such identities. This is possible via the selection of methods that can address the complex nature of the provision of the ES, including, on one hand, assessing the current and potential flow profiles of the ES under consideration, while, on the other hand accounting for the differences among economic sectors in industrial organizational ES use efficiency and sector profitability profiles. Such an approach demonstrates some important dimensions of ecosystem services: input productivity, economic value, quality and sustainability of supply. These together will define the market, monetary value of the ES, and its relevance and contribution to national accounting.

Key messages of this report can be synthesized as follows:

KEY MESSAGES

- This study demonstrates the ability to quantify the contribution of natural capital to a regional economy, a first step towards the incorporation of natural capital into a national accounting framework, and provides a foundation for additional studies.
- The methods presented in this analysis facilitate replicability as they provide a systematic and rigorous way to assess the importance of ecosystem services for studied areas.
- The (i) relative biophysical and economic values of ecosystem services, as well as (ii) trade-offs demonstrated by multidimensionality of indicators resulting from this analysis -- input productivity, economic value, sustainability of supply, and quality of supply, can inform management, fiscal and pricing policies, particularly those associated with managing watersheds and water resources, as well as value of protected areas and forest ecosystems, important goals for WAVES in Madagascar.
- Replication of additional pilot studies can help to develop a protocol that reduces the inaccuracies inherent in any national accounting based on partial assessments, and to facilitate scaling up.

7. LIMITATIONS AND FURTHER WORK

The present economic analysis focuses on the quantification of water (marginal and average) productivity, through the econometric estimation of production functions in four different economic sectors in the CAZ area. This is a critical step toward the computation of the economic value of ecosystem services. This analysis demonstrates the role ecosystem services play in the production of quantities of selected market goods, and thus estimates their weight on national accounting. Next steps recommended are an analysis of the selected industrial markets/sectors, and the determination of monetary values of services for use into national accounting. These values should then fully integrate with the biophysical analysis such that the “actual” value of CAZ for water supply to the intended users can be determined.

From a biophysical perspective, we recommend modeling experiments to pinpoint precise thresholds in the extent and quality of the natural environment that supports critical services. For example, simulation of land use conversion at different degrees can be used to determine the precise amount of forest loss that causes unrecoverable, non-linear changes in water supply for each class of users. The same methods demonstrated in this study are also suitable for integrated simulation of bundled ES, so that the consequence of policy aimed at optimizing the output for one can be assessed in terms of its consequences on others. Such consequences can be fed back to the economic analysis to complete the quantification of the associated societal costs in an integrated ES perspective. One can hypothesize that this function will have interesting thresholds that can be later studied as a function of other variables. An economic analysis can be done on the results to establish some optimal balance between forest use and conservation. Such an analysis can also be an exercise on scaling up, given that the functions inferred would have more general relevance.

Lastly, performing a pilot analysis as demonstrated here in as many pilot areas as practical can help define a protocol to reduce the inaccuracies inherent in any national accounting based on partial assessments. A future study may be specifically directed to extract this protocol from physical accounts and parameterize a ‘best case’ transfer matrix that can help adjust economic estimates to the national level based on percent coverage of biophysical and socio-economic characteristics of interest. For example, we have demonstrated in this study how specific landscape characteristics can determine sensitivity of the ES supply. In this case we see a four-fold change in quality and a ten-fold change in sustainability of supply in protected versus non-protected areas. Such a matrix is likely to be country-specific or even region-specific within a country, and needs to be defined on a case-by-case basis. Yet this information can greatly help contextualize economic value and reduce uncertainties. The protocol can be completed with an assessment of the relative uncertainty (as well as errors) and could be analyzed under both current conditions and projected global or local change scenarios.

REFERENCES

Aswani, S., Cramer, L.A., Stoms, D.M., Kennedy, C.J., Bael, D., Kappel, C.V., Perillo, G.M. and D.J. Reed. 2008. Coastal ecosystem-based management with nonlinear ecological functions and values. Science **319**: 321–323.

Bagstad, K.J., Villa, F., Johnson, G.W. and B. Voigt. 2011. ARIES – Artificial Intelligence for Ecosystem Services: A guide to models and data, version 1.0 beta release. The ARIES Consortium.

Barbier, E.B. 2007. Valuing ecosystem services as productive inputs. *Economic Policy* **22**: 177–229.

Barbier, E.B. 2009. Ecosystems as natural assets. *Foundations and Trends in Microeconomics* **4**(8): 611–681.

Barbier, E.B., Koch, E.W., Silliman, B.R., Hacker, S.D., Wolanski, E., Primavera, J., Granek, E.F., Polasky, S., Markandya, A. and D.W. Pearce. 1990. Environmental sustainability and cost—benefit analysis. *Environmental Planning* **22**(9): 1259–1266.

Bateman, I.J., Mace, G.M., Fezzi, C., Atkinson, G. and K. Turner. 2011. Economic Analysis for Ecosystem Service Assessments. *Environmental Resource Economics* **48**: 177–218.

Brouwer, C., Goffeau, A., M. Heilbloem. 1985. Irrigation Water Management training manual n.1. FAO electronic document: http://www.fao.org/docrep/R4082E/R4082E00.htm.

Bruijnzeel, L.A. 2004. Hydrological functions of tropical forests: not seeing the soil for the trees? *Agriculture, Ecosystems & Environment* **104**: 185–228.

Carret, J.C. and D. Loyer. 2003. Madagascar protected area network sustainable financing economic analysis perspective. World Parks Congress/Durban: Workshop building comprehensive protected area systems. World Bank/French Agency for Development.

Centre d'analyse stratégique. 2009. La valeur tutélaire du carbone Rapport de la commission présidée par Alain Quinet. Rapports et documents N.16/2009. http://www.strategie.gouv.fr/IMG/pdf/Rapp_16_VTC_web.pdf.

Conservation International. 2010. Ankeniheny-Zahamena (CAZ), Madagascar Case Study. Daniela Raik, Program Management and Planning.

Conservation International. 2012. http://blog.conservation.org/2011/02/10-most-threatened-forest-hotspots/

Costanza, R., Mitsch, W.J. and J.W. Day, Jr. 2006. A new vision for New Orleans and the Mississippi delta: Applying ecological economics and ecological engineering. *Frontiers in Ecology and the Environment* **4**(9): 465-472.

Day, J.W., Jr., Boesch, D.F., Clairain, E.J., Kemp, G.P., Laska, S.B., Mitsch, W.J., Orth, K., Mashriqui, H., Reed, D.J., Shabman, L., Simenstad, C.A., Streever, B.J., Twilley, R.R., Watson, C.C., Wells, J.T. and D.F. Whigham. 2007. Restoration of the Mississippi Delta: Lessons from Hurricanes Katrina and Rita. *Science* **315**: 1679-1684.

Department for Energy and Climate Change (DECC). 2009. Carbon Valuation in UK Policy Appraisal: A Revised Approach. (Table 6.3, page 44). http://www.decc.gov.uk/assets/decc/what%20we%20do/a%20low%20carbon%20uk/carbon%20valuation/1_20090715105804_e_@@_carbonvaluationinukpolicyappraisal.pdf

Ding, H., Carter, P. and P.A.L.D. Nunes. 2011. The Estimation of Carbon Value for Project Appraisal. STAREBEI final report to the European Investment Bank, Luxembourg 2011.

EurActiv (2012) Published at http://www.euractiv.com, Source URL: http://www.euractiv.com/climate-environment/carbon-prices-slump-eu-ets-fix-h-news-514016

European Commission (EC). 2008. Commission Staff Working Document - Impact Assessment - Document accompanying the Package of Implementation measures for the EU's objectives on climate change and renewable energy for 2020. SEC(2008) 85/3. (Page 7): http://ec.europa.eu/clima/documentation/docs/sec_2008_85_ia_en.pdf

FAD. 2005. Madagascar: Programme d'Alimmentation en Eau Potable et D'Assainissement en Milieu Rural: Rapport D'Evaluation.

FAO. 2012. Aquastat: Global Information System on Water and Agriculture. Country Fact Sheet – Madagascar. http://www.fao.org/nr/water/aquastat/data/factsheets/aquastat_fact_sheet_mdg_en.pdf

Forest Trends Ecosystem Marketplace. 2012. www.forestcarbonportal.com

Fraser, R. 1999. SEDMOD: A GIS-based Delivery Model for Diffuse Sources Pollutants. Doctoral dissertation, Yale University, May 1999.

Freeman, A.M. 2003. The measurement of environmental and resource values: theory and methods, 2nd edn. Resources for the Future, Washington.

Hanley, N. and E.B. Barbier. 2009. Pricing nature: cost-benefit analysis and environmental policy-making. Edward Elgar, London.

Harper, G.J., Steininger, M.K., Tucker, C.J., Juhn, D. and F. Hawkins. 2007. Fifty years of deforestation and forest fragmentation in Madagascar. Environmental Conservation 34 (4): 325-333.

Harvey, C.A., Zerbock, O., Papageorgiou, S. and A. Parra. 2010. What is needed to make REDD+ work on the ground? Lessons learned from pilot forest carbon initiatives. Conservation International, Arlington, Virginia, USA. 132 pp.

Hawkins, K. 2003. Economic Valuation of Ecosystem Services. Mimeo, University of Missesota.

Heal, G. 2000. Valuing ecosystem services. *Ecosystems* **3**(1): 24–30.

Heal, G.M., Barbier, E.B., Boyle, K.J., Covich, A.P., Gloss, S.P., Hershner, C.H., Hoehn, J.P., Pringle, C.M., Polasky, S., Segerson, K. and K. Shrader-Frechette. 2005. Valuing ecosystem services: toward better environmental decision making. The National Academies Press, Washington.

Health, T. 2010. Madagascar Climate Change Briefing. http://www.wsup.com/sharing/documents/Madagascarclimatechangesummary2010.pdf

Johnson, G., Bagstad, K.J., Snapp, R. and F. Villa. 2010. Service Path Attribute Networks (SPANs): Spatially quantifying the flow of ecosystem services from landscapes to people: *Lecture Notes in Computer Science* **6016**: 238-253.

Kremen, C., Niles, J.O., Dalton, M.G., Daily, G.C., Ehrlich, P.R., Fay, J.P., Grewal, D. and R.P. Guillery. 2000. Economic Incentives for Rain Forest Conservation Across Scales. *Science* **288**(5472): 1828-1832.

Kull, V.S. 2000. Deforestation, erosion, and fire: Degradation myths in the environmental history of Madagascar. *Environment and History* **6**: 423-450.

Martin, S. 2004. Advanced Industrial Economics, Blackwell Publishing.

Miray, T. 2003. Rapport Socio-Economique du Corridor Zahamena-Mantadia.

Mundlak, Y. and I. Hoch. 1965. Consequences of Alternative Specification of Cobb-Douglas Production Functions. *Econometrica* **33**: 814–28.

Nevo, A. 2009. Estimation of Production Functions. Mimeo, Northwestern University.

Pagiola, S., Ritter, K.V. and J.T. Bishop. 2004. How much is an ecosystem worth? Assessing the economic value of conservation. The World Bank, Washington.

Peter-Stanley, M. (2012) 'Bringing it Home: Taking Stock of Government Engagement with the Voluntary Carbon Market', Forest Trends' Ecosystem Marketplace, March 2012.

Rakotoarison, H. F. 2003. Evaluation Economique des Bassins Versants Dans Les Regions de Fierenana et D'Andekaleka. Mémoire de fin d'Etudes. Université d'Antananarivo, Madagascar.

Rakotoarison, H.F. 2003b. Evaluation Economique des Bénéfices Hydrologiques du Programme Environnement III a Madagascar. Mémoire de fin d'Etudes. Université d'Antananarivo, Madagascar.

Renard, K.G., Foster, G.R., Weesies, G.A., McCool, D.K. and D.C. Yoder. 1996. Predicting Soil Erosion by Water: A Guide to Conservation Planning with the Revised Universal Soil Loss Equation (RUSLE). Handbook 703, US Department of Agriculture, 404 pp.

Satoyama Initiative. 2012. http://satoyama-initiative.org/en/case_studies-2/area_africa-2/ankeniheny-zahamena-corridor-a-field-demonstration-model-conservation-international-madagascar/

SEEA. 2012. Monitoring Framework for Water: The System of Environmental-Economic Accounts for Water (SEEA-Water) and the International Recommendations for Water Statistics (IRWS). http://unesdoc.unesco.org/images/0021/002112/211296e.pdf

UNCTAD. 2011. The Least Developed Countries Report 2011: The Potential Role of South-South Cooperation for Inclusive and Sustainable Development.

UNDP. 2011. Bilan Diagnostic Hydraulic Urbaine. Rapport Provisoire.

UNDP. 2011b. Situation des autres usages de l'eau dans le Grand Sud Malgache. Rapport Provisoire.

USAID. 2007. Conservation and Development of the Greater Ankeniheny-Zahamena Corridor (CAZ). Task Order 687-M-00-04-00177-00.

USAID. 2012. Madagascar Water and Sanitation Profile. http://pdf.usaid.gov/pdf_docs/PNADO933.pdf.

Campbell, R. J. 2010. Small Hydro and Low-Head Hydro Power Technologies and Prospects. Congressional Research Center, March 2010.

Varian, H.R. 1992. Microeconomic Analysis. New York: Norton, 1992. p. 198-215.

Villa, F. 2009. Semantically-driven meta-modeling: automating model construction in an environmental decision support system for the assessment of ecosystem services flow. Pp. 23-36 in: Information Technology in Environmental Engineering, I.N. Athanasiadis, *et al.*, eds. Springer: New York, NY.

Villa, F., Bagstad, K.J., Johnson, G. and B. Voigt. 2011. Scientific instruments for climate change adaptation: Estimating and optimizing the efficiency of ecosystem services provision. *Economia Agraria y Recursos Naturales* **11**(1): 83-98.

Voogd, H. 1983. Multicriteria Evaluation for Urban and Regional Planning. Pion ltd., Amsterdam, The Netherlands.

Watkiss, P., Anthoff, D., Downing, T., Hepburn, C., Hope, C., Hunt, A. and R. Tol. 2005. Social Costs of Carbon Review – Methodological Approaches for Using SCC Estimates in Policy Assessment. AEA Technology Environment, UK.

Wendland, K.J., Honzák, M., Portela, R., Vitale, B., Rubinoff, S. and J. Randrianarisoa. 2010. Targeting and implementing payments for ecosystem services: Opportunities for bundling biodiversity conservation with carbon and water services in Madagascar. *Ecological Economics* **69**: 2093-2107.

Wischmeier, W.H. and D. Smith. 1978. Predicting rainfall erosion losses: a guide to conservation planning. USDA-ARS Agriculture Handbook. Washington DC.

World Bank. 2011. World Development Indicators. Washington, DC.

World Bank. 2011b. Madagascar Country Environmental Analysis (CEA): Taking stock and moving forward. World Bank Country Office, Antananarivo, Madagascar. DRAFT (version 7).

World Bank. 2012. http://web.worldbank.org/WBSITE/EXTERNAL/COUNTRIES/AFRICAEXT/0,,contentMDK:22951123~pagePK:146736~piPK:226340~theSitePK:258644,00.html?cid=3001_2

World Bank. 2012b. Carbon Finance at the World Bank, BioCarbon Fund: Projects. Accessed 22 May 2012. wbcarbonfinance.org/Router.cfm?Page=BioCF&FID=9708&ItemID=9708&ft=Projects&ProjID=9638.

World Bank. 2012c. Wealth accounting and valuation of ecosystem services (WAVES) Madagascar, phase 2 scoping study and workplan. WAVES Madagascar National Steering Committee, March 2012.

Yang, D., Kanae, S., Oki, T., Koike, T. and K. Musiake. 2003. Global potential soil erosion with reference to land use and climate changes. *Hydrological Processes* **17**: 2913-2928.

Zellner, A., Kmenta, J. and J. Dreze. 1966. Specification and Estimation of Cobb-Douglas Production Functions. *Econometrica* **34**: 784–95.

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Ferdinando Villa holds a Ph.D. in theoretical Ecology and had a long parallel career as a scientific software designer and engineer. After working in many fields of Ecology, from theoretical island biogeography to spatially-explicit decision analysis, he conducted interdisciplinary research in a 14-year career in ecological economics at the universities of Maryland and Vermont. Dr. Villa's research has since expanded to the interface of policy, ecology and economics, concentrating on artificial intelligence approaches to assist environmental decision making and natural system assessment and valuation. Dr. Villa best known project is ARIES (Artificial Intelligence for Ecosystem Services: http://www.ariesonline.org), which is producing a next-generation web application meant to make environmental decisions easier and more effective. The ARIES project builds on a partnership of international experts, NGOs, and academics, and couples user and expert knowledge with advanced artificial intelligence to construct a model of a case study, incorporating all possible relevant data or knowledge.

Anderson Shepard holds a Master's degree in Environmental Science and Management from the University of California, Santa Barbara and a B.A. in Biology from Colorado College. Sheppard specialized in watershed management and conservation planning with a particular interest in the delicate balance between technical expertise and broader science and socioeconomic goals for effective conservation. His past project work relates to natural resource management, climate change, habitat conservation, and landscape ecology. As a result of his demonstrated commitment to environmental protection, Shepard earned support as a 2010-2011 Doris Duke Conservation Fellow. Shepard recently worked with Dr. Frank Davis and other UC and agency researchers on an NSF-funded project investigating how macroecological responses to climate change emerge from microclimate and fine-scale population processes, and is currently the Conservation Planning Associate with Defenders of Wildlife.

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TECHNICAL APPENDIX

I. COBB-DOUGLASS PRODUCTION FUNCTION

In order to compute the value of selected ecosystem services – and to assess their weight on national accounting, it is important to consider the role they play in the production of (quantities) of (selected) market goods. To do this we have to consider and control for all the other inputs which affect that production. There are a number of ways to undertake such an analysis, but one which illustrates the underlying principles is to consider a 'production function' such as the following:

(1) $Q_t = q(L;K;N,Z)$

where Q_t is the output of some good at time t, L is a vector of human capital inputs (e.g. labor); K is a vector of capital inputs (e.g. infrastructures); Z is a vector of other inputs (e.g. land) and N denotes a vector of natural capital inputs of which one is the ecosystem service we are focusing upon (water). For more details, see Bateman *et al.*, 2011. Obviously, the marginal productivity of an input is calculated as a partial derivative of the production function with respect to the selected input. For instance, the marginal productivity of labor will be calculated as: $MP_L = \frac{\partial Q}{\partial L}$.

There exist a number of possible specifications of the production function (see Nevo, 2009) and the task of defining a given form typically involves considering both the empirical suitability of a form and how well it reflects reality. For the purposes of the present study, we can consider the Cobb-Douglas (CD) production function (Nevo, 2009), which has some properties likely to be reflected in ecosystem services.

A typical Cobb-Douglas function presents the following functional form:

(2) $Q = L^{\alpha}K^{\beta}$

where L is labor and K capital, α and β are output elasticities of labor and capital, respectively. In this case, the marginal productivity of labor will equal $MP_L = \alpha L^{\alpha-1}K^{\beta}$. The Cobb-Douglas production function implies a nonlinear relationship between inputs and has many analytical properties. For instance, the Cobb-Douglas production function (like most feasible production functions) exhibits the property that as we reduce the level of one input so we have to increase levels of one or more other inputs in order to maintain the level of output of q. The rate at which one input can be substituted for another while keeping output constant is known as the *technical rate of substitution* (TRS) and measures how one of the inputs must adjust in order to keep output constant when other inputs changes. *The elasticity of substitution*, on the contrary, measures the percentage change in the inputs ratio divided by the percentage change in the technical rate of substitution, with output being held fixed. In the study at issue we do not consider none of this concepts, even if are easily derivable from the estimates, since it would go beyond the scope of the analysis that consists in estimating marginal productivity of the input/water, adopted in four different sectors.

From the empirical point of view, a general the Cobb-Douglas (production function) is described in equation

(3) $Q_t = e^{\alpha} L_t^{\chi_L} K_t^{\beta_k} e^{u_t}$

Where the dependent variable is the output of the firm at time t, L_t is labor (or more generally a variable input) K_t is capital (a quasi-fixed input), u_t is an error term; α, β_L β_k are parameters. We include additional right-hand side variable like material, energy, land, and water. The output and input measures are in physical units. In most cases, however, since it involves aggregation across products will be measured in dollars. The error term, includes, among the others, technology or management differences, measurement errors, variation in external factors (e.g., weather).

In the easiest formulation, Cobb-Douglas production functions imply that elasticity of substitution between factors equals 1 (we can remove this stringent hypothesis by testing CES; or translog production function in a later period). Taking logs we obtain

(4) $y_t = \alpha + \beta_L L_t + \beta_k K_t + u_y$

Where y_t *= log(Q) and so on*

More generally,

(5) $y_t = \alpha + x_i^{'} \beta_{i,t} + u_y$

Where y_t *= log(Q) and x are the logs of input i, u is an error term.*

After an analysis of the industrial structure and production technologies of the selected sectors, we can credibly assume that the Cobb-Douglas production functions realistically describe the productive systems in mining, agriculture-farming, tourism and energy of the CAZ area. The basic model, presented in Eq.4 is then adapted to the specific data availability and market structure of the selected sectors. In addition, Cobb-Douglas production functions are very tractable in empirical analysis. It is worth highlighting, that real world production relationships are often more complex than the Cobb-Douglas case and may involve a plethora of inputs exhibiting a variety of output and substitution relationships within a single function. Despite this, it is important to identify a solid theoretical and empirical framework to value ecosystem services. In the following paragraphs, we show how we have adapted the general empirical framework to the study of each sector.

A. ESTIMATES OF COBB-DOUGLASS PRODUCTION FUNCTIONS IN THE CAZ MINING SECTOR

In the case of the mining sector our empirical general empirical model of the Cobb-Douglas production function become a couple of (separate) log-linear models, as described in equations (6-7):

(6) $Log(quantity\ of\ cobalt)_{i,t} = \alpha_{i,t} + \beta_1 log(machinery)_{I,t} + \beta_2 log(energy)_{I,t} \beta_3\ log(work)_{I,t} + \beta_4 log(land)_{I,t} +$

$+\beta_5 log(water)_{I,t} + \beta_6 log(land)_{I,t} + \beta_7 log(primary\_material\_inputs\ )_{I,t} + u_{y,i,t}$

(7) $Log(quantity\ of\ nickel)_{i,t} = \alpha_{i,t} + \beta_1 log(machinery)_{I,t} + \beta_2 log(energy)_{I,t} \beta_3\ log(work)_{I,t} + \beta_4 log(land)_{I,t} +$

$+\beta_5 log(water)_{I,t} + \beta_6 log(land)_{I,t} + \beta_7 log(primary\_material\_inputs\ )_{I,t} + u_{y,i,t}$

Where the dependent variables are the logarithms of total quantity of respectively cobalt and nickel in period t; and the explanatory variables are the logarithms of the selected production inputs, including water. The model is estimated by the ordinary least squares estimation technique.

B. ESTIMATES OF COBB-DOUGLASS PRODUCTION FUNCTIONS IN THE CAZ AGRICULTURAL SECTOR

In the case of the agricultural sector our empirical general empirical model of the Cobb-Douglas production function becomes a system of 3 log-linear models, as described in equations (8):

$$(8)\ Log(quantity\ of\ rice)_{i,t} = \alpha_{i,t} + \beta_2\ log(work)_{I,t} + \beta_3 log(land)_{I,t} + \beta_4 log(water)_{I,t} + \beta_5 log(sickle)_{I,t} + u_{y,i,t}$$

$$Log(quantity\ of\ manioc)_{i,t} = \alpha_{i,t} + \beta_2\ log(work)_{I,t} + \beta_3 log(land)_{I,t} + \beta_4 log(water)_{I,t} + \beta_5 log(sickle)_{I,t} + u_{y,i,t}$$

$$Log(number\ of\ animals)_{i,t} = \alpha_{i,t} + \beta_2\ log(work)_{I,t} + \beta_3 log(land)_{I,t} + \beta_4 log(water)_{I,t} + \beta_5 log(sickle)_{I,t} + u_{y,i,t}$$

Where the dependent variables are the logarithms of total quantity of respectively rice, manioc and animals in period t; and the explanatory variables are the logarithms of the selected production inputs, including water. We model production in the agricultural sector as a set of integrated productive activities, where a commonality of inputs of production is used (see Varian, 1992, chapter 12). The model is estimated by the three stage least squares routine.

C. ESTIMATES OF COBB-DOUGLASS PRODUCTION FUNCTIONS IN THE CAZ TOURISM SECTOR

Given the scarcity of available data, we were not able to perform an econometric analysis. Therefore, in order to be consistent with the selected analytical framework, we reasoned as follows. Supposing that water is the only input affecting output (because we keep the other inputs fixed, in a typical short run analysis. This is a realistic assumption, since a hotel does not change its capacity or a hotel manager does not change the number of employees in the short run in terms of number of arrivals, but water use, e.g. showers and personal hygiene changes with the number of arrivals. We can write the Cobb-Douglas production function, as follows:

$$(9)\ Q = AW^{\alpha} Z^{\beta}$$

Where Q represents the number of total arrivals at the selected destination in the A is a technological parameter; W is the input water, and *Z* represents all other variables. Assume that α equals 1 and β equals zero. We can write the technological relationship as a linear relationship, described by the slope in Equation (10).

$$(10)\ Q = AW$$

In this case, the parameter A also measures both average and marginal productivity, which are equal. In fact, it is a pretty realistic assumption to consider that an additional tourist will use (for personal hygiene) about the same quantity of water than the other tourists.

D. ESTIMATES OF COBB-DOUGLASS PRODUCTION FUNCTIONS IN THE CAZ HYDROELECTRICITY SECTOR

For the energy sector, we have no data al all about production, which can be easily represented by a Cobb-Douglas, where the inputs are labor, capital, energy, machinery and water, as in equations (1) and (5). The estimated value of marginal and average productivity where provided by the JIRAMA experts via e-mail.

II. A SURVEY OF THE INTEGRATED ASSESSMENT MODELS[22]

The analyst faces a number of significant challenges when attempting to quantify the economic impacts of CO_2 emissions. In particular, analysts must make assumptions about four main steps of the estimation process: (1) the future emissions of greenhouse gases; (2) the effects of past and future emissions on the climate system; (3) the impact of changes in climate on the physical and biological environment; and, (4) the translation of these environmental impacts into economic damages.

Integrated assessment models (IAMs) have been developed to combine these steps into a single modeling framework. In short, these models combine scientific and socio-economic aspects of climate change and are primarily for the purpose of assessing policy options for climate change control. Well-known IAMs in the literature include MERGE[23], IMAGE[24], FUND[25], DICE[26] and RICE[27] – Table 9 presents a survey of the existing IAMs. They differ on the level of detail in modeling, and the respective capacity to deal with climate-economic-atmospheric complexity and the economic modeling strategy, as well as the capacity to deal with uncertainty and the ability of incorporating an economic response. All these aspects will affect the final estimates of the social costs of carbon.

TABLE 10. A SURVEY OF THE EXISTING IAMS.

Model	Author	Type	Detail			Uncertainty	Economic Response
			Climate	Economy	Atmospheric chemistry		
PAGE	CEC (1992)	Evaluation	Complex (C)	Complex (C)	Simple (S)	Stochastic simulation	None
MERGE	Manne, et. al. (1993)	Optimization	S	C	S	Discrete	Investment, energy
DICE	Nordhaus (1994)	Optimization	S	S	S	Stochastic simulation	Investment
MIT	MIT (1994)	Evaluation	C	C	C	Stochastic simulation	None
IMAGE	Alcamo (1994)	Evaluation	C	C	C	Sensitivity	None
FUND	Tol et al (1995)	Optimization	S	S	S	Stochastic simulation	None
RICE	Nordhaus and Yang (1996)	Optimization	S	C	S	None	Investment, control*

Note: Evaluation means a model that evaluates an exogenous policy; optimization refers to endogenously find the optimal policy.
Refe: David L.Kelly and Charles D. Kolstad (1998) "Integrated Assessment Models For Climate Change Control" in Henk Folmer and Tom Tietenberg (eds), International Yearbook of Environmental and Resource Economics 1999/2000: A Survey of Current Issues (Cheltenham, UK:Edward Elgar, 1999).

The interagency group relied on three IAMs commonly used to estimate the SCC: the FUND, DICE, and PAGE models, which are frequently cited in the peer-reviewed literature and are used in the IPCC

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[22] Source: Ding *et al.*. (2011)
[23] MERGE – the Model for Estimating the Regional and Global Effects of GHG policies.
[24] IMAGE – the Integrated Model to Assess the Greenhouse Effect.
[25] FUND – the Climate Framework for Uncertainty Negotiation and Distribution model.
[26] DICE – the Dynamic Integrated Climate Economy model.
[27] RICE – the Recursive Integrated Climate Economy model.

assessment. Each model was given equal weight in the SCC values developed through this process, bearing in mind their different limitations.

DICE, PAGE, and FUND all take stylized, reduced-form approaches. Other IAMs may better reflect the complexity of the science in their modeling frameworks but do not link physical impacts to economic damages. Underlying the three IAMs selected for this exercise are a number of simplifying assumptions and judgments reflecting the various modelers' best attempts to synthesize the available scientific and economic research characterizing these relationships.

These three IAMs translate emissions into changes in atmospheric greenhouse gas concentrations, atmospheric concentrations into changes in temperature, and changes in temperature into economic damages. The emissions projections used in the models are based on specified socio- economic (GDP and population) pathways. These emissions are translated into concentrations using the carbon cycle built into each model, and concentrations are translated into warming based on each model's simplified representation of the climate and a key parameter, climate sensitivity. Finally, transforming the stream of economic damages over time into a single value requires judgments about how to discount them.

Each model takes a slightly different approach to model how changes in emissions result in changes in economic damages. In PAGE, for example, the consumption-equivalent damages in each period are calculated as a fraction of GDP, depending on the temperature in that period relative to the pre-industrial average temperature in each region. In FUND, damages in each period also depend on the rate of temperature change from the prior period. In DICE, temperature affects both consumption and investment.

III. ECONOMIC ANALYSIS DATA AND SOURCES

TABLE 11. SELECTED VARIABLES FOR EMPIRICAL ANALYSIS IN THE MINING AND AGRICULTURAL SECTORS.

Variable	*Description*	*Sources*
MINING SECTOR		***1.*** *2010 Ambatovy Sustainability Report;* ***2.*** *2010 Ambatovy Supporting Growth and Development in Madagascar;* ***3****. 2011 Ernst & Joung, Extractive Industries Transparency Initiative, EITI, Madagascar*
Log(Quantity)	Quantity of Cobalt and Nickel in tons produced per year	
Log(labor)	Total number of white and blue collars employed per year	
Log(machinery)	Machinery used in production, measured in capital investment per year	
Log(energy)	Total amount of electricity (measured in Kw/h) used in production per year	
Log(primary_ material_inputs)	Total amount of limestone, sulphur, ammonia, coal, measured in tons	
Log(land)	Total amount of land devoted to mining, measured in hectares	
Log(water)	Total amount of water measured in cubic meters used in production per year	
AGRICULTURAL SECTOR		***1.*** *2010 Enquéte Périodique auprés de Ménage, Ministerè de l'Etat, Charge l'Economie et del'Industrie ;* ***2.*** *2005 Recensement De l'Agriculture.Ministére de l'Agriculture de l'Elevage et de la Peche;* ***3.*** *Observatoire du Riz;* ***4.*** *2010 Rapport Final, Renforcement de la Disponibilité et de l'Accès aux Statistiques Rizicoles : une contribution à l'initiative d'urgence pour le Riz en Afrique Subsaharienne,Centre National de Recherche Appliquée au Développement Rural Service de la Statistique Agricol;* ***5.*** *Conservation International Madagascar Regional Development Plans*
Log(Quantity)	quantity in tons of produced rice, manioc, number of households' farm animals in 12 selected administrative areas within the CAZ in 2004-6.	
Log(labor)	Number of farmers and/or breeders active in production per year	
Log(sickle)	Number of sickles used in production per year.	
Log(land)	Total amount of land devoted to agriculture and/or farming per year, measured in hectares	
Log(water)	Total amount of water measured in cubic meters used in production per year	

Table 12. Receptive infrastructure in the CAZ.

Hotel / Lodge	*No. Rooms*	*No. Suites*	*No. Bungalows*	*No. Lodging*	*Total no. Beds*
Vakona Forest Lodge	0	0	26	26	**42**
Bezanozano	11	3	16	30	**49**
Andasibe	0	0	12	12	**20**
Feon'ny Ala	0	0	44	44	**72**
Site Eulophiella	0	10	7	17	**28**
Zama Meva	7	0	0	7	**11**
Espace Diamant	17	13	0	30	**49**
Hazavana	10	0	0	10	**16**
Tsara	5	1	0	6	**10**
Les Orchidees	7	0	0	7	**11**
Max'irene	26	0	0	26	**42**
Paradis Du Lac	0	9	0	9	**15**
Motel Restaurant Mialy	7	0	0	7	**11**
Rindra	9	0	4	13	**21**
Espace Mirindra	12	0	4	16	**26**
Diamant Vert	1	0	0	1	**2**
Manantena	2	0	0	2	**3**
Ny Aina Antanandava	2	0	0	2	**3**
Vohitsara	14	0	0	14	**23**
Total	**130**	**36**	**113**	**279**	**454**

Source: Own elaboration (based on Moramanga Tourism Office and World Tourism Organization)

Table 13. Energy data.

Andekaleka Hydropower Generator	
Cubic Meters of water used for producing 1000 kWh of Hydropower	0.5
Total cubic meters of water	12.5 million
Total Produced Electricity (2001)	25 million kWh

Source: JIRAMA

IV. ECONOMIC ANALYSIS DETAILED MODEL RESULTS

TABLE 14. COBB-DOUGLAS PRODUCTION FUNCTION FOR NICKEL EXTRACTION IN THE CAZ AREA.

Variable	*Model 1*	*Model 2*	*Model 3*
Log(work)	-0.40*	-0.260*	-0.26*
Log(land)	0.31 *	0.59***	1.35***
Log(machinery)	-0.54 **	-0.66***	-0.67***
Log(Energy)	0.093*	0.052*	0.05*
Log(primary_ material_inputs)	0.038*	0.06**	0.03**
Log(water)	-	0.70***	-
*Log(water*land) (Interaction effect)*	-	-	0.76***
Constant	19.99***	24.82***	24.84***
R-squared	0.30	0.40	0.41

*With *** 1% statistically significant, ** 5% statistically significant, * 10% statistically significant*

TABLE 15. COBB-DOUGLAS PRODUCTION FUNCTION FOR COBALT EXTRACTION IN THE CAZ AREA.

Variable	*Model 1*	*Model 2*
Log(work)	0.41*	0.49**
Log(land)	0.05*	0.10*
Log(machinery)	0.22*	0.15*
Log(energy)	-0.46**	-0.48***
Log(primary_material_inputs)	0.02***	0.03**
Log(water)	-	0.43**
Constant	6.16*	8.91*
R-squared	0.25	0.28

*With *** 1% statistically significant, ** 5% statistically significant, * 10% statistically significant*

TABLE 16. COBB-DOUGLAS PRODUCTION FUNCTION FOR RICE, MANIOC, AND FARM ANIMALS IN THE CAZ AREA.

Equation / Variable	*Coefficient Estimate*	*P-Value*
(1) Loggricequantity		
Logwater	0.9158	0.000
Logsickle	0.0324	0.560
Logwork	0.1751	0.064
Logland	0.0998	0.029
Constant	1.6156	0.014
"R-squared"	0.9875	
(2) Logomaniocquantity		
Logwater	0.8290	0.000
Logland	0.0457	0.579
Logsickle	0.1029	0.477
Logwork	0.3586	0.019
Constant	2.1443	0.189
"R-squared "	0.9632	
(3)Lognumberoffarmanimals		
Logwater	0.9376	0.000
Logwork	0.0195	0.155
Constant	8.6340	0.000
"R-squared "	0.9985	