

CONSERVATION AND LAND USE PLANNING APPLICATIONS IN GABON, CENTRAL AFRICA

A THESIS SUBMITTED FOR THE DEGREE
DOCTOR OF PHILOSOPHY

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ABSTRACT

Spatial prioritization and systematic conservation planning methods are designed to improve land use decisions and conservation outcomes, yet remain underutilized in many biologically-rich places that need them most. This thesis applies the theory and methods developed in the discipline of spatial prioritization to conservation and land use decisions in the Central African country of Gabon. Creating a spatial information base of priority species, habitats and land uses in a region that is notoriously data-poor, I reveal that many features important for both conservation and natural resource production are highly localized; their coincidence has important implications for management. Setting conservation targets for species and habitats, I find that representation in existing protected areas is relatively low, and identify a number of near-optimal solutions that meet all targets, with minimal impact on land used for local livelihoods. I distill these solutions down to a handful of critical biodiversity sites that are top priority to protect, and make management actions explicit for the species and habitats they contain. To make the work more widely applicable, I also develop a novel method to identify where field surveys are most likely to improve decisions about protected area expansion, providing decision-makers with more options of places that could be protected to achieve conservation goals. This study contributes to the research, development and practice of conservation prioritization and spatial planning, particularly in data-poor contexts like Gabon, which still have a wealth of biodiversity, and need to carefully plan for its conservation alongside development.

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Chapter 1

GENERAL INTRODUCTION

1.1 MAKING INFORMED LAND USE DECISIONS

Competition for land and water resources is increasingly intense, under global demand for basic necessities like energy, food and water, and raw materials needed for development (Millennium Ecosystem Assessment 2005). However, current land use and development trajectories already pose important risks to the ecological functions sustaining life on Earth (Barnosky et al. 2012) – as these pressures escalate and evolve, decision-makers will face ever more difficult political choices about how to use limited land and water resources to achieve different, often competing societal goals linked to the land. Increasingly, scientists are drawing public and political attention to the environmental risks associated with development decisions (Griggs et al. 2013, Barnosky et al. 2014), and contributing to the search for more sustainable solutions by designing and communicating science to provide sound, new information and policy advice (for example, Solomon 2007).

The goal of this thesis was to investigate how a science-based approach to conservation and land use planning could support, improve and possibly change the course of management action or decision, particularly in a data-poor tropical rainforest

context – arguably that with the most at stake, in terms of global biodiversity goods and services, from taking poor decisions. This applied research was grounded in decision theory, which provides a framework for formally assessing the complex of factors involved in a decision-making process (objectives, variables, risks and uncertainties) and informing the rational choice of actions to take to achieve a desired outcome (Keeney 1982). A decision-analytic approach breaks a decision into a series of logical, structured steps, from defining the problem, objectives and constraints, to identifying and vetting possible actions and likely outcomes, thereby clarifying what a sensible course of action would be. Such structured analysis brings greater defensibility to the evaluation process and its acceptance than decisions made in an ad-hoc manner (Gregory and Keeney 2002). Applied to land use problems, the decision-analytic approach can clarify priorities for managing resource use at different locations to achieve particular objectives (Polasky et al. 2008) My interest in this thesis was to apply a decision-analytic approach and spatial prioritization techniques to real-world conservation problems, to help land managers and policy-makers make more informed land use decisions.

1.1.1 SYSTEMATIC CONSERVATION PLANNING

Spatial prioritization is of particular interest in the field of conservation science, since conservation problems often require efficiency and justification for protecting land against alternative economic uses (Possingham et al. 2005). Indeed, compared to land used for production purposes, protected areas cover a relatively small part of the globe, yet are the world's main mechanism for conserving nature (Chape et al. 2008,

Watson et al. 2014) – their siting and configuration is vital to ensuring that they achieve conservation objectives efficiently (Possingham et al. 2005, Venter et al. 2014). Early work on spatial prioritization recognized that doing this efficiently would require a systematic evaluation of the protected area network as a whole (Kirkpatrick 1983, Pressey 1994) to ensure that protected areas met core principles, several of which are presented in Table 1 (Joint Nature Conservation Committee 2010). Systematic conservation planning emerged as a logical process for ensuring that conservation actions, which are often protected areas, are effective in conserving a comprehensive range of biological features, in adequate amounts, and in efficient locations and configurations for their long-term survival (Margules and Pressey 2000).

Table 1: Core protected area design principles

<i>Representativeness</i>	Protected areas should preserve a sample of the full range of ecological features and processes (Margules et al. 2002, Rodrigues et al. 2004).
<i>Adequacy</i>	The protected area network should ensure that enough of a feature, system, or ecological process is protected to promote its long-term viability or persistence (Pressey et al. 2003).
<i>Efficiency</i>	Conservation objectives should be met as efficiently as possible, to increase likelihood of success, on sites that complement, rather than replicate, each other (Pressey and Nicholls 1989).

Initially, systematic conservation planning was conceived mostly as an environmental problem-solving exercise, spurning a variety of analytical methods to map biodiversity, quantify conservation goals and gaps in protection, and formally assess options

(locations and actions) to close gaps efficiently (Sarkar et al. 2006, Moilanen et al. 2009b). Despite the underlying intention for planning to support real-world decisions, however, less attention was given to its implementation, with practical applications so rare in the peer-reviewed literature (Prendergast et al. 1999, Knight et al. 2008) that the discipline was said to suffer an “implementation crisis” (Knight et al. 2006a). Over the last decade, the systematic planning process has evolved considerably, in part to address this “crisis” (Pressey and Bottrill 2009), yet implementation remains a major challenge (see section 1.4 below). Nevertheless, at the heart of any successful application lies the original core process of careful analytical problem-solving, which is essential to spatial prioritization and defensible conservation decision-making in general (Moilanen et al. 2009b). In the next section I explain some fundamental aspects of this spatial planning problem, which formed an important part of this thesis, before exploring how it might support decision-making in a data-poor context.

1.2 SOLVING A SPATIAL PLANNING PROBLEM

1.2.1 ESSENTIAL STEPS IN THE DECISION-ANALYTIC PROCESS

Formulating conservation problems correctly is critical, since it requires the user to think through and specify each element of the decision, which determines how the problem is represented and solved, and can therefore profoundly impact the conservation outcome (Possingham 2001). Essential steps of the spatial problem-solving process involve articulating, mapping and quantifying the objectives, variables and constraints involved in the decision, and formulating and solving them, often as mathematical problems using classical optimization techniques (Moilanen et al. 2009a).

Although these steps form a logical framework (Table 2), meaningfully translating real-world problems into these components is often not straightforward and can pose a genuine challenge in applying decision theory to conservation problems (Game et al. 2013).

Table 2: Essential steps in decision analysis

<i>Clarification</i>	<i>Example</i>
Step 1: Define the problem: state the objective or rationale for decision	
<p>In optimization terms, the defined goal is called the <i>objective function</i>.</p> <p>Requires a well-defined measure of performance towards the goal, often set as targets (Svancara et al. 2005).</p>	<p>Objective: maximize the number of habitat types conserved</p> <p>Performance metric: number of habitat types conserved</p>
Step 2: Identify actions that could be taken at different sites	
<p>In optimization terms, different actions are called <i>control variables</i>.</p> <p>Managers control these actions by their decision.</p>	<p>Actions influencing conservation may be protection-oriented, like land acquisition or stewardship (Carwardine et al. 2008), or production-oriented, like agriculture and urban development (Moilanen et al. 2011).</p>
Step 3: Account for the impact of different actions on features	
<p>Planners must know:</p> <ol style="list-style-type: none"> 1) The state or distribution of features (species, habitats, etc.) in the landscape, known as <i>state variables</i>. 2) How the variables will change under a given action, described by <i>state equations</i>. 	<p>Natural features may be represented by a map of forest types whose distribution changes under different harvesting scenarios.</p>

Models, often presented as maps, are used to describe the system and how it works.	
Step 4: Define costs and constraints to the decision	
This may represent monetary cost to implement an action, opportunity cost for foregone activities, or a proxy for any difficulty or constraint in achieving the objective (Naidoo et al. 2006).	Land available to protect may be limited, constraining the solution. Different management actions may entail different costs, which also vary by location.

1.2.2 ASSEMBLING INFORMATION FOR SPATIAL PLANNING

The relevance of a spatial solution can depend largely on the quality of the information base with respect to the decision at hand (Ferrier 2002), yet compiling this information can be challenging, since our knowledge of the features, their distributions and responses to actions, and costs and target levels is almost always incomplete, often indeterminably so (Flather et al. 1997). Assembling robust information for planning is especially difficult in data-poor contexts, which are often hampered by basic gaps and misinformation about how land is allocated and used, how other socio-economic factors are distributed over the landscape, or where important biological features are located. Lack of knowledge about what species exist and their distributions is known as Linnean and Wallacean shortfalls, respectively (Whittaker et al. 2005), and can strongly influence conservation decisions and outcomes.

To overcome these problems, planners are often obliged to use surrogates – better-known variables which serve as proxies for a wider range of features or constraints that

are important but impossible to fully express in a decision (Wilson et al. 2009).

Surrogates must be mapped across the landscape, which can be achieved a variety of ways using different tools, techniques and sources of information (Elith and Leathwick 2009). Making the most of sometimes paltry and patchy data may require synthesizing multiple forms of information and analysis using a variety of complementary approaches to form a more complete picture of the planning situation (Ferrier and Wintle 2009).

1.2.3 PROBLEM FORMULATION AND SOLUTION

Different problem formulations solve different types of prioritization problems; formulating a conservation problem correctly is crucial to solving it (Possingham 2001). For the applications in this thesis, the primary goal was to meet all conservation targets efficiently. The appropriate problem formulation was therefore the minimum set coverage problem, which seeks to meet all targets with minimum cost (Moilanen et al. 2009a). The minimum set problem formulation can be formalized as:

$$\text{minimize } \sum_{i=1}^{N_s} c_i x_i$$

subject to the constraint that targets are met for all features j

$$\sum_{i=1}^{N_s} x_i r_{ij} \geq T_j$$

and the control variable is either 0 or 1 for all sites

$$x_i \in \{0,1\}$$

where r_{ij} is the amount of feature j in site i , c_i is the cost of site i , N_s is the total number of sites, and T_j is the target for feature j . The control variable x_i determines whether sites are selected ($x_i = 1$, therefore incurring cost), or not ($x_i = 0$, no cost). The amount of each feature is summed across selected sites, with the goal of meeting targets for all features as cheaply as possible.

Once a problem is defined and described by data, different computational tools can be used to solve them (Sarkar et al. 2006). I used the site selection software Marxan (Ball and Possingham 2000), since it specializes in solving large minimum set problems very quickly (Ball et al. 2009). Marxan's simulated annealing algorithm works by generating an initial set of sites, evaluating them, and then iteratively searching for and accepting improvements to the set, while also stochastically accepting non-improving sites, to avoid becoming trapped prematurely in a local optima that misses the global pattern (Ball et al. 2009). Each solution is evaluated by an objective function value, with lower values meeting targets more efficiently. Marxan accepts that some solutions may fail to meet some targets, or be more costly or widespread than desired, yet still be useful alternatives; in these cases, it applies penalties to the objective function value to reflect these less-desirable conditions. Thus, Marxan's objective function is based on the minimum set formulation, with additional terms that penalize missing targets and try to create spatial clumping of protected sites.

1.3 APPLYING SPATIAL PRIORITIZATION TO REAL-WORLD PROBLEMS

This thesis investigates ways that the theory and basic research developed in the discipline of conservation prioritization can be applied to real-world problems. Three themes of the work are that it (1) addresses a data-poor context; (2) focuses on elements that matter most to the decision outcome; and (3) is designed to be able to serve different needs. These themes, summarized below, are relevant to solving applied conservation problems (beyond planning) almost anywhere in the world today, yet real-world applications remain somewhat scarce in the peer-reviewed literature; exploring them in this thesis thus contributes to their advancement, and development of the field of applied conservation planning in general.

1.3.1. CHALLENGES IN DATA-POOR CONTEXTS

Despite well-developed concepts, principles and techniques about how to prioritize actions and locations for conservation, it is thought that relatively few plans in the scientific literature actually result in real-world outcomes (Prendergast et al. 1999, Knight et al. 2008), due to various gaps between research (prioritization) and implementation (Knight et al. 2006a). Most explanations for the research-implementation gap are social in nature – plans and planning processes have failed to take human factors into account adequately, due to using limited socioeconomic data (Polasky 2008), insufficiently involving stakeholders and local institutions (Smith et al. 2009), and not working closely with managers (Game et al. 2011a), among other shortfalls. Less commonly is the research-implementation gap attributed to limits in the data or spatial prioritization itself, despite the fact that many places on Earth are still

considered data vacuums (Gardner et al. 2007) – a situation which can present extreme challenges to real-world planning.

Tropical countries provide some of the most challenging conditions for applied planning: their biological diversity is both particularly concentrated and unknown (Dirzo and Raven 2003), land uses and threats can be difficult to document and regulate, and decision-making processes may be relatively opaque. Planning in these countries tends to be additionally hampered by lack of education, technical capacity, and accessible, current information – well-recognized factors limiting environmental management throughout the developing world (Lundquist and Granek 2005, Meijaard and Sheil 2012). With the increasing availability of remotely-sensed data, online datasets, freeware to treat them, and greater technical expertise, lack of information and capacity is no longer a commonly-cited explanation for the research-implementation gap (Knight et al. 2008), yet in my experience is still one of the most serious impediments to producing useful solutions on the ground. I identified four potential challenges to rational planning in a data-poor context, which could be addressed at least partially through applied research using spatial prioritization techniques in this thesis (Table 3), thereby increasing the chance of real-world application and contributing to the body of knowledge that aims to close the research-implementation gap. These challenges are addressed in the objectives of this study (see section 1.5.2).

Table 3: Potential challenges to rational planning in a data-poor context, which spatial prioritization can help to address

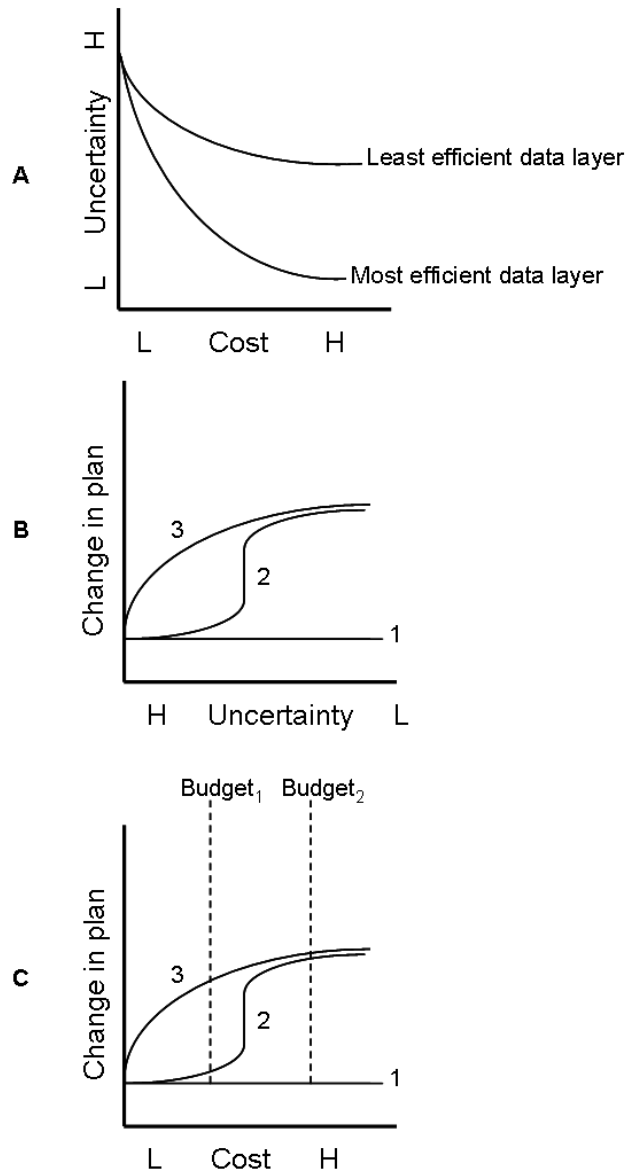
<p>1. <i>Lack of information</i></p>	<p>For conservation plans to make sense on the ground, they must be built on a reliable foundation of place-based knowledge (Cowling and Pressey 2003). Studies commonly rely on existing 'best available' data (Ardon et al. 2008), yet in data-poor contexts, such data are often so meager as to yield meaningless results, eroding confidence in the planning process itself.</p>
<p>2. <i>Unclear goals, therefore difficulty defining priorities</i></p>	<p>Plans are driven by different sets of goals: high-level goals that reflect societal or cultural values are translated into detailed, technical goals (measures and actions) for achieving them (Ferrier and Wintle 2009). Clarifying and aligning these different goal sets is important in closing the knowing-doing gap.</p>
<p>3. <i>Unclear decision-making structure</i></p>	<p>A structured process of decision-making organizes and guides the decision-maker through different potential courses of action, to evaluate how well they meet the objectives (Goodwin and Wright 2014). Unstructured decisions are often less measured and rational, and the decision-making process less transparent.</p>
<p>4. <i>Incomplete translation of the plan into action</i></p>	<p>Planning outputs must go beyond maps, to specify the actions and actors who need to implement management at different sites (Game et al. 2013) – planners and managers must work together to achieve this. Scale mismatch between planning and action often hampers this translation but can be overcome by good design (Game et al. 2011a).</p>

1.3.2 FOCUS ON WHAT MATTERS

Most decisions involve uncertainty; part of the planning process is to assemble information that reduces this uncertainty to improve the soundness of a decision (Burgman et al. 2005). However, not all information or actions that reduce uncertainty

matter to the decision. For example, an ornithologist might survey a region to document bird status and distribution to inform management – but if the conservation objectives do not include birds or that region, the information will not assist the decision. Valuable information is that which not only reduces uncertainty, but in so doing, has the most potential to influence or change a decision that would have been made without it. This concept, formally developed in Chapter 5, is illustrated in Figure 1.

Figure 1: Planning should focus on the action with most potential to change a decision that would have been made without it. The following example is applicable to many other situations. (A) Different data layers that inform a plan may initially have high uncertainty, which can be reduced by gaining information in field survey or by other development. Such development incurs a cost, and developing different layers may incur different costs. Reducing uncertainty can be achieved more efficiently in some layers than others. (B) Reducing uncertainty in different layers can impact a decision differently, since some layers matter to the outcome more than others. For example, reducing uncertainty in effort 1 does not change the decision (or plan). In efforts 2 and 3, reducing uncertainty changes the decision, at different rates. (C) Because uncertainty can be reduced with cost (as in (A)), we can evaluate the efficiency with which reducing uncertainty changes a decision. Efficient strategies will change a decision cheaply. For a limited budget₁, effort 3 would be more cost-efficient than effort 2. For a larger budget₂, efforts 2 & 3 would have similar cost-efficiency.



Prioritizations designed for implementation must keep the end decision in mind (Pierce et al. 2005). For example, when deciding whether to develop maps of mining or logging potential in a tropical forest context, effort might be better spent on mining, since its high-value, spatially-heterogeneous pattern may be more likely to influence a land-use plan than the lower-value, more spatially-even pattern of logging (Naidoo et al. 2006). Similarly, a highly-legislated, spatially-restricted species may be more likely to

influence a conservation plan than one which is more common or ubiquitously distributed. Resource-limited planning conditions benefit from thinking the entire decision process through, to identify the elements that will matter in the end and therefore merit attention in the planning process.

1.3.3 DESIGN THAT IS ROBUST TO DIFFERENT NEEDS

Planning is inherently dynamic (Pressey et al. 2007). Systematic plans intended for implementation require a careful design (Knight et al. 2006b) that allows them to be reasonably robust to evolving needs, barriers, and opportunities for implementation. Employing a design that follows established steps of conservation assessment, is information-based, properly documented, and technically well-conceived in terms of using relevant variables, spatial scales, adequate data and strong justifications will increase the chance that the design may be useful to different applications. For example, biodiversity priorities used to inform protected area expansion might also be useful to inform low-impact development, as different parts of the same equation.

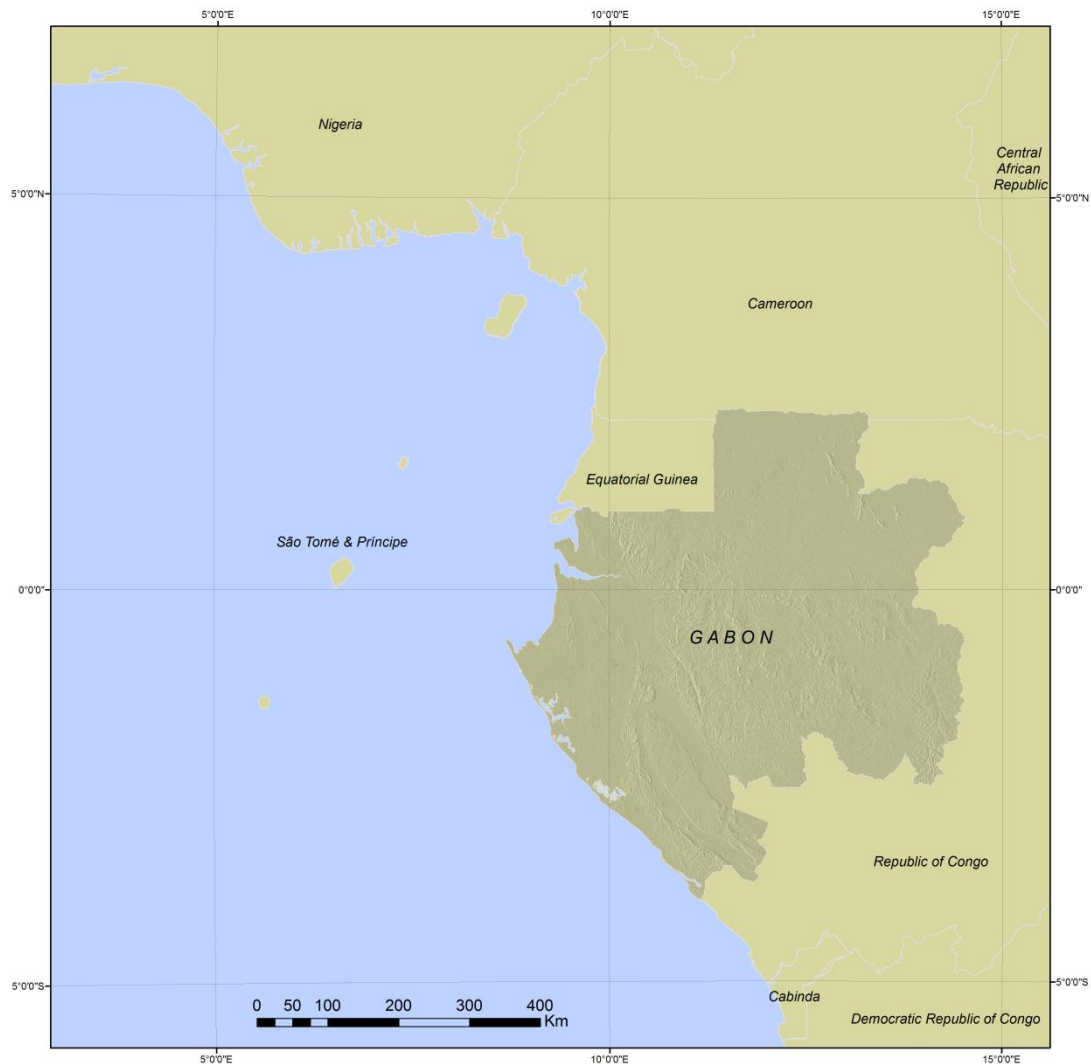
1.4 RESEARCH CONTEXT, AIMS AND THESIS STRUCTURE

1.4.1. CONTEXT OF STUDY

1.4.1.1 Planning context

This study applied to the Republic of Gabon, a forest-covered country roughly the size of Italy (26.7M ha) on the west coast of Central Africa (Figure 2). Gabon is characterized by a small population (1.6M) with the highest rate of urbanization (86%) in sub-Saharan Africa (United Nations 2012), leaving large expanses of rainforest largely uninhabited and relatively intact – closed canopy forest covers 81% of the country (Saatchi et al. 2011), with some of the strongest remaining populations of forest wildlife in Africa (Walsh et al. 2008, Maisels et al. 2013). Floristically, Gabon is part of the Guineo-Congolian regional center of endemism (White 1983), with the richest lowland plant species density (species per plot) documented on the continent (Breteler 1996), as well as a diverse range of non-forest vegetation types such as grasslands, shrublands and prairies (Walters et al. 2012). With some of the largest lagoon and wetland systems on the continent, and a marine area that mirrors its land area in size, Gabon also harbors the most important nesting beaches for leatherback sea turtles in the world (Witt et al. 2009), important breeding habitat for migratory whale populations (de Boer 2010), and a diversity of continental shelf and deepwater habitat types.

Figure 2. Gabon is located on the west coast of equatorial Africa.



Gabon's economy is based on natural resource production – primarily oil, but also mining and timber. The country is currently engaged in major reform programs to increase industrial growth, with the goal of achieving 'emerging economy' status by 2025 (raising GDP from 11B USD to over 20B USD (Bongo Ondimba 2011)), and doing so in a sustainable manner that maintains its green reputation (Oxford Business Group 2011). Like many tropical countries, Gabon increasingly faces important new

investments and demands from many parts of the world, for agricultural land, raw natural resources and finished products, bringing a host of land use opportunities, pressures, questions and decisions to the country and its communities, often for the first time. Indeed, land is central to livelihoods and culture in Gabon, with the highly-urbanized population still maintaining considerable ties to village life, geographically-based ethnic identity, and natural resource production in rural areas – the country's growth and stability may depend in large part on how land and water resources are secured, used and managed. Part of the country's national reform program therefore aims to prepare and implement a national land use plan to help plan for, prioritize, and coordinate land use and growth across sectors (Republique Gabonaise 2012).

1.4.1.2 Planning application

This thesis constitutes part of a greater body of work undertaken during its course, in collaboration with the government of Gabon, private operators and the NGO community, towards developing various aspects of conservation prioritization and spatial planning in Gabon, ultimately assisting the development of the national land use planning process. Indeed, work presented in this thesis was developed at a time when the framing and conceptualization of the national land use planning process was crystallizing within the government – being able to show proof of concept of the systematic approach applied to conservation may have lent confidence in adopting a rational spatial planning approach for other sectors. This systematic approach, adapted to fit the social and political context, currently serves as the base for the National Land Use Plan today, which includes ten sectors: oil, mining, logging, agriculture, fisheries, infrastructure, energy and water, settlement areas, conservation and defense.

1.4.2 RESEARCH AIMS AND OBJECTIVES

The overall goal of this applied research was to investigate how a science-based approach to conservation and land-use planning could support, improve and possibly change the course of management action or decision, particularly in a data-poor tropical rainforest context. To achieve this goal, I set three objectives that respond to the challenges identified in Table 3:

1. Characterize species, habitat, and land use features for conservation assessment and spatial planning, creating a new information base (Challenge 1)
2. Define priority species, habitats and locations for conservation and management action (Challenge 2, 4)
3. Demonstrate a structured but adaptable decision-support process for management decisions (Challenge 2, 3)

1.4.2.1 Objective 1: Characterize species, habitat and land use features for conservation assessment and spatial planning

At the outset of this study, Gabon lacked most basic data layers needed for national spatial planning – there were almost no maps of vegetation types, continuous river coverages, faunal distributions, or data available on land uses other than logging permits, roads and protected areas, at scales relevant to national planning. Lack of fundamental information was a barrier to planning and therefore implementing better environmental management. To address this problem, I created a national-scale information base that could support conservation assessment and spatial planning in

Gabon, beyond this study. Working with a range of experts, a wealth of information was harnessed into (1) a biodiversity database, which has spatial and non-spatial components (presented in Chapters 2 and 3, and used in all chapters), and (2) a national spatial land use database (presented in Chapter 2, and used mainly in Chapter 4). Together, these datasets set a new starting point for national-level conservation and land use planning in Gabon.

1.4.2.2 Objective 2: Define priorities for conservation and management action

Like many places in the world, Gabon's protected area network and environmental management systems were not founded in a rigorous systematic approach that might allow for defensible identification of conservation priorities. As a result, conservation decisions are often opportunistic, reactionary, and lack coherence and coordination among different groups of the conservation sector itself. I applied well-developed methods from systematic conservation planning to define priorities for Gabon in terms of vertebrate species (Chapter 3) and habitat types (Chapter 2) to protect, and locations that merit conservation or management attention (Chapters 2-4). In addition, I developed a method to define priority locations for field surveys (Chapter 5) and identified management actions needed at particular sites to conserve the species they hold (Chapter 4).

1.4.2.3 Objective 3: Demonstrate a structured decision-support process for management decisions

Increasingly, governments are required to employ greater transparency and accountability in environmental management and natural resource use (McDonald-Madden et al. 2009). Countries in Sub-Saharan Africa perform especially poorly in issues related to transparency and natural resource governance. Structured decision-making can help increase both the rational basis for a decision and its reporting. In this thesis, I demonstrate how structured decision-support can be applied to environmental planning in this Central African context, as an example of what could be implemented for conservation, or perhaps developed later for sectors beyond conservation. This demonstration is most illustrated in Chapters 3 and 4, but used in all chapters.

1.4.3 THESIS STRUCTURE AND CONTENT

This thesis consists of six chapters describing work performed as part of this thesis, and one appendix highlighting other work published during its course. Chapters 2-5 are prepared for scientific journals.

Table 4. Thesis chapters and content

<p><u>Chapter 1</u> General Introduction</p>	<ul style="list-style-type: none"> • Explains context and rationale for study • Provides background on systematic conservation planning and spatial prioritization • Describes major themes to which this thesis contributes • Identifies objectives, which are addressed in chapters 2-5
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<p><u>Chapter 2</u></p> <p>The lay of the land: Mapping land units, land uses, and conservation gaps in Gabon</p>	<ul style="list-style-type: none"> • Maps major biogeophysical land units across the country • Presents first compilation of formal-sector land uses in Gabon • Measures conservation progress by setting representation targets for land units and assessing gaps in protection • Addresses gaps pragmatically with the National Parks Agency • Identifies a subset of land units requiring new efforts to protect • Prepared for submission to <i>Ecological Applications</i> as a Communication piece, thus divided between main text and supplementary material to respect space limits.
<p><u>Chapter 3</u></p> <p>Putting biodiversity on the map: Conservation priorities in Gabon</p>	<ul style="list-style-type: none"> • Assesses conservation status of terrestrial vertebrates • Defines priority species to manage in Gabon • Maps priority species distributions • Sets targets, assesses coverage and gaps in protected areas • Identifies an optimal set of sites that complement existing parks to meet targets for species and habitat types (land units) • Provides an important information base for future planning efforts • Prepared for submission to <i>PLOS ONE</i>. Extensive supplementary material documents detailed methods and data.
<p><u>Chapter 4</u></p> <p>Building nature into industrial development in Gabon, Central Africa</p>	<ul style="list-style-type: none"> • Examines the feasibility of protecting critical sites identified in Chapter 3, given existing land uses identified in Chapter 2 • Describes specific management actions needed to maintain priority species and habitat types at particular locations, assuming many areas would need to remain in production • This work is serving the base for discussions in Gabon, which will lead to publication
<p><u>Chapter 5</u></p> <p>Targeting field</p>	<ul style="list-style-type: none"> • Develops a new method for targeting field surveys to support protected area decisions • Accounts for uncertainty in species' distributions prior

surveys to reduce uncertainty in protected area priorities	<p>to survey, and clarifies the decision that would be taken on <i>a priori</i> information alone</p> <ul style="list-style-type: none"> • Identifies sites where gaining new information might challenge this <i>a priori</i> decision • Identifies sites where investing in field surveys might reveal new options to achieve conservation targets efficiently • Although presented last, this chapter was actually prepared first and thus uses preliminary data, while the process of data compilation for Chapters 2-4 was being conducted. • Prepared for submission to <i>Journal of Applied Ecology</i>.
<p><u>Chapter 6</u> General Discussion</p>	<ul style="list-style-type: none"> • Outlines key findings • Explains importance of findings and application to conservation in Gabon today • Recognizes how the work relates to other literature • Acknowledges limitations and identifies potential future research
<p><u>Appendix 1</u></p>	<ul style="list-style-type: none"> • Other peer-reviewed publications related to Central African ecology and conservation: <ul style="list-style-type: none"> ○ Buij et al. (2007) ○ Croes et al. (2007) ○ Laurance et al. (2008) ○ Kolowski et al. (2010) ○ Anthony et al. (2012) ○ Bahaa-el-din et al. (2013) ○ Abernethy et al. (2013) ○ Eggert et al. (2014)

Chapter 2

THE LAY OF THE LAND: MAPPING LAND UNITS AND LAND USES TO ASSESS CONSERVATION GAPS IN GABON¹

2.1 ABSTRACT

Land units are the biogeophysical building blocks that structure the landscape and maintain the ecological functions that support human and natural systems.

Conservation progress is often measured by how well these building blocks are protected, yet accurate maps of land units are often incomplete or altogether absent.

We identified 30 land units characterizing the country of Gabon, based on geology, topography, climate, hydrology and land cover. The new map reveals that many land units are restricted to relatively small areas. We then compiled a national dataset of six

¹Manuscript in preparation. Potential authors include: Michelle Lee, Tariq Stévant, Jean Pierre Vande weghe, Daniel Segan, Chris Wilks, Hugh Possingham, Simon Lewis, Edward Game, David Macdonald. Statement of authorship: ML designed the study, collected and analysed data; TS, JPV, CW, DS, SL contributed data and/or participated in mapping; DS, EG, HP advised with spatial analysis; HP, DM oversaw the work; ML wrote the first draft document and all authors contributed to revisions. In addition, land use data was provided by Landry Olouchy Essongue (Ministry of Hydrocarbons), Yvon Oterigui (Ministry of Mines), Pierre Migolet (Ministry of Waters and Forestry), Parfait Ndong (National Parks Agency), and Isaac Manu, Gagan Gupta and Gérard Malaval (private sector), facilitated by Etienne Massard Makaga and Pacôme Moubelet-Boubeya as part of the National Land Use Plan. Buffer zone analysis was done with Lee White, Malcolm Starkey and Stephan Le-duc Yeno on behalf of the National Parks Agency. Miguel Leal and Josie Carwardine provided useful early discussions about land unit mapping.

land uses – oil extraction, mineral extraction, industrial agriculture, logging, national parks and partly-protected areas – to assess how land units are allocated by use. We discovered that many land uses are also spatially restricted, and highlight the conservation implications of these uses occurring on rare land units in particular. Setting representation targets for conservation, we found that three-quarters of units have conservation gaps in national parks, and several are missed completely. Most of these gaps could be met on a relatively small land area – for example, the ten smallest gaps could be met on 1% of Gabon’s land – but some would require larger surfaces. By accounting for land units located in existing partly-protected areas and proposed national park buffer zones, gaps could be reduced to one-third of units, but protection levels in these areas would need to be increased. We highlight 10 units that lie outside of these areas, most of them rare and easy to overlook by development: these relatively discrete units require new protection mechanisms for Gabon to achieve these conservation targets. As land use opportunities and pressures grow in Central Africa – still one of the world’s least-charted regions – it is important to build an information base to first get the lay of the land across sectors and resources, and use it to guide land use decisions.

2.2 INTRODUCTION

Governments face important decisions about how to allocate their finite land and water resources to meet growing demands for food, energy and raw materials, while ensuring the security of ecosystem services such as freshwater provision and biodiversity conservation. Many countries are poorly prepared to make informed decisions about

land allocation, in part because they lack a strategic spatial planning framework that helps clarify the future they are planning for in geographic space, assess different scenarios, and explore the trade-offs of different decisions (Albrechts 2004). Spatial planning – the deliberate political and social process of designing use of the landscape for particular purposes (Harris 1989) – is becoming increasingly important to reconcile multiple goals on a limited extent of land. A critical early step in spatial planning is to understand and characterize the land resource base and its allocation among different uses – to get the lay of the land – as a starting point from which to move towards more optimal solutions.

One approach to characterizing the land resource base is to map its land units, relatively homogeneous land areas which represent the biogeophysical building blocks that structure the landscape and underpin ecological functions supporting human and natural systems (Bailey 1983, Cowling and Heijnis 2001, Sayre et al. 2014). The purpose of their mapping is to represent the key elements and processes regulating this structure and function, to help decision-makers manage land resources better (Lugo et al. 1999). Hence, delineating land units can be a critical step for countries wishing to improve land allocation decisions. Within systematic conservation planning, ecological land units are frequently used as spatial surrogates for our incomplete knowledge of the distribution of biodiversity (Grantham et al. 2010). Land units have also been proposed as a robust base for planning the conservation of ecological communities under climate change (Anderson and Ferree 2010, Game et al. 2011b), and are increasingly used to set national conservation targets and measure progress towards those goals (McDonald-Madden et al. 2009).

Delineating land units is not, however, straightforward; their definition depends on the environmental context, data available, and planning problem at hand (Loveland and Merchant 2004, Mackey et al. 2008). Different methods produce different results (Hazeu et al. 2011, Kent and Carmel 2011) and no single 'best' method exists (Olson et al. 2001, Bryan 2006). However, we consider that classifications should be grounded in: 1) a strong conceptual framework based on scientific theory (Hazeu et al. 2011); 2) a solid, field-based understanding of the geographic and ecological systems being planned for (Grantham et al. 2010); and 3) a consistent, reproducible, transparent process of synthesizing quantitative datasets to reflect these patterns (Lugo et al. 1999, Leathwick et al. 2003).

We develop a novel characterization of land units for Gabon, an emerging economy in Central Africa that is currently developing a National Land Use Plan to coordinate broad-scale zoning across sectors (Republique Gabonaise 2012). Our analysis supports this national planning process in three ways. First, we characterize the country's land units, based on the permanence of major environmental features over time, from geology to topography, climate, hydrology and finally land cover. In doing so, we develop the first synthetic land resource map as a common currency for discussions about national spatial planning. Second, we map current major formal-sector land uses, from mining to national parks, and make the allocation of the country's land units to these major production and protection uses explicit. Finally, as an example of the kind of application that is possible, we set targets for the amount of

each land unit to conserve, and assess their coverage in existing protected areas, thereby also revealing the most important gaps in protection.

2.3 METHODS

2.3.1. CONTEXT: THE REPUBLIC OF GABON

Situated on the west coast of equatorial Africa (Fig. 1 inset), Gabon's sedimentary basin extends inland to meet three low-lying mountain zones before rolling out to a broad interior plateau. The plateau and mountain zones are comprised of Archaean basement geology overlain by later Palaeo- and Neoproterozoic formations. The sedimentary geology consists of more recent Quaternary sandstone and alluvial or colluvial deposits (Chevallier et al. 2002). Gabon is primarily drained by the Ogooué River, a vast dendritic network that provides extensive water, food, and transportation services to most of the country, before emptying to the Atlantic through an intricate wetland delta of lakes, lagoons and braided rivers. With a small (~1.6M people), highly-urbanized population (86%; United Nations 2013), Gabon has the highest rate of forest surface per capita in Africa (Chevalier 2009), with large areas almost uninhabited. Lowland rainforest is estimated to cover 88% of the country (Fichet et al. 2012), the rest mostly edaphic and secondary vegetation, including fire-maintained savanna. In Gabon, habitat types are often simply described by their primary vegetative cover as either 'forest' or 'savanna', despite spanning a diversity of ecological gradients and histories of human use that yield great habitat differentiation (Maniatis et al. 2011, Walters et al. 2012, Dauby et al. 2014).

Five sectors – oil, mining, agriculture, logging and conservation – dominate formal-sector land allocation today. Gabon’s economy is based on oil production, which accounted for >50% of GDP in 2010, making it the fourth largest producer in Sub-Saharan Africa (Oxford Business Group 2011). Oil is produced both onshore and offshore; we estimate that the top handful of most productive onshore permits over the years have occupied a fraction (~0.1%) of land, reducing the need for activities requiring large-scale forest clearance like agriculture. Mining has historically focused on uranium and manganese, with most of the production coming from permits occupying ~0.5% of the territory. Mining currently accounts for about 4.4% of GDP (Oxford Business Group 2011). Industrial agriculture, originally developed by the State and now privatized, has primarily occupied plantations covering ~0.7% of land. The agriculture sector contributed 4.1% of GDP in 2008 (Oxford Business Group 2011). In contrast to these small allocations, industrial logging has expanded steadily since post-WWI, with permits covering nearly half of the territory in 2007 (47%; World Resources Institute 2009). However, harvest is highly-selective and limited by logistical and market access, accounting for 4.5% of GDP in 2009 (Oxford Business Group 2011). Land protection laws, introduced in 1955, were designed not for “conservation” in today’s sense of the word, but to protect certain wildlife populations and timber stocks so that they could regenerate to supply hunting and harvest activities (Christy et al. 2003). Several of these historic partly-protected areas still exist today, often on land also used for oil and logging production. The first fully-protected national parks were established in 2002, covering 11% of the country.

2.3.2 MAP CONSTRUCTION

We applied ecological theory to our collective knowledge of Gabon's terrestrial systems to characterize its land units. Land units were based on a hierarchical conceptual model of the main factors driving ecosystem structure in space and time (Bailey 1987, Willis and Whittaker 2002, O'Brien 2006), specifically geology, topography, rainfall, hydrology and land cover. The data used to represent these features and the rationale for their classification is presented in Table 1, and processing methods detailed in Appendix 1. In order of permanence, we first represented macroscale dynamics – the outcomes of broad-scale geological, topographic, and climatological processes that give rise to biogeographic patterns over periods >10,000 years – by intersecting geological types, mountain zones, and regional rainfall influences. We then represented mesoscale dynamics, and the outcome of processes which give rise to features like vegetation types over ~100s to 1000s of years, by adding information on terrain ruggedness, surface water and land cover. The combination of these macroscale and mesoscale patterns provided a level of delineation relevant to national-scale analysis. The resulting classification provides a base upon which microscale dynamics – patterns like edaphics which influence habitat patches over 10s to 100s of years – could be incorporated in future studies.

Table 1. Data, sources, definitions, classifications, and rationales used to build land units. Detailed information in Appendix 1.

	Rationale for classification	Classes	Definition	Data source
Geology	6 classes with known influence on drainage or geomorphology (Chevallier et al. 2002), water conductivity (Ibanez et al. 2007), plant species composition (Louis and Fontès 1996)	1. Alluvium (young fluvial deposits)	A (source map code)	Carte Géologique de la République Gabonaise (Thomas et al. 2000)
		2. Well-drained clay-rich & sands, coastal basin	PLc	
		3. Sandstones & well-drained sands, Batéké Plateaux	PNb	
		4. The rest of the coastal sedimentary basin	Ca-Cz, Em, Jm, Ma, Mn, PEm, Pra	
		5. Sandstone, limestone containing dolomite, calcite	Nsc1-4	
		6. All other geological terranes	All other codes	
Topography	2 mountain zones characterized by different plant species (Sosef et al. 2004)	1. Monts de Cristal - Massif du Chaillu	Contiguous rugged areas & 500m contour line	SRTM dataset (Jarvis et al. 2008)
		2. Monts Doudou - Mayumbe	Areas >300m	
	2 types of terrain. Ruggedness (the variability of relief) influences species composition (Leal 2004)	1. Flat	Std deviation of elevation in 1km radius < 0-23	
		2. Rugged	Std deviation of elevation in 1km radius \geq 23	
Rainfa	4 climatic zones based on regional influences on amount of	1. Hyperhumid influence, north coast	Annual rainfall >2500mm	WorldClim 1.4 dataset (Hijmans et al. 2005), Gabon

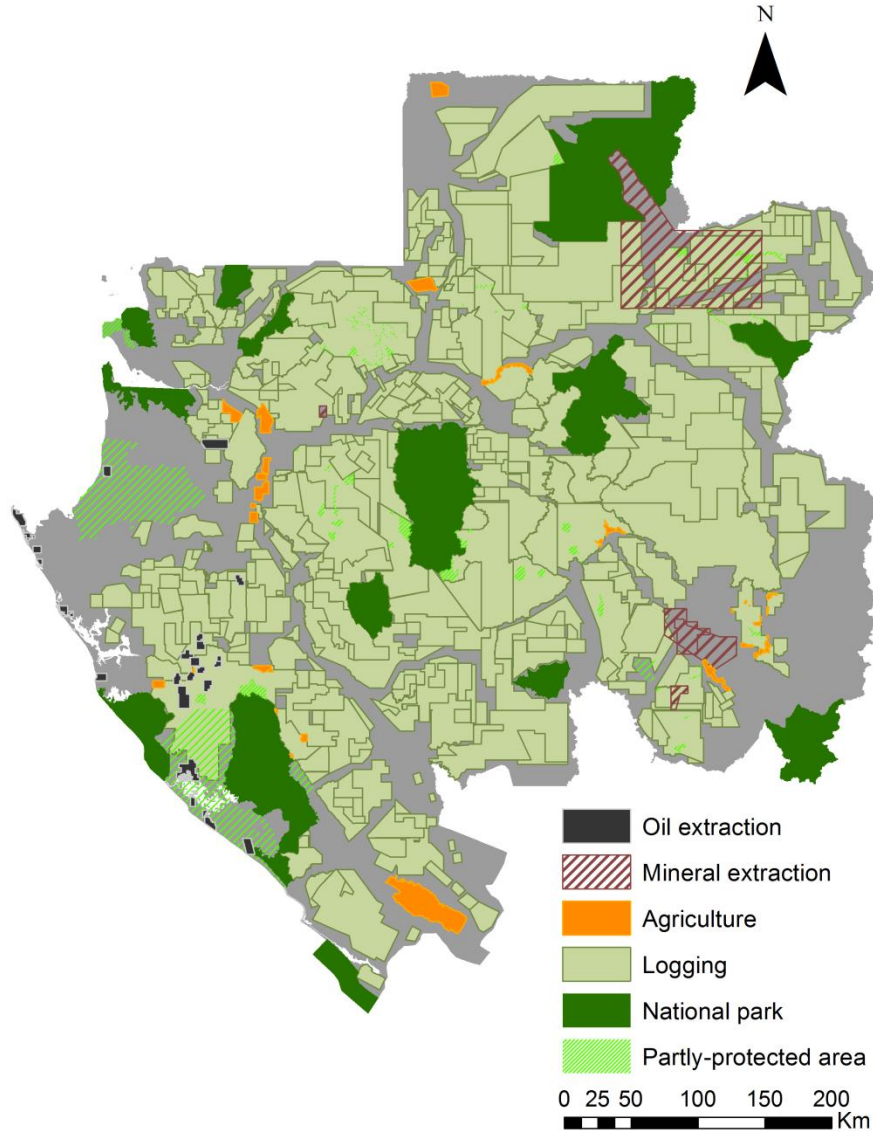
	rainfall and duration of dry season (Doumenge et al. 2001)	2. Continental influence, 2 short dry seasons/yr	<200mm at least 8 months/year	National Meteorological Service dataset (unpublished data)
		3. Austral influence, 1 long & 1 short dry season/yr	<200mm at least 8 months/year	
		4. All other areas, humid	All other areas	
Hydrology	3 surface water formations that affect connectivity in the landscape	1. Lakes	Waterbodies >10ha or 200m wide	National surface water dataset (available at World Resources Institute 2009), Aerial navigation maps (US Army Map Service 1966)
		2. Lagoons		
		3. Wide stretches of large rivers		
	3 types of basin geomorphology, which affects the flood regime, habitats, and access (Bwangoy et al. 2010)	1. Broad river basins	Std deviation of elev/catchment >38	Hydrosheds SRTM dataset (Lehner et al. 2008)
		2. Narrow river basins	Std deviation of elev/catchment 38.0-149.5	
		3. Main river basins	Std deviation of elev/catchment >149.5	
Land cover	3 types of non-forested land cover, reflecting restricted habitat types that can be distinguished from the forest domain by distinctive vegetation	1. Predominantly grass or shrub	>50% non-forest per pixel	MODIS Vegetation Continuous Fields (Hansen et al. 2006)
		2. Mangrove	Digitized from government map	Formations Végétales de la Première Zone Forestière du Gabon (Tecsult 1998)
		3. Submontane	Increasing elevation with distance to coast: >600m Doudou-Mayombe, >733m core Chaillu, >758m Cristal-northern Chaillu, >785m Mitzic-Oyem, >816m Belinga, >688m Plateaux Batéké	SRTM dataset (Senterre and Lejoly 2005, Jarvis et al. 2008)

2.3.3 EVALUATING LAND ALLOCATION

2.3.3.1 Land use data

We compiled formal-sector permit data from government ministries, agencies and private companies in October 2011, as pilot project for the National Land Use Plan. Six land use types were used in this study (Appendix 2): 1) oil extraction permits; 2) mineral extraction permits; 3) agriculture permits (oil palm, rubber, sugarcane, cattle, and agricultural set-asides within logging concessions); 4) logging permits; 5) national parks; and 6) partly-protected areas (Figure 1). Partly-protected areas included lands designated for special management, such as the Presidential Reserve, faunal reserves, hunting domains, arboretum, and conservation set-asides within logging concessions, but these areas can also be used for other activities such as oil development, settlement, tourism, or other activities. For the purpose of this study, we assumed these six uses were spatially-independent and any overlap was handled by assigning priority in the order listed above, which roughly approximates the order of economic value.

Figure 1. Six major land uses considered in this study.



2.3.3.2 Conservation representation and bias

We overlaid a map of these uses on the land units to assess how land units were distributed, and measured representation, gaps and bias in protection (Scott et al. 1993). To measure representation and gaps, we set targets that were scaled so that a greater proportion of smaller

units would be required for conservation, and a greater proportion of larger units would be available for production, following Ardon et al. (2008):

$$x_p / y_p \sim (x_t / y_t)^{0.5}$$

where x was the area of the smallest land unit, y was the area of a different land unit, p = protected, t = total, and the proportion set was relative to protecting 80% of x . Smaller units were therefore assigned higher proportional targets, on the basis that conserving functional properties of smaller units may require protecting a greater proportion of its area (Table 2, Appendix 3).

We also assessed bias in protection using the Gini coefficient (Gini 1921), a measure of inequality used widely in economics and recently applied to land use (Zheng et al. 2013) and conservation (Barr et al. 2011, Barr and Possingham 2013). Assessing protection bias is important, since globally, protected areas have tended to be located in places with low demand for development, thereby missing species and habitats found primarily in high-demand areas (Pressey et al. 2002). Equitable protection would assure that small or rare units are proportionally as well protected as larger ones, and that large units are not dominating the protected area system. We calculated the adapted Gini coefficient as described in Barr et al. (2011) for protected lands and for scaled targets, to ensure that the targets we proposed would improve not only representation but also protection equality. Gini coefficient values range from 0 (perfect equality) to 100 (complete inequality). Gini coefficients were calculated in *r* (R Core Team 2013) and interpreted after Zheng et al. (2013): <20 = equal; 20-30 = relatively equal; 30-40 = reasonable equality; 40-50 = relatively unequal; >50 = unequal (Appendix 4).

2.4 RESULTS

2.4.1 LAND UNIT MAP

Our analysis produced 30 land units: 19 geophysical types covered in forest spanning 89.8% of Gabon, ten in grass or shrub covering 9.0%, and surface water over 1.1% (Figure 2, Table 2, Appendix 5; land unit labels in [brackets]). The largest unit was flat forest of the central inland plateau [22], covering one-fifth of the country; the smallest was rugged, well-drained grassland of the central coastal plateau, covering 0.1% [6]. Most units were small: 11 units covered <1% of Gabon (hereafter 'rare'), 13 covered 1-3%, and six were more common, covering >3%. Of the rare units, four were forested, seven were grass/shrub, and most occurred in the coastal margin. Landscape heterogeneity (the number of units) declined west to east, reflecting strong ocean and topographic gradients from the coast, inland.

Figure 2. Land units describing major biogeophysical gradients across Gabon

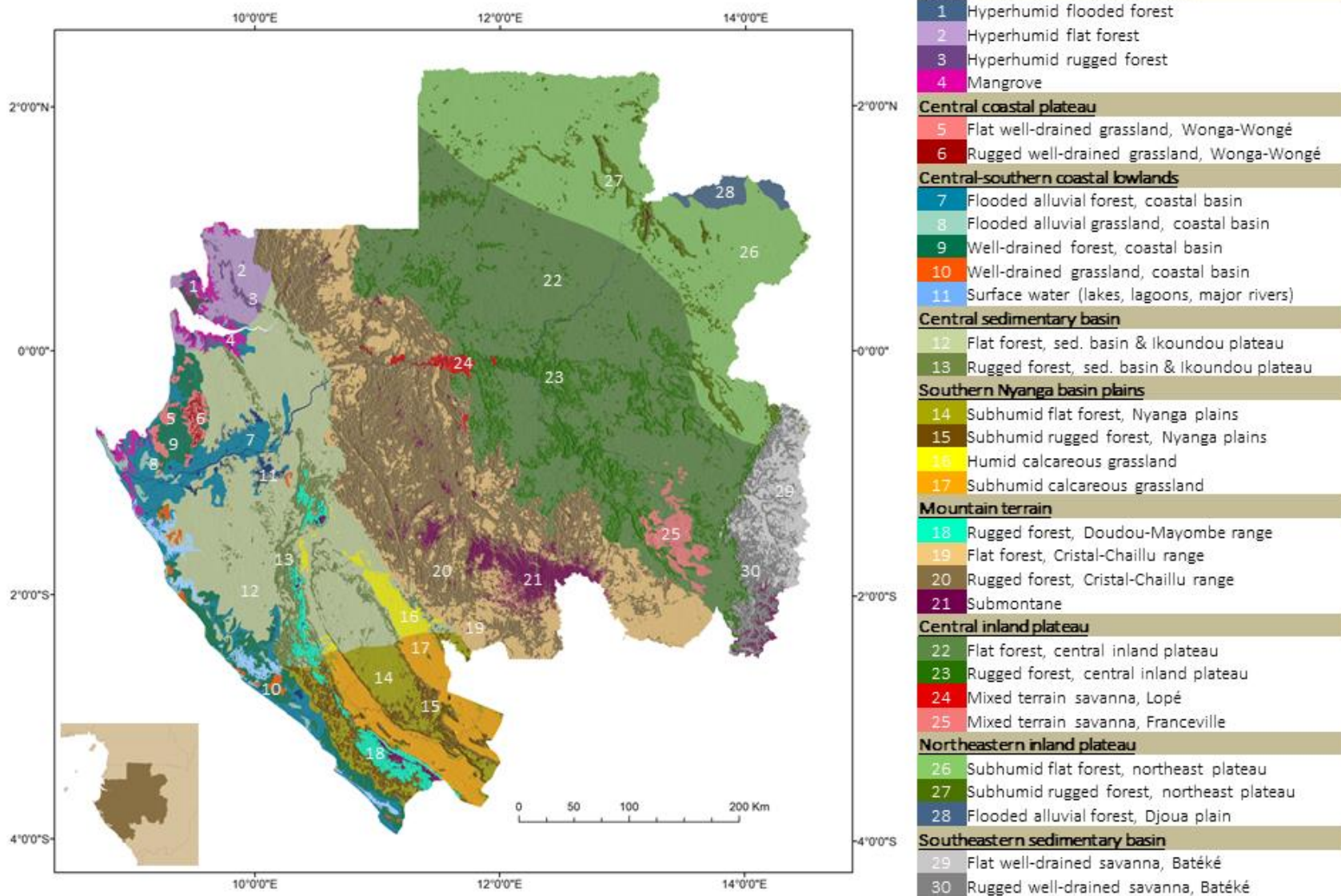


Table 2. The distribution of land units across land uses, conservation targets and gaps.

				<u>Oil</u>		<u>Mining</u>		<u>Agriculture</u>		<u>Logging</u>		<u>National Park</u>	
		<u>Total km²</u>	<u>% of country</u>	<u>km²</u>	<u>% of type</u>	<u>km²</u>	<u>% of type</u>	<u>km²</u>	<u>% of type</u>	<u>km²</u>	<u>% of type</u>	<u>km²</u>	<u>% of type</u>
Northern coastal sedimentary basin													
1	Hyperhumid flooded forest	397	0.15%	-	-	-	-	-	-	37	9.28%	106	26.69%
2	Hyperhumid flat forest	3,974	1.50%	-	-	-	-	-	-	2,182	54.89%	112	2.83%
3	Hyperhumid rugged forest	357	0.13%	-	-	-	-	-	-	188	52.76%	-	-
4	Mangrove	1,815	0.68%	58	3.22%	-	-	-	-	30	1.66%	751	41.36%
Central coastal plateau													
5	Flat well-drained grassland, Wonga-Wongé	1,037	0.39%	1	0.14%	-	-	-	-	-	-	-	-
6	Rugged well-drained grassland, Wonga-Wongé	316	0.12%	0.31	0.10%	-	-	-	-	-	-	-	-
Central-southern coastal lowlands													
7	Flooded alluvial forest, coastal basin	7,076	2.67%	219	3.10%	-	-	-	-	1,389	19.63%	586	8.29%
8	Flooded alluvial grassland, coastal basin	846	0.32%	113	13.33%	-	-	-	-	5	0.54%	53	6.26%
9	Well-drained forest, coastal basin	5,321	2.01%	172	3.24%	-	-	-	-	664	12.49%	809	15.21%
10	Well-drained grassland, coastal basin	564	0.21%	37	6.47%	-	-	-	-	130	23.02%	50	8.87%
11	Surface water (lakes, lagoons, major rivers)	2,937	1.11%	92	3.14%	29	0.99%	9	0.32%	96	3.25%	289	9.83%
Central sedimentary basin													
12	Flat forest, sed. basin & Ikoundou plateau	30,807	11.62%	644	2.09%	-	-	580	1.88%	18,357	59.59%	1,186	3.85%
13	Rugged forest, sed. basin & Ikoundou plateau	5,568	2.10%	7	0.12%	-	-	44	0.79%	3,023	54.29%	1,332	23.92%
Southern Nyanga basin plains													
14	Subhumid flat forest, Nyanga plains	5,541	2.09%	1	0.02%	-	-	7	0.12%	3,638	65.66%	333	6.00%
15	Subhumid rugged forest, Nyanga plains	4,444	1.68%	-	-	-	-	17	0.38%	2,429	54.65%	544	12.24%
16	Humid calcareous grassland	1,854	0.70%	-	-	-	-	26	1.41%	324	17.48%	27	1.46%
17	Subhumid calcareous grassland	6,790	2.56%	-	-	-	-	960	14.14%	466	6.87%	232	3.41%
Mountain terrain													
18	Rugged forest, Doudou-Mayombe range	2,793	1.1%	-	-	-	-	6	0.23%	1,416	50.71%	779	27.89%
19	Flat forest, Cristal-Chaillu range	17,342	6.5%	-	-	136	0.78%	-	-	12,063	69.56%	616	3.55%
20	Rugged forest, Cristal-Chaillu range	35,148	13.3%	-	-	50	0.14%	-	-	25,202	71.70%	5,571	15.85%
21	Submontane	5,182	2.0%	-	-	67	1.29%	-	-	2,648	51.11%	1,158	22.35%

		<u>Protected Area</u>		<u>Other land</u>		<u>Prop. Buffer Zone</u>		<u>Target</u>		<u>Target MET & Gaps</u>		
		<u>km²</u>	<u>% of type</u>	<u>km²</u>	<u>% of type</u>	<u>km²</u>	<u>% of type</u>	<u>% Target</u>	<u>Target km²</u>	<u>Park gaps km²</u>	<u>Park&PA gaps km²</u>	<u>Park,PA&Bzone gaps km²</u>
<u>Northern coastal sedimentary basin</u>												
1	Hyperhumid flooded forest	30	7.48%	224	56.55%	126	31.86%	71	283	177	148	21
2	Hyperhumid flat forest	104	2.62%	1,576	39.65%	1,110	27.93%	23	897	784	680	MET
3	Hyperhumid rugged forest	-	-	169	47.24%	120	33.57%	75	269	269	269	149
4	Mangrove	35	1.91%	941	51.86%	192	10.57%	33	606	MET	MET	MET
<u>Central coastal plateau</u>												
5	Flat well-drained grassland, Wonga-Wongé	894	86.19%	142	13.67%	-	-	44	458	458	MET	MET
6	Rugged well-drained grassland, Wonga-Wongé	299	94.37%	18	5.53%	-	-	80	253	253	MET	MET
<u>Central-southern coastal lowlands</u>												
7	Flooded alluvial forest, coastal basin	1,016	14.36%	3,866	54.63%	490	6.93%	17	1196	610	MET	MET
8	Flooded alluvial grassland, coastal basin	84	9.89%	592	69.97%	28	3.32%	49	414	361	277	249
9	Well-drained forest, coastal basin	2,170	40.79%	1,505	28.28%	670	12.59%	19	1037	228	MET	MET
10	Well-drained grassland, coastal basin	170	30.05%	178	31.59%	23	4.11%	60	338	288	118	95
11	Surface water (lakes, lagoons, major rivers)	470	15.99%	1,953	66.48%	327	11.13%	26	771	482	12	MET
<u>Central sedimentary basin</u>												
12	Flat forest, sed. basin & Ikoundou plateau	1,685	5.47%	8,354	27.12%	5,616	18.23%	8	2496	1310	MET	MET
13	Rugged forest, sed. basin & Ikoundou plateau	108	1.94%	1,055	18.94%	453	8.13%	19	1061	MET	MET	MET
<u>Southern Nyanga basin plains</u>												
14	Subhumid flat forest, Nyanga plains	109	1.97%	1,453	26.22%	353	6.37%	19	1059	726	617	264
15	Subhumid rugged forest, Nyanga plains	2	0.04%	1,453	32.69%	409	9.20%	21	948	404	402	MET
16	Humid calcareous grassland	56	3.00%	1,421	76.65%	8	0.43%	33	612	585	530	522
17	Subhumid calcareous grassland	84	1.23%	5,048	74.35%	795	11.71%	17	1172	940	856	61
<u>Mountain terrain</u>												
18	Rugged forest, Doudou-Mayombe range	74	2.65%	517	18.51%	59	2.11%	27	752	MET	MET	MET
19	Flat forest, Cristal-Chaillu range	244	1.41%	4,283	24.70%	2,915	16.81%	11	1873	1257	1013	MET
20	Rugged forest, Cristal-Chaillu range	634	1.80%	3,691	10.50%	6,819	19.40%	8	2666	MET	MET	MET
21	Submontane	100	1.93%	1,208	23.32%	1,116	21.54%	20	1024	MET	MET	MET

		Total km ²	% of country	Oil		Mining		Agriculture		Logging		National Park	
				km ²	% of type	km ²	% of type	km ²	% of type	km ²	% of type	km ²	% of type
Central inland plateau													
22	Flat forest, central inland plateau	53,591	20.2%	-	-	938	1.75%	367	0.68%	39,317	73.36%	2,856	5.33%
23	Rugged forest, central inland plateau	16,192	6.1%	-	-	325	2.01%	68	0.42%	12,323	76.11%	962	5.94%
24	Mixed terrain savanna, Lopé	681	0.26%	-	-	-	-	-	-	93	13.60%	370	54.35%
25	Mixed terrain savanna, Franceville	2,121	0.80%	-	-	780	36.77%	68	3.18%	62	2.92%	-	-
Northeastern inland plateau													
26	Subhumid flat forest, northeast plateau	36,899	13.9%	-	-	4,719	12.79%	123	0.33%	14,926	40.45%	7,992	21.66%
27	Subhumid rugged forest, northeast plateau	4,078	1.5%	-	-	1,439	35.28%	-	-	1,342	32.90%	684	16.77%
28	Flooded alluvial forest, Djoua plain	1,566	0.59%	-	-	156	9.94%	-	-	978	62.44%	-	-
Southeastern sedimentary basin													
29	Flat well-drained savanna, Batéké	4,448	1.7%	-	-	-	-	1	0.02%	81	1.83%	75	1.69%
30	Rugged well-drained savanna, Batéké	5,151	1.9%	-	-	-	-	-	-	265	5.14%	1,255	24.37%

		Protected Area		Other land		Prop. Buffer Zone		Target		Target MET & Gaps		
		km ²	% of type	km ²	% of type	km ²	% of type	% Target	Target km ²	Park gaps km ²	Park&PA gaps km ²	Park,PA&Bzone gaps km ²
Central inland plateau												
22	Flat forest, central inland plateau	224	0.42%	9,890	18.45%	5,706	10.65%	6	3292	436	213	MET
23	Rugged forest, central inland plateau	106	0.66%	2,408	14.87%	1,929	11.91%	11	1810	848	742	MET
24	Mixed terrain savanna, Lopé	-	-	218	32.05%	263	38.65%	55	371	1	1	MET
25	Mixed terrain savanna, Franceville	-	-	1,212	57.13%	63	2.99%	31	655	655	655	592
Northeastern inland plateau												
26	Subhumid flat forest, northeast plateau	285	0.77%	8,855	24.00%	8,874	24.05%	7	2732	MET	MET	MET
27	Subhumid rugged forest, northeast plateau	82	2.02%	531	13.03%	1,142	28.01%	22	908	224	142	MET
28	Flooded alluvial forest, Djoua plain	-	-	433	27.62%	-	-	36	563	563	563	563
Southeastern sedimentary basin												
29	Flat well-drained savanna, Batéké	-	-	4,291	96.46%	32	0.71%	21	949	873	873	842
30	Rugged well-drained savanna, Batéké	-	-	3,631	70.49%	208	4.05%	20	1021	MET	MET	MET

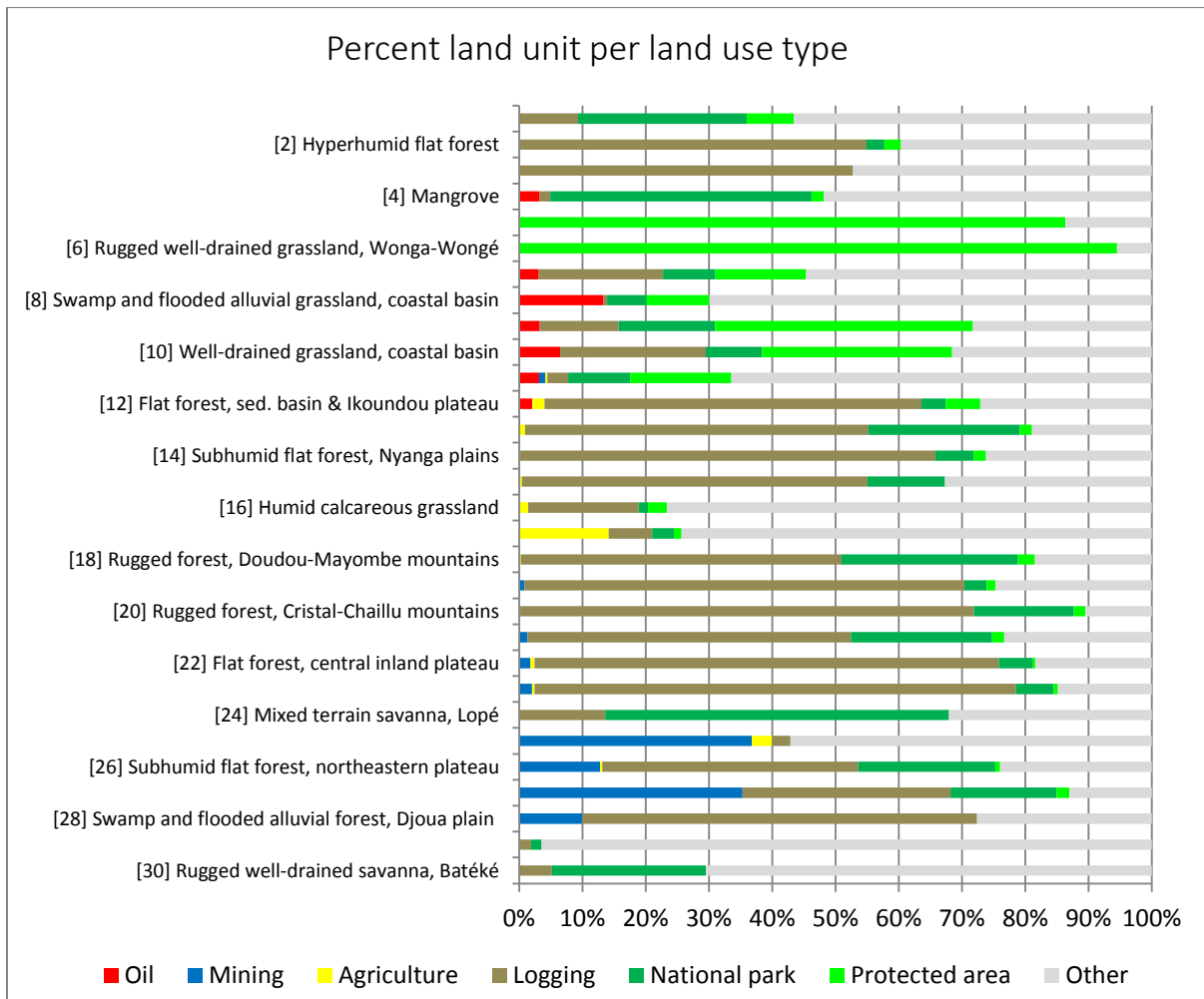
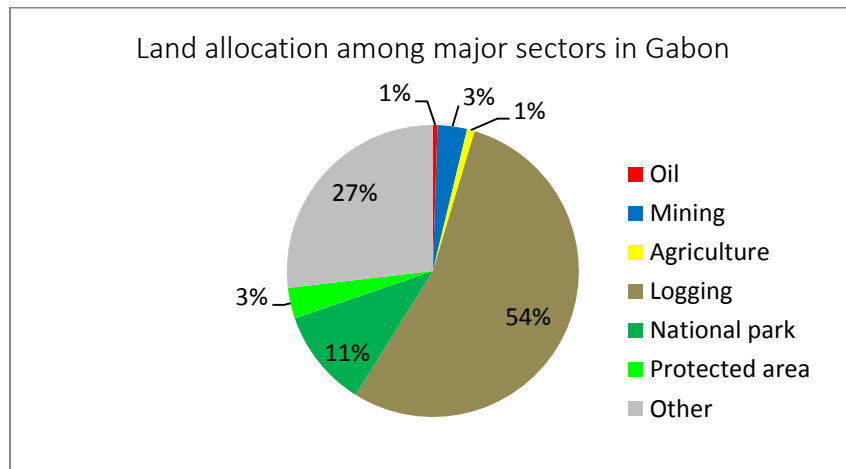
2.4.2 DISTRIBUTION OF LAND UNITS BY USE

The six land use types occupied 72.9% of Gabon (Fig. 3a), with over half the country under logging permits (54.1%), one-tenth in national parks (10.8%), and smaller amounts in partial protection (3.4%), mineral extraction (3.3%), agriculture (0.9%) and oil extraction (0.5%). The remaining quarter (26.8%) was for special use (i.e. military training), prospection (i.e. oil exploration), or informal-sector activities that were beyond the scope of this study.

2.4.2.1 Land units under production use

All production land uses were spatially structured across the landscape and included rare, underprotected units (Table 2, Fig. 3b). Oil and mining were stratified by geology, with oil restricted to the coastal basin and mining to older formations. Oil extraction permits covered only 0.5% of land, but occurred in highly heterogeneous areas, including notable portions of seven units, three of them rare [4, 8, 10]. For example, oil permits held twice the amount of coastal herbaceous wetlands [8] than national parks. Mineral extraction permits included parts of ten units, with a large share of two rare, unprotected units: one-third of inland plateau savannas near Franceville [25] and one-tenth of inland alluvial swamp forest [28]. Agriculture permits were nearly all on flat terrain, absent on flooded or well-drained substrates (i.e. sand) or in hyperhumid conditions, and occupied small parts of two rare, underprotected units [16, 25]. Logging permits were so extensive they touched every unit except two [5, 6], including non-forested units. Of logging permits on terra firma, two-thirds were flat, versus rugged. Logging permits included parts of nine rare units, three of them unprotected [3, 25, 28], including over half of all hyperhumid rugged forest [3] and inland alluvial swamp forest [28].

Figure 3. (a) Land allocation among major sectors. (b) Percent of land unit by land use type.



2.4.2.2 Conservation representation and bias

National parks protected part of 25 of the 30 units, leaving five unprotected (Table 2, Appendix 5). Over half of national park area was comprised of just three units [26, 20, 22], whereas 1.5% of the area consisted of six small units [1, 2, 8, 10, 16, 29]. The Gini coefficient for parks was 55, which is considered unequal. Parks were almost exclusively (94.8%) situated on terra firma (versus flooded) ground, nearly equally flat and rugged. Replication of units in multiple parks was moderate, with nine units found in just one park and eight units in two. Units which cross-cut geographic gradients (such as surface water) were better replicated.

Partly-protected areas were nearly as diverse as parks despite being one-third the size, representing part of 24 units (Table 2). Like parks, partly-protected areas were dominated by a few large units, yet were considerably more biased, with a Gini coefficient of 79. Nearly three-quarters of partly-protected areas were located in the heterogeneous coastal basin.

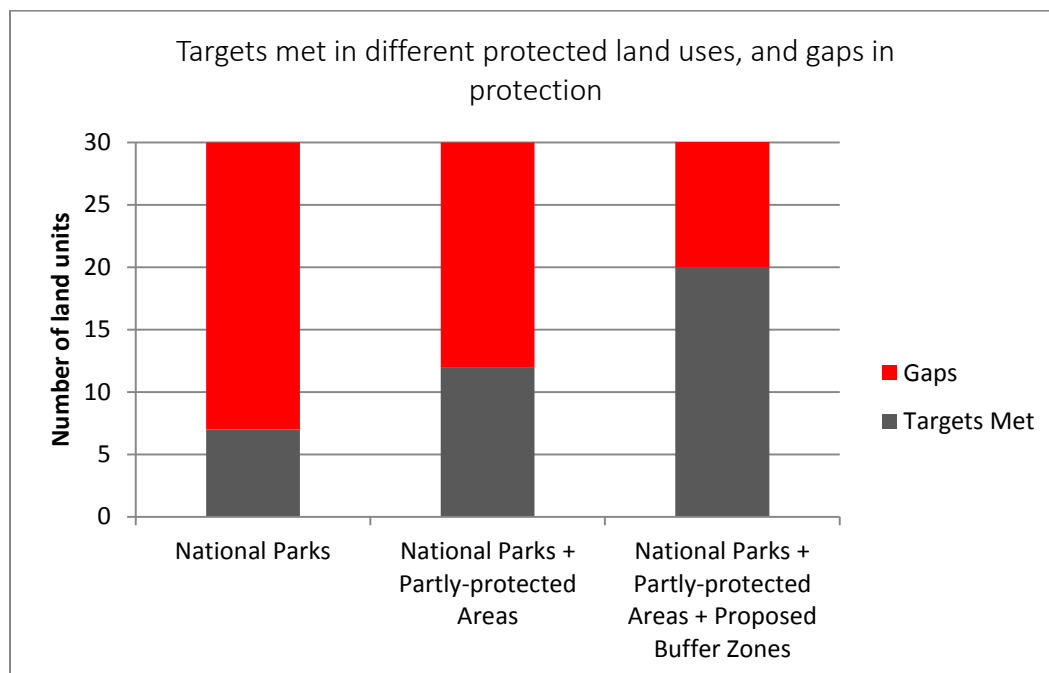
In terms of conservation targets, 80% of the smallest land unit (rugged well-drained grassland at Wonga-Wongé) was targeted, while 6% of the largest land unit (flat forest of the central inland plateau) was targeted. National parks met targets for seven land units, and four others had small percent shortfalls (Fig. 4, Table 2, Appendix 5). Nevertheless, half the units had important gaps in national parks, and five were completely absent. Most of these gaps could be met on a relatively small land area – for example, the ten smallest gaps could be met on 1% of Gabon's land – but some would require larger surfaces (for example [12, 19]).

Partly-protected areas contributed a large share of small units which, if adequately protected, could raise the number of targets met in parks from seven units to 12 (Table 2, Fig. 4).

However, three units were completely absent from both parks and partly-protected areas and are therefore unprotected in Gabon: hyperhumid rugged forest [3], inland plateau savannas near Franceville [25] and inland alluvial swamp forest [28].

In terms of bias, national parks and partly-protected areas together were slightly more even than either alone (Gini coefficient = 52). However, the proposed target was far more equal, with a Gini coefficient of 36, suggesting that protecting land units at the proposed target levels would both improve representation and reduce bias in the conservation network.

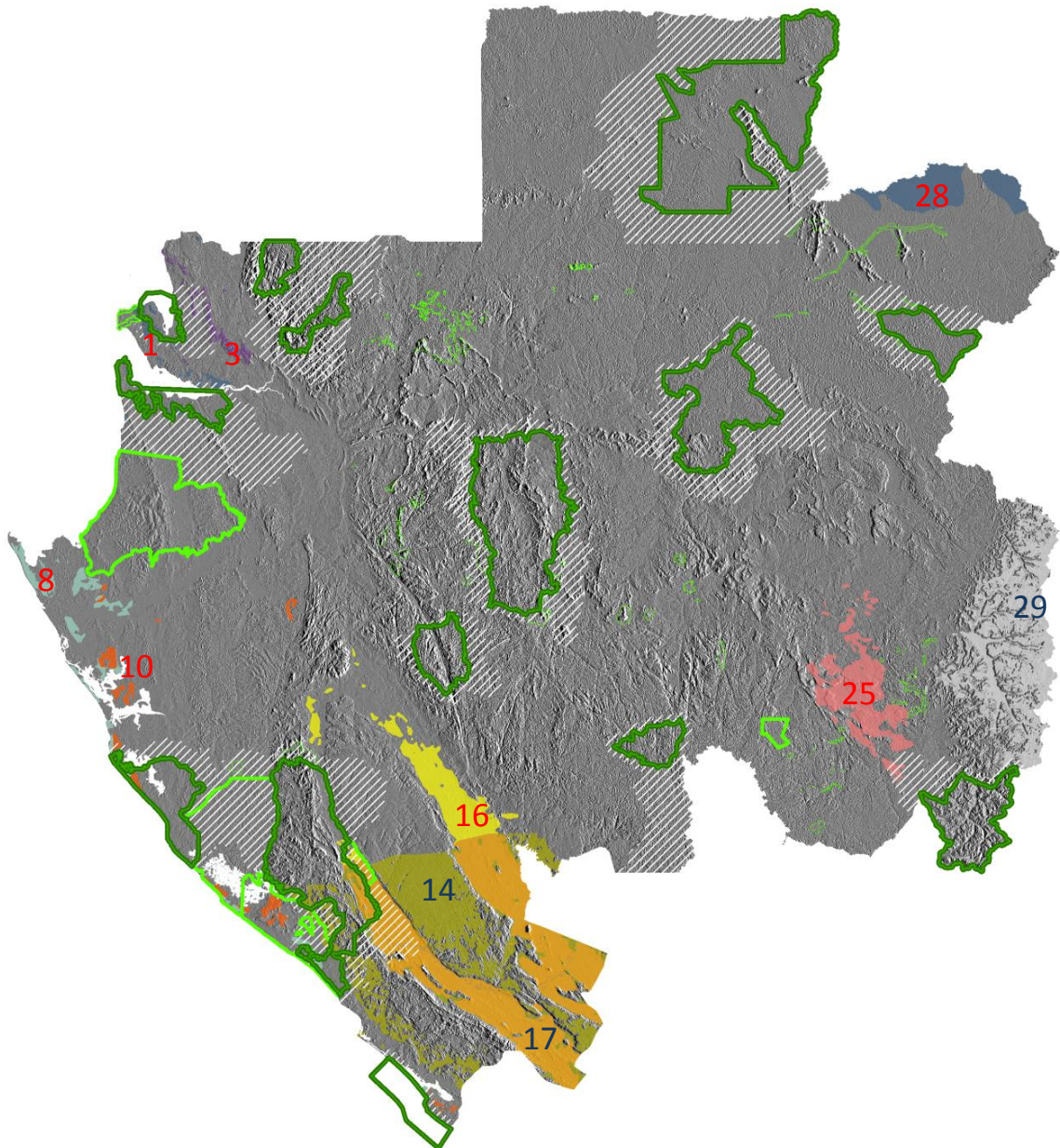
Figure 4. Targets met in national parks, partly-protected areas, and proposed national park buffer zones, and gaps in protection



2.4.2.3 Conservation gaps

We investigated the potential coverage that could be afforded from a series of buffer zones currently being proposed by the National Parks Agency to safeguard park resources from outside uses. Based on our gap analysis, these proposed buffer zones could substantially raise the number of conservation targets met in parks and partly-protected areas from 12 to 20 (Table 2, Fig. 4). This proposal is currently being refined and reviewed. Importantly, however, this revealed 10 outstanding gap units, located at a greater distance to these conservation lands, where a new protection mechanism would likely be needed to close gaps (Table 2, Fig. 5). Seven of these gap units were rare, and three were more common.

Figure 5. Gap units whose targets cannot be met on existing or proposed conservation lands, and therefore require a different protection mechanism. National parks outlined in dark green; partly-protected areas in light green; proposed buffer zones in white hash. Rare land units (red labels): flooded forest of the Djoua plain [28], inland savannas near Franceville [25], humid calcareous grasslands [16], well-drained coastal grasslands [10], flooded grassland of the coastal sedimentary basin [8], hyperhumid rugged forest [3], and hyperhumid flooded forest [1]. More common units (blue labels): flat subhumid forest [14], subhumid calcareous grassland [17], and flat, well-drained savannas of the Batéké Plateaux [29].



2.5 DISCUSSION

Our analysis revealed a strong spatial structure of both land units and land uses across Gabon: 80% of land units covered <5% of the country, while permits for oil extraction, mineral extraction and agriculture together also covered <5%. The coincidence of these ecologically diverse and economically important areas has important implications for conservation and land use planning. For example, oil permits include three rare land units [4, 8, 10], mining permits include important parts of two rare, unprotected units [25, 28], and logging permits include nine rare units, three of which are unprotected [3, 25, 28]. Few other places exist where these rare habitat types could be conserved, so their persistence rides heavily on managing impacts to them in these permit areas. In addition, we found that while relatively few conservation targets are met in national parks alone ($n = 7$), many more could be met ($n=20$) if partly-protected areas and proposed national park buffer zones are appropriately managed as part of the conservation network. Importantly, our analysis revealed a handful of outstanding gap units ($n=10$) that need to be directly targeted for new protection, most of which ($n=7$) are rare and therefore face particular risk of being overlooked in the face of development.

Insights like these are timely, as Gabon is currently engaged in an ambitious economic development program to increase production, yet to do so in 'green' ways (Republique Gabonaise 2012). Results from this work are being used to guide management and planning in this vein. For example, in the conservation sector, information on land units situated within national parks has been explicitly incorporated into park management

plans (M. Starkey, pers. comm.). In fact, we found that only five parks harbor rare units, two with large proportions of them (Pongara NP contains $>1/4$ of all mangroves; Lopé NP contains $>1/2$ of inland mixed terrain savannas), and that one park is exceptionally heterogeneous (Moukalaba-Doudou NP; Appendix 5). Such insights – which are most easily perceptible from a national-level analysis – can provide context to fine-scale zoning of activities on the ground. Similarly for the agricultural sector, information on unprotected or poorly-protected gap units is being incorporated as one factor to avoid in siting potential agricultural prospection areas (Austin et al., unpublished data). Hence, our results may reduce the risk that poorly-protected ecological units (particularly rare ones) are inadvertently converted by agriculture. Furthermore, the land use and biophysical information generated is being used by the National Land Use Plan to assess the current allocation of land resources and work towards more optimal solutions (Conseil National Climat, unpublished data). For example, we found that nearly 4,000 km² of savanna or inundated units are currently allocated to logging, despite these areas having low productivity for timber harvest. In a similar vein, compiling national land use data for the first time revealed a number of allocation overlaps, inconsistencies and data gaps, which can now be brought to the attention of relevant administrations to address. Our study thus demonstrates, despite the African continent being notoriously data-poor (and Gabon is no exception), spatial planning problems are not intractable – existing information, discriminatively harnessed across disparate fields, may be able to provide a rational base to assist decision-makers in many ways.

Nonetheless, we consider this first version of the land unit map to be a hypothesis to be field-tested and improved (Rowe and Sheard 1981) as our understanding of the landscape and its potential and need for production and protection evolve, and recognize a number of important caveats that merit attention. Important recommendations for improvement are to firstly field validate the land units (particularly the smallest units), to ensure they provide a sound basis for decisions. Field validation is currently done on an ad-hoc basis for certain applications mentioned above, but needs to be done more completely. Second and related, adding fine-scale features that are known to be important, such as bays, caves and inselbergs, but which were not detectable with the data available, will provide valuable information. Ecological units often contain smaller areas of discrete habitats that differ from the larger unit, and require special attention in mapping and management (Olson et al. 2001). Third, it would be useful to map the condition or level of intactness of contiguous areas of a land unit, to guide development towards parts of the unit that are already disturbed. Addressing this issue is important since Gabon's forest canopy is characterized as mostly closed-canopy by remote sensing standards (Saatchi et al. 2011), yet many degrees of forest use and degradation are evident in the field that are currently not available in mapped form to inform land use planning.

Finally, an important improvement to this study would be to identify subtypes within the largest units, since certain units are currently too undifferentiated to be useful for national-level planning. Based on the data and field observations available, we could not defensibly subdivide the large units further. However, we caution that one repercussion of using area-scaled conservation targets on larger units is that they will

be less-well conserved than smaller ones, and may bring into question their adequacy of protection. We chose area-scaled targets on the principle that larger, more common units will likely need proportionally less protected to retain ecological function than smaller, rarely occurring units. The method used to calculate targets is a tested way to represent such multi-scalar units when protecting rare types is particularly desired (Ardron 2008). Pending a more substantial effort of vegetation mapping based on tree inventory data (similar to Maniatis et al. 2011), subdividing larger units through expert mapping with input from the forestry sector would help ensure a greater level of conservation of these forest types at least in the short term. In addition, minimum target thresholds could be applied following standards derived from species-area methods elsewhere (for example, Metcalfe et al. 2013) as an adequacy standard.

Mapping should not be a barrier to spatial planning, despite imperfect information (Giakoumi et al. 2012). Maps are always imperfect reflections of reality (Burgman et al. 2005) and must be created and used discriminately to be able to inform land use decisions. Our study provides an example of a data-to-decision process applied to land use planning in a data-poor tropical country. Similar environmental information is likely to exist for other emerging or developing countries, and we encourage its use and synthesis to inform and support political decision-making (Rands et al. 2010).

2.6 SUPPORTING MATERIAL FOR CHAPTER 2 – THE LAY OF THE LAND: MAPPING LAND UNITS AND LAND USES TO ASSESS CONSERVATION GAPS IN GABON

APPENDIX 1: BIOGEOPHYSICAL DATASETS AND PROCESSING

Building land units involved an iterative process of identifying the variables to represent at each level, assembling and evaluating datasets, and processing them individually and in combination to represent landscape patterns and processes as they are understood at this time based on natural history observations throughout the country. We used eight datasets to represent six geological types, topographic patterns at two scales, four climatic influences, six hydrological formations, and three types of non-forest land cover (Table 1 in main text).

GEOLOGY

Geology is an important factor underpinning topography, hydrology, soils, as well as in shaping tree species distribution, and therefore forest composition, in Central Africa (Fayolle et al. 2012). We identified six major geological types based on observations of how geology influences substrate drainage or geomorphology (Chevallier et al. 2002), water chemistry (Ibanez et al. 2007), and plant species composition (Louis and Fontès 1996) in Gabon. Even though these influences are relatively surficial, we used the national geological dataset (Thomas et al. 2000) instead of the national soil map (Martin et al. 1981, ORSTOM 1981) to represent them, because the geology map was more recent, accurate and informative for the types of interest.

We defined six geological classes (map codes for each class are presented in Table 1 of main text): 1) alluvium (young fluvial deposits), mostly inundated and thus a proxy for wetlands, mainly lining the Ogooué delta in the coastal plain, and the Djoua River in the northeast; 2) well-drained clay-rich and sandy sequences of the coastal basin, which give rise to cirque and erosive U-shaped valley formations of Wonga-Wongé; 3) sandstones and well-drained, deep Kalahari sands of the Batéké Plateaux, comprising the western edge of the Congo Basin; 4) the rest of the coastal sedimentary basin; 5) sandstone and limestone containing dolomite and calcite from the Nyanga basin, part of the West Congolian orogenic belt; and 6) all other geological terranes, comprising a mixed geology from Precambrian (3200Ma), Palaeoproterozoic (~2000Ma), and Neoproterozoic (~500Ma) sequences. Many of these types, especially in the last category, have distinct geological properties but are generally covered by thick pedogenic deposits, which obscure their surface influence except in riverbeds or rare outcrops (Chevallier et al. 2002).

TOPOGRAPHY

We represented the influence of topography at two scales by delineating major mountain zones and identifying areas of topographic ruggedness (the variability of relief). Topography is observed to underpin biological patterns in Gabon, for example, by determining mountain zone ecology at the macroscale (Sosef 1994), the influence of ruggedness on species' distributions at the mesoscale (Leal 2004), and the local-level effect of landforms and geomorphology on species' occurrence at a particular site (Dauby et al. 2014).

We used the Shuttle Radar terrestrial elevation model (Jarvis et al. 2008), since complete national topographic maps only existed at coarser scales. We first defined landforms at a local level by identifying ridges, slopes, and valleys using the Topographic Position Index (Jenness 2006), which evaluates the difference in height for each pixel relative to all pixels, using a 15-cell radius. We calculated the standard deviation of the resulting raster and classified it into three landform categories to indicate ridges, slopes, and valleys (after Jenness 2006). To represent ruggedness, we calculated the standard deviation of elevation per pixel using a 1-km circular radius, with the Spatial Analyst extension in ArcGIS (ESRI 2011). After inspecting the result with the landform and elevation models, we divided it in three classes using the “natural breaks” function, assigning the lowest class as ‘flat’ and the two higher classes as ‘rugged’ terrain. Finally, two mountain zones were delineated. We considered the Monts de Cristal and Massif du Chaillu as a single zone because botanical field data demonstrate chorological continuity among these two ranges (Stévant, unpublished data). This zone was delineated by selecting the contiguous ‘rugged’ class around these ranges, following the 500m contour based on field observations of a vegetation shift around this level (Stévant, unpublished data), using geological limits to fill gaps. We considered the Monts Doudou and Mayombe mountains as a separate mountain zone, which we delineated by selecting areas $\geq 300\text{m}$ around them, based on a documented shift in plant species composition at this elevation in this particular mountain range, which is located closer to the coast (Sosef et al. 2004).

RAINFALL

We represented three macroscale influences on the amount and seasonality of rainfall in Gabon: 1) an Atlantic influence on the northern coast; 2) a continental influence driven by Harmattan winds in the northeast; and 3) an austral influence from ocean currents in the southwest (Doumenge et al. 2001). The rest of the country was considered to have a tropical wet rainfall regime, giving four classes of rainfall for the country. Monthly rainfall data from the country's 13 weather stations document these trends, with highest average rainfall on the northern coast (3276 mm/yr at Cocobeach), lowest in the southwest (1406 mm/yr at Tchibanga), and relative dryness in the northeast (1610 mm/yr at Mekambo; averaged for years 1944-2006 with complete data from Gabon's National Meteorological Service, unpublished data). These data also document a bimodal distribution of two wet and dry seasons per year, with considerable differences in dry season length between the north and south of the country. Length of the dry season is a key ecological factor for agricultural growing season for certain crops in Gabon (S. Ponnappa, pers. comm.), partly controls the forest-savanna boundary (G. Walters, pers. comm.) and influences species composition of forests (T. Stévant, pers. comm.).

To depict these influences, we used monthly precipitation data from the WorldClim 1.4 dataset (Hijmans et al. 2005), a 1-km resolution global interpolation of weather station records which include part of the national data described above. We defined a 'hyperhumid' zone receiving >2500 mm/yr on the north coast, strongly influenced by the Atlantic, where vegetation is notably different than elsewhere in Gabon due to pluviosity (Vande weghe, pers. comm.). To delimit the continental and austral influences, we mapped areas receiving <200 mm during at least 8 months per year. Because of the distribution of rainfall throughout the year, the continental portion displayed two short dry seasons, whereas the austral portion displayed one long dry

season per year. This definition encompassed both total rainfall and duration of the dry season, and produced patterns broadly consistent with broad phytogeographic patterns outlined for Gabon (see below) as well as more localized patterns such as turnover in grass species composition (Koechlin and Aubreville 1962) and vegetation structure and greenness detected from remote sensing (Gond et al. 2013).

HYDROLOGY

We mapped major lakes, lagoons and rivers. Gabon is structured by the Ogooué River basin, which drains approximately 74% of the country's surface (this study), followed by the Nyanga basin in the south (draining 8% of Gabon), Ntem basin in the north (4% of Gabon), and numerous coastal basins such as the Mbé (approximately 3%). Estuarine systems include three large bays in the northern half of the country, four large lagoons in the southern half, the Nyanga River mouth, multiple river mouths for the Ogooué River, and numerous smaller lagoons and coastal river outlets. With high rainfall and runoff across a topographically-complex landscape, river systems are still actively evolving across much of the country (Chevallier et al. 2002). Areas with flatter relief result in sediment accumulation and swampy, braided floodplains, particularly along the northeastern country border and approaching the coast (Chevallier et al. 2002).

To map surface water, we first extracted lakes and lagoons larger than ~10 ha, and surface water associated with large rivers, from the national surface water dataset (available at World Resources Institute 2009) and manually corrected it (due to aerial photography errors) to fit the elevation model as necessary. We supplemented this data layer by digitizing additional water bodies larger than ~10 ha identified from aerial navigation charts (US Army Map Service 1966)

and the elevation model. For main rivers, in the absence of a complete national hydrological base map, we used Arc Hydro Tools (ESRI 2011) with a hydrologically-corrected SRTM (Lehner et al. 2008) to delineate drainage networks.

LAND COVER

Gabon is predominantly covered in dense evergreen lowland rain forest. Restricted habitats with a different mature land cover arise where local conditions, such as altitude or edaphics, mask the general conditions maintaining the humid, dense forest (White 1983, Senterre and Lejoly 2005). We focused on mapping just three types of restricted habitats that can be distinguished from the main forest domain by distinctive vegetation: 1) grass / shrub / savanna, 2) mangrove and 3) submontane. Although other types exist (for example, swamp vegetation), we chose these types because of reliable data, and because of the potential of the land in these areas for industrial uses (especially grass / shrub / savanna), their unique species-level biodiversity, and the ecosystem services they provide (especially mangrove and submontane types).

To map grass / shrub / savanna, we used the MODIS Vegetation Continuous Fields dataset (Hansen et al. 2006), applying a >50% threshold of herbaceous cover per pixel to indicate non-forest. Using the Majority Filter function in ArcGIS, we eliminated small patches which appeared to reflect recent disturbance or small canopy gaps, thereby retaining larger, mostly contiguous patches of non-forest. To map mangroves, we digitized data from a satellite-based vegetation map of the coastal basin produced for the Ministry of Waters and Forestry (Tecsult 1998), which reflects mangroves reasonably well in the northern half of the country (J.P. Vande weghe, pers. comm.). Since it does not represent mangroves well in south, we did not map mangroves south of approximately Ozouri. Finally, since the location of submontane habitat is driven primarily by

altitude and distance from the coast (Senterre and Lejoly 2005), we used those variables as physical proxies. We approximated the submontane distribution modeled from botanical records in Senterre and Lejoly (2005) by selecting areas $\geq 600\text{m}$ in the Monts Doudou and Mayombe mountain range, $\geq 733\text{m}$ in the core Massif du Chaillu; $\geq 758\text{m}$ from Monts de Cristal to northern Massif du Chaillu; $\geq 785\text{m}$ in the Mitzic to Oyem area; $\geq 816\text{m}$ in the Belinga area; and $\geq 688\text{m}$ in the Plateaux Batéké.

After mapping these restricted vegetation formations, the large remaining forest domain was divided into four zonal types based on the rainfall gradient identified above. By zonal types, we refer to broad phytogeographic regions determined by macroscale climatic gradients (or 'zones'; White 1983, Senterre and Lejoly 2005). Four forest zones were recognized based on climate: 1) wet evergreen lowland forest, subject to the hyperhumid influence, which we refer to as 'hyperhumid'; 2) continental lowland and semi-deciduous forest, subject to the Congolian influence, which we refer to as 'subhumid forest, northeastern plateau'; 3) southern lowland and semi-deciduous forest, subject to the austral influence, which we refer to as 'subhumid forest, Nyanga plains'; and 4) evergreen lowland forest, which is any area outside of the three climatic influences. These zonal types approximate phytogeographic patterns previously sketched by hand over the country (Caballé 1978), now reproduced from quantitative datasets in a repeatable process to reflect main mature forest types along a climatic gradient.

MAP CONSTRUCTION

Data layers were combined to reflect hierarchical scales of ecological process and stability over time. At the base level we intersected geology, mountain zones, and rainfall influences to represent macroscale patterns. At the second level we added terrain ruggedness, surface water and land cover. All layers were scaled to the resolution of the elevation model, and were combined one at a time using Spatial Analyst functions in ArcGIS. After each combination we inspected the results and manually corrected small or artifact types that merged more logically with others, or for which we lacked evidence to represent in the model. For example, although the eastern limit of the coastal sedimentary basin forest was mostly delimited by geology, we extended this forest type east, past the geological limit of the sedimentary basin, in the region of the Ikoundou plateau, since botanical surveys have not documented different species composition between these substrates in this region of the country (Stévant, pers. comm.). Rivers derived from the digital elevation model were overlaid to interpret landscape structure but were not included in area calculations; area calculation for water was only based on the surface water dataset.

APPENDIX 2: LAND USE DATA

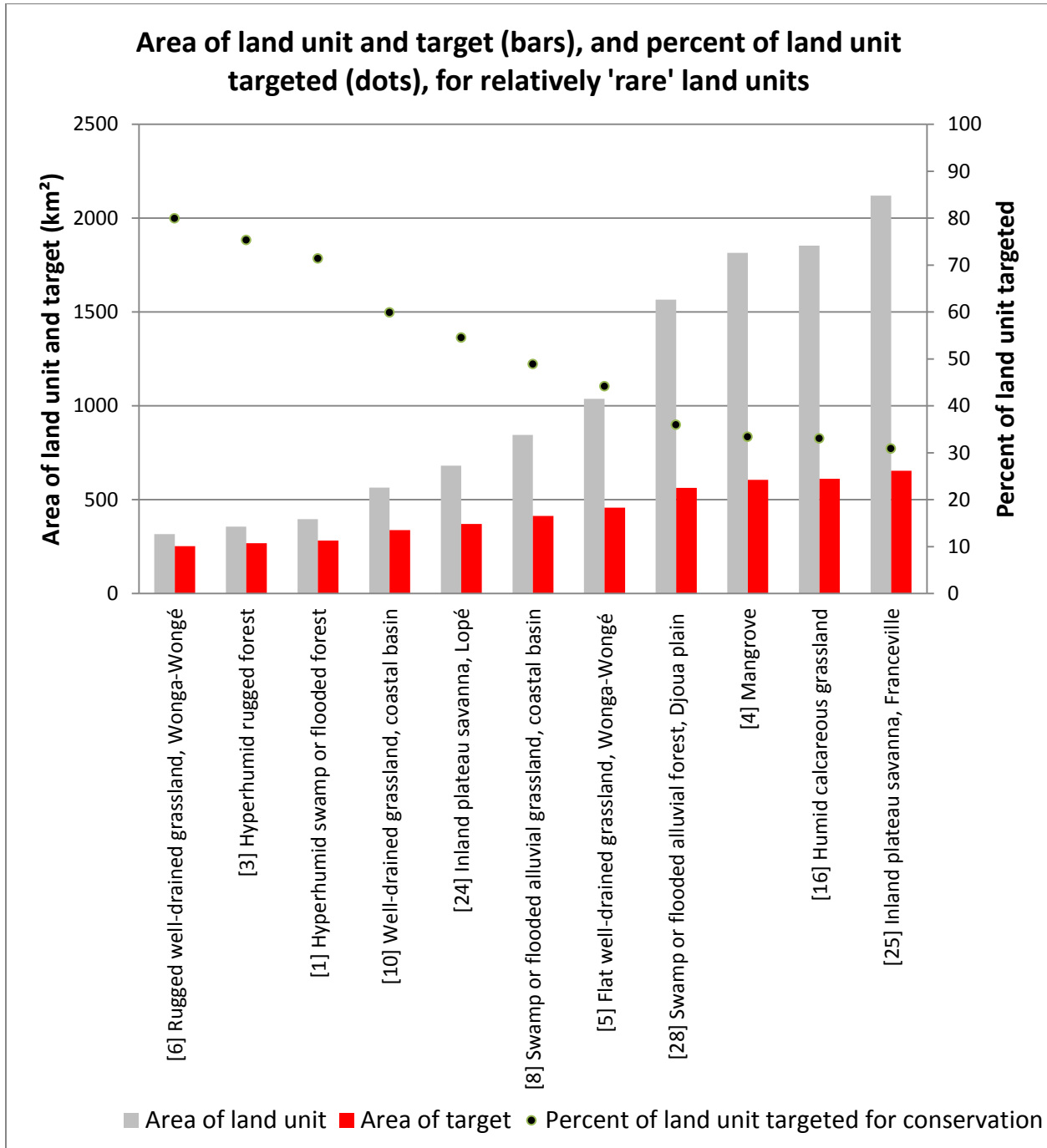
Government land use data were collected between October and December 2011. Oil extraction permits were those labeled 'Autorisation exploitation pétrole' in the Government dataset. Mineral extraction permits included both 'Permis exploitation minière' and 'Concession'. For agriculture, we used data provided by private companies for oil palm, rubber, sugarcane and cattle, and data provided by the Ministry of Waters and Forests for areas designated for agriculture within logging concessions (referred to as 'série agricole'). Logging permits included those labeled 'Concession forestière sous aménagement durable', 'Convention provisoire d'aménagement,

exploitation, transformation' and the same kind 'en cours', 'Permis forestier non-aménagé' and 'Plantation forestière'. The national park dataset included 13 parks. For partly-protected areas, we included the Wonga-Wongé Presidential Reserve, the Rapondah Walker Arboretum, three partly-protected areas referred to as hunting domains (Setté Cama, Ngové-Ndongo and Lékédi), two faunal reserves (Plaine Ouanga and Moukalaba), the proposed Mondah Classified Forest, and areas designated for protection within logging concessions (referred to as 'série de conservation').

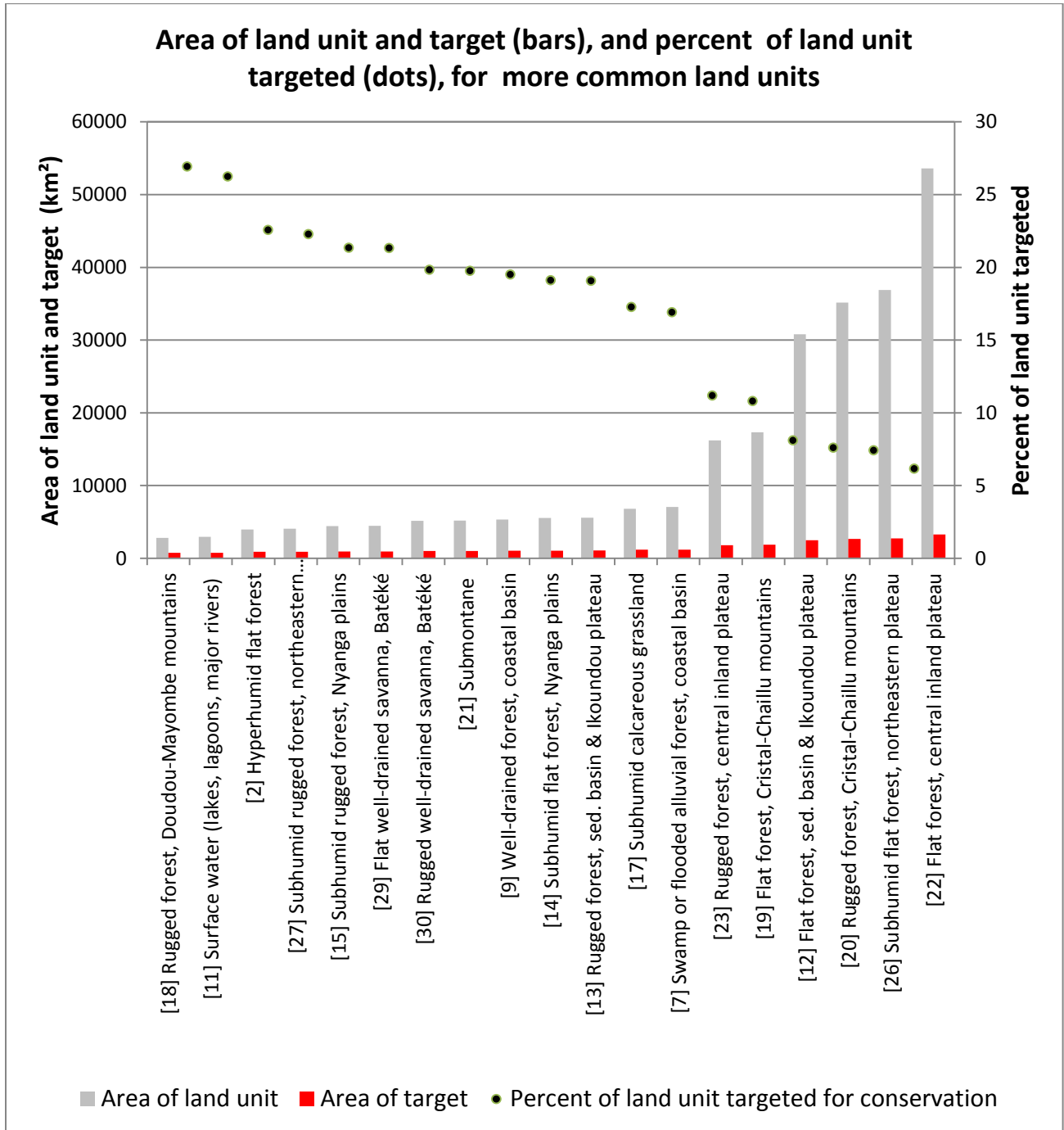
APPENDIX 3: TARGETS

Targets were scaled so that a greater proportion of smaller units would be required for protection, and a greater proportion of larger units would be available for production (Ardon et al. 2008, Ardron 2008). Figures below show the overall area of the land unit (in gray bars) and the target (in red bars) on the principal vertical axis. The proportion of each land unit targeted is illustrated by black dots corresponding to the secondary vertical axis. Relatively 'rare' units covering <1% of Gabon are shown in (a) and more common units covering >1% of Gabon shown in (b). Thus, 80% of the smallest land unit (rugged well-drained grassland at Wonga-Wongé) was targeted, while 6% of the largest land unit (flat forest of the central inland plateau) was targeted.

(a) Area of land unit, target and percent of land unit targeted for relatively rare units, which cover <1% of Gabon



(b) Area of land unit, target and percent of land unit targeted for more common land units, which cover >1% of Gabon



APPENDIX 4: GINI COEFFICIENT

We calculated the adapted Gini coefficient as described in Barr et al. (2011) for national parks, partly-protected areas, both together, and the scaled targets presented above. To do so we first calculated Lorenz curves, cumulative distribution functions that describe inequality (Lorenz 1905), by ranking the percent of each land unit in those groups against the cumulative percent of land units. We then calculated the Gini coefficient, which describes the difference in area between the Lorenz curve and a line representing equal distribution, called the line of equality, using Brown's formula as described in Barr et al. (2011). Possible values range from 0, representing perfect equality, to 100, representing complete inequality. Interpretation of values follows Zheng et al. (2013). We found that the distribution of land units in all types of protection was unequal, particularly in partly-protected areas, but that the scaled target produced reasonably equal results.

	Gini coefficient	Interpretation
National parks	55	Unequal
Partly-protected areas	79	Unequal
National parks and partly-protected areas	52	Unequal
Area-adjusted target	36	Reasonably equal

APPENDIX 5: EXTENDED RESULTS

LAND UNIT MAP

Forest was distributed across all macroscale rainfall and topographic gradients and most geological types, providing a basis for distinguishing forest types by their underlying geophysical properties. Of all units on terra firma (non-alluvial geology), two-thirds were flat versus rugged; the same held true for forested units only. However, forest did not occur on all geological types, such as calcareous areas [16, 17] and well-drained sands [29, 30]. Grass/shrub/savanna did not occur under hyperhumid or continental rainfall conditions, nor in mountain zones.

Of the 11 rare units, four were forested, and seven were grass/shrub. The two smallest forest types occurred in hyperhumid rainfall, under rugged (0.13% [3]) and alluvial conditions (0.15% [1]), followed by inland alluvial swamp forest (0.59% [28]) and mangrove (0.68% [4]). The smallest non-forest units all occurred along the coast in well-drained forest-savanna mosaics (0.12% [6], 0.21% [10], 0.39% [5]) or wetlands (0.32% [8]). Two rare savanna units occurred on the central inland plateau at Lopé (0.26% [24]) and Franceville (0.80% [25]).

CONSERVATION REPRESENTATION

National parks met targets for seven land units: mangroves [4], flat subhumid forest of the northeastern plateau [26], four rugged forest types [13, 18, 20, 21], and one rugged savanna type [30]. Thus, even though more of the country was flat versus rugged overall, and the park network was about equal in flatness and ruggedness, parks met more targets for rugged types – types which are already somewhat naturally protected by difficult access. In addition to the seven targets met, four others had small percent shortfalls [9, 22, 24, 27].

However, parks completely missed five units: hyperhumid rugged forest [3], flat and rugged well-drained grassland at Wonga-Wongé [5, 6], inland plateau savanna at Franceville [25], and swamp and flooded inland alluvial forest of the Djoua plain [28]. Six units were poorly represented [2, 12, 16, 17, 19, 29]. Most of these gaps could be met on a relatively small land area – for example, the ten smallest gaps could be met on 1% of Gabon’s land – but some would require larger surfaces (for example [12, 19]).

Individual parks contributed differently to unit representation (Table A5.1). We highlight the exceptional diversity of Moukalaba-Doudou NP, which spanned coastal to submontane habitats under two topographic zones, four geological classes, two rainfall influences, and several types of landcover. Pongara NP protected the greatest number of rare units including a large part of the country’s mangroves. Lopé, Loango, and Akanda national parks together protected parts of five rare units.

Table A5.1 Total number of land units and number of rare land units per national park

National Park	Total number of units	Number of rare units
Moukalaba-Doudou	12	2 [10, 16]
Pongara	8	3 [1, 4, 10]
Lopé	7	1 [24]
Loango	6	2 [8, 10]
Akanda	4	2 [1, 4]
Plateaux Batéké	5	0
Mwagne	2	0

Mayumba	2	0
Monts de Cristal	3	0
Minkébé	3	0
Ivindo	3	0
Waka	3	0
Birougou	3	0

Chapter 3

PUTTING BIODIVERSITY ON THE MAP: CONSERVATION PRIORITIES IN GABON²

3.1 ABSTRACT

In data-poor tropical rainforest countries, “conserving biodiversity” can be an unclear and therefore elusive goal, hampered by lack of information on what should be conserved and where conservation priorities lie. The Central Africa nation of Gabon established a national park network covering 11% of its land in 2002, with the intention of eventually adding smaller sites, such as biodiversity sanctuaries, to complete the network. We assess how well the park network conserves the country's priority wildlife species, and where additional efforts are needed to close conservation gaps. Using international conservation criteria, we assessed the country's terrestrial vertebrates (n = 1069) and discovered that nine percent of them (n = 99) met criteria for conservation attention. More than half of these 99 priority species (n = 58) are globally and/or likely to be nationally threatened, many of which (n = 23) are unprotected by national or

² Manuscript in preparation. Potential authors include: Michelle Lee, Philipp Henschel, Patrice Christy, Olivier Pauwels, Daniel Segan, Fiona Maisels, Lee White, David Macdonald, Hugh Possingham. Statement of authorship: ML designed the study, collected and analysed data; PH, PC, OP, FM contributed data and participated in the species assessment and mapping; DS, HP advised with spatial analysis; LW advised on conservation application; DM, HP oversaw the work; ML wrote the first draft document and all authors contributed to revisions. In addition, global datasets were contributed by Luigi Boitani, Carlo Rondinini, and Moreno DiMarco. Field observations were contributed by Kate Abernethy, Gaspard Abitsi, Nicolas Bout, Lauren Coad, Pauwel de Wachter, J. Michael Fay, Bas Huijbreghts, Lucy Keith, Sally Lahm, Franck Makanga, Emmanuel Mve Mebia, Richard Osisly, Norbert Pradel, Tim Rayden, Matt Shirley, Jacqueline van de Pol and Jean Pierre vande Weghe.

international law. Using natural history and locality information, we mapped the distributions of 45 of the priority species, finding that most distributions were highly restricted – one-third of habitat suitability maps covered <1% of the country, and another third covered 1-5%. We set conservation targets for the amount of each species' distribution to be conserved; national parks met only 12% of conservation targets. We identified locations that complemented parks to meet 100% of targets for these species and also for habitat types, with minimum impact on land used for local livelihoods. Our analysis revealed several priority conservation areas that merit attention as the country develops, and provides a critical information base to support future planning efforts.

3.2 INTRODUCTION

Nearly every nation on Earth has pledged to conserve biodiversity under the UN Convention on Biological Diversity (CBD), yet global biodiversity is still in precipitous decline (Butchart et al. 2010). The CBD sets a shared vision, mission, goals and targets to guide these efforts (CBD 2010), but the onus is on each country to define their own national objectives, methods and means to achieve them. Delivering on CBD targets can be particularly challenging for tropical countries, which hold a great share of global biodiversity (Dirzo and Raven 2003) but often lack the resources, capacity or sociopolitical context to meet CBD goals (Melick et al. 2012). This study supports the government of Gabon in developing its approach to managing biodiversity, particularly fauna, thereby contributing to several CBD Aichi Biodiversity Targets (CBD 2010) by collating and diffusing knowledge about the distribution and conservation status of species (Targets 1, 12, 19), and identifying sites to manage that improve species-level conservation and minimize habitat loss (Targets 5, 11), thus helping to integrate biodiversity in national planning processes (Target 2).

Located in the tropical forest belt of Central Africa, Gabon is characterized by a small, highly-urbanized population (1.6M people, 86% urban; United Nations 2013), political stability and an oil-based economy earning upper-middle income status (World Bank 2013). These factors have moderated deforestation (Rudel 2013), channeling the footprint of development into halos around villages, cities and roads (Sanderson et al. 2002, Laurance et al. 2006a), thus curbing habitat loss and overharvesting of wildlife, two main threats to biodiversity globally (Macdonald et al. 2013) and in the region (Abernethy et al. 2013). Gabon occupies <1% of the African continent, but harbors 11% of its humid rainforests (Mayaux et al. 2013), most of which are still closed-canopy (80.8%; Saatchi et al. 2011). Its relatively intact landscapes support strongholds of iconic wildlife – African forest elephants (Maisels et al. 2013), western lowland gorillas (Walsh et al. 2008), leatherback sea turtles (Witt et al. 2009) – which face higher levels of threat elsewhere. Diversity and distributions of less-iconic fauna is not well-studied or documented, with relatively few multi-taxa surveys (for example, Malbrant and Maclatchy 1949, Fisher ed. 2004, Alonso et al. 2006), and national species lists for even the best-known groups – birds and mammals – only relatively recently compiled (Christy et al. 2008).

Protected areas have long been part of Gabon's national heritage, predating its independence (Christy et al. 2003). Compared to surrounding countries, these historic areas covered some of the largest proportions of land, but offered the lowest or most poorly-defined levels of protection (Doumenge et al. 2001). The first national parks in Gabon were created in a "hot moment" (a short window of opportunity for conservation; Radeloff et al. 2013) in 2002, considerably elevating the level of protection of several existing protected areas and adding nine new ones, to form a 13-park network (Anonymous 2002). Site selection for parks drew on expert

knowledge of biologically-important areas (IUCN 1990), and field and aerial surveys. Two regional conservation prioritizations were also available, one which scored places by biological value and threat but did not map them (Doumenge et al. 2003), and one which expert-mapped large important landscapes across the Congo Basin (Kamdem Toham et al. 2006). Using formal prioritization methods (sensu Margules and Pressey 2000) to identify conservation areas at the scale needed for practical park or national-level planning was limited by a distinct lack of spatial data capable of providing a transparent, measurable biodiversity information base. Since park creation, several studies have investigated the presence of certain taxa in parks (Pauwels et al. 2006, Pauwels and Rodel 2006, Christy et al. 2008, Walters et al. 2012, Bahaa-el-din et al. 2013) but no systematic work has been completed to evaluate species-level conservation priorities, gaps in the coverage of species, and options to close the gaps subject to socio-economic constraints.

This study serves this need by: 1) prioritizing and mapping terrestrial faunal species of conservation importance in Gabon; 2) assessing their representation in national parks relative to a set of conservation targets; and 3) identifying sites that complement protected areas so that these species as well as habitat types meet international conservation targets. Evaluating and mapping conservation priorities is timely for Gabon, since the country is engaged in an ambitious development program aimed to double its GDP (Bongo Ondimba 2011) and earn it emerging market status by 2025 (Oxford Business Group 2011). One aspect of this program involves spatial planning and formalizing land allocation across sectors (Republique Gabonaise 2012) to achieve national development goals, as well as international commitments, such as those under the CBD. Our results are intended to inform political processes in species protection, protected area management and land use planning at a critical time in the development of the country.

3.3 METHODS

3.3.1 PRIORITIZING AND MAPPING SPECIES

To identify priority species for conservation, we conducted an internal review of established conservation assessment criteria (Stattersfield et al. 1998, Eken et al. 2004, IUCN 2012b, a) among conservation scientists in Gabon and identified 12 criteria (Table 1) that would be feasible to apply given the level of knowledge, time and expertise available. Criteria addressed national and international legal protection, levels of threat, and distribution patterns. Then, using a national list of 1069 primarily-terrestrial vertebrate species – 88 amphibians, 122 reptiles, 693 birds and 166 mammals (Christy et al. 2008) – we assessed all species by the criteria through a literature and database review, verified by taxonomic and natural history specialists in Gabon. Any species meeting criteria 1 – 4a(i) in Table 1 was considered “priority” in this study, while those meeting criteria 4a(ii) – d have special distributions relevant to spatial planning. Detailed information about the criteria and assessment are presented in Appendices 1 and 2, and species assessment results in Supplementary Table 1.

Table 1. Conservation assessment criteria used to evaluate species. For details see Supplementary Materials.

	Type	Criteria	Explanation	Citation
Legal	1. Protected nationally	1a. National law	Species listed as Fully protected (FP) or Partially protected (PP) under Gabonese law	Decree n° 0164/PR/MEF,19/01/2011
	2. Protected internationally	2a. Protected by CBD	Species listed as Critically Endangered (CR), Endangered (EN), or Vulnerable (VU) on the IUCN Red List of Threatened Species are considered globally threatened by extinction, protected under the Convention on Biological Diversity (CBD)	www.cbd.int, www.redlist.org
		2b. Protected by CITES Appendix I	Species listed on CITES Appendix I are considered threatened with extinction, protected under the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES)	www.cites.org
		2c. Protected by CMS Appendix I & Agreements	Species listed in CMS Appendix I are considered endangered migratory species. In addition, Gabon is bound by the African Eurasian Waterbird Agreement and the Agreement on the Conservation of Gorillas and their Habitats. Species listed under these agreements are protected under the Convention on the Conservation of Migratory Species of Wild Animals (CMS)	www.cms.int
Scientific	3. Likely to be threatened at national level	3a. Declining population	Population decline $\geq 30\%$ in the past (10 years or 3 generations)	Modified after criterion A2 in IUCN (2012b)
		3b. Small declining range	Globally range restricted ($< 20,000 \text{ km}^2$ EOO) and/or narrow occupation ($< 2,000 \text{ km}^2$ AOO), and either severely fragmented, known from ≤ 10 locations, or in range decline or fluctuation	Modified after criterion B in IUCN (2012b)
		3c. Small, declining population	Population $< 10,000$ mature individuals. In addition, population either declining at 10% (in 10 years or 3 generations), or in continuing decline with all individuals in one subpopulation, or in pop. fluctuation	Modified after criterion C in IUCN (2012b)
		3d. Small range, restricted pop.	Very narrow occupation ($< 20 \text{ km}^2$ AOO) or known from ≤ 5 locations in Gabon (presumably due to actual rarity, versus low level of survey)	Modified after criterion D2 in IUCN (2012b)
	4. Important populations or distributions	4a. Endemic	Endemic (i) occurs only in Gabon; near-endemic (ii) occurs in ≤ 3 contiguous countries including Gabon	Modified after Anderson (2002)
		4b. Important part of global population	A species which is globally limited (global range $< 50,000 \text{ km}^2$) with an important proportion (5% or more) of its global population in Gabon	Modified after criterion 2A in Stattersfield et al. (1998) or criterion 2 in Eken et al. (2004)
		4c. Migratory & congregating	Migratory species with $> 1\%$ global population congregating in Gabon	Modified after criterion A4 in Stattersfield et al. (1998) or criterion 3 in Eken et al. (2004)
		4d. Rare or special distribution	Species of other justified, scientific importance with a rare or special distribution relevant to spatial planning	Expert review

We assembled locality and habitat preference information for reptiles, birds and mammals in Supplementary Table 1; we lacked data for amphibians. Information was compiled from the literature, online databases, field reports and observations, carefully screening records by quality, age and source of information, taxonomic and geographic precision, and spatial coverage of observation data (Boitani et al. 2011). Data were sufficient to map 45 species. Two kinds of maps were produced depending on the information available. For species with better-known natural histories and habitat preferences, we mapped relative habitat suitability ($n=35$), using the method in Rondinini et al. (2011). In addition, for species with limited distributions, observations, or points of interest to conserve (such as nesting sites), we mapped confirmed localities ($n=21$). The 45 species were represented by 56 data layers, since 11 species were mapped both ways (Table 2). Detailed mapping methods are provided in Appendix 3.

In addition to species maps, we incorporated data on habitat types, which act as surrogates for a wider suite of biodiversity (Grantham et al. 2010). Habitat types were represented by data on land units, which depict major gradients of geology, topography, rainfall and landcover across Gabon (Chapter 2 of this thesis).

We overlaid national parks onto all species distribution and habitat maps to assess protection inside the current fully-protected network. Gabon also has a network of partly-protected areas which include, for example, a Presidential Reserve, faunal reserves, park buffer zones, Ramsar sites, and an arboretum, among others. However, for accounting purposes (Table 2), we only considered national parks, since they are the only areas that reliably contribute fully to species-level protection at this time.

3.3.2 CONSERVATION TARGETS AND PLANNING SCENARIOS

We ran two site-selection scenarios. The first exploratory scenario identified conservation priorities based only on the distribution of species without accounting for targets already met in protected areas. The second planning scenario identified sites that complemented existing protected areas to meet conservation targets for species and habitat types. Site-selection results were generated using Marxan (Ball and Possingham 2000), an optimization software that identifies efficient solutions for meeting representation targets while minimizing cost. In this study, higher costs reflect relative constraints or anticipated difficulties in achieving conservation at a site.

3.3.2.1 Planning units

We chose watershed catchments as the unit of analysis, since topographic limits such as ridges and rivers are time-tested boundary markers in Gabon's rainforest. We delineated 12,454 catchments (mean size 125 km²) using Arc Hydro Tools (ESRI 2011) on a 90-m resolution hydrologically-corrected digital elevation model (Lehner et al. 2008). Catchments along the coast were manually corrected due to flat terrain.

3.3.2.2 Conservation targets

Species conservation targets were scaled to ensure a relatively high minimum standard for larger distributions, with proportionally more area conserved for smaller distributions. For suitable habitat maps we used the method in Rodrigues et al. (2004), setting an 80% target for distributions covering <0.1% of the country, a 30% target for a distribution covering the entire country, and applying linear interpolation to set targets for distributions in between. We lowered values to 30% for six species which prefer human-modified habitats, as they may be expected

to survive outside of protected areas. For presence records, we scaled targets to reflect the number of catchments in which they occurred: 100% for species known from one or two catchments; 60% for species known from three to ten; 30% for species known from 11-30; and 10% for more widely-recorded distributions. Targets for habitat types were sourced from Chapter 2 of this thesis, set at 80% of the smallest type, and scaled downwards in proportion to increasing habitat area.

3.3.2.3 Planning scenarios

1) Species-only. We first ran an exploratory scenario to evaluate the spatial coincidence between patterns in the species data and existing protected areas. This scenario was not meant to produce a planning solution per se, but to illustrate priority areas for species in relation to, but unbiased by, the location of protected land. In this species-only scenario, catchments were subject to only one constraint: to avoid settlement halos, thereby minimizing both the burden of management on local livelihoods and potential human-wildlife conflict. We buffered villages (3 km), large towns (10 km) and the capital city (15 km) as settlement halos to be avoided if possible; these distances represent average spheres of influence around human settlements in Gabon as approximated from Landsat images. To reflect this constraint, we assigned a base cost per catchment equal to its area (ha), and multiplied any area within the settlement halo by ten (detailed in Appendix 4). Marxan will avoid selecting more costly settlement areas if targets can be met elsewhere.

2) Species and habitat. We then broadened the scenario and made it more realistic for planning by including habitat targets as a complementary measure of biodiversity, and accounting for targets already achieved on existing protected land. All national parks and five partly-protected areas were considered protected land, and assumed that new sites would be easier to protect in

their proximity. The five partly-protected areas included the Presidential Reserve, two faunal reserves, a hunting domain, and an arboretum (detailed in Appendix 4; we did not include partly-protected areas currently under discussion for reconfiguration). The area of protected land was calculated per catchment. Any catchment with $\geq 50\%$ of its area on protected land was locked into the solution. In addition, any catchment with $\geq 10\%$ of its area on protected land was exempt from the settlement halo constraint; its cost was equal to area alone. Any catchment $< 10\%$ on protected land was subject to the settlement halo constraint. Land use and cost information is presented in Appendix 4.

3.3.3 IDENTIFYING PRIORITY CONSERVATION AREAS

Marxan was calibrated by best-practice guidelines (Ardon et al. 2008) and used to generate 100 different near-optimal solutions. Results were evaluated based on efficiency (lowest objective function score) and priority (selection frequency; Ball et al. 2009). To select an individual solution, we mapped the 20 most efficient solutions and selected the one with the least overlap with production land uses presented in Chapter 2 of this thesis. We present this individual solution for the species and habitat scenario only. To identify priority areas, we mapped the catchments that were selected most frequently in the 100 solutions. We present *critical sites*, selected 90-100% of the time, and *important sites*, selected 70-89% of the time, for both scenarios.

3.4 RESULTS

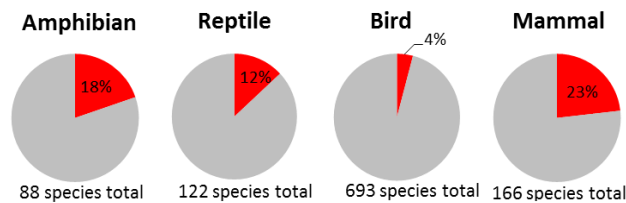
3.4.1 PRIORITY SPECIES AND LEGAL PROTECTION

Nine percent of Gabon's primarily-terrestrial vertebrates – 99 species – met at least one priority criterion (criteria 1 – 4a(i) in Table 1), representing 23% of mammals, 18% of amphibians, 12% of reptiles and 4% of birds in this study (Fig 1a, Supplementary Table 1). Twelve species are endemic to Gabon and 25 near-endemic (Supplementary Table 1). In terms of threat, 25 globally-threatened species (IUCN 2014) are documented in Gabon, 15 of which are also thought to be threatened nationally (as evaluated in Appendices 1 and 2). An additional 33 species meet criteria for threat at a national level (often due to restricted distribution or small population within Gabon), but not globally.

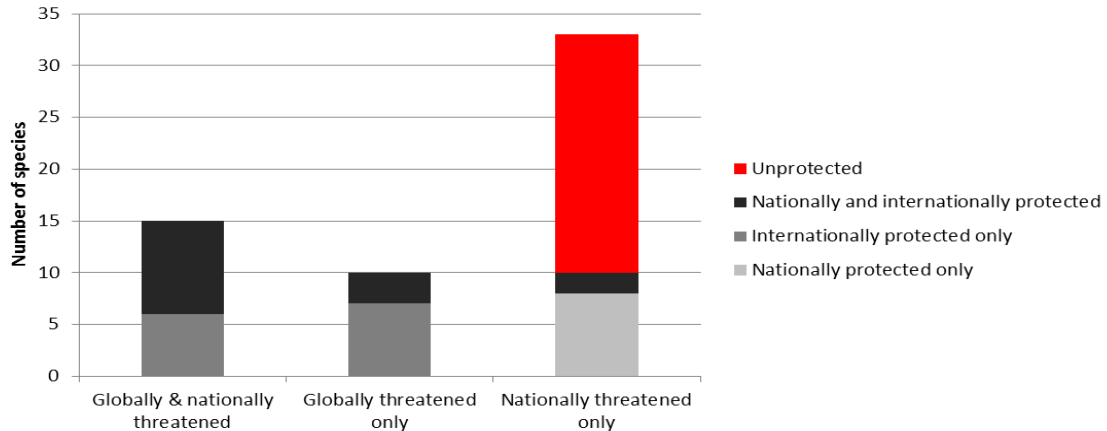
Nearly three-quarters (72%) of the priority species are protected by law: 30 by international law alone, 27 by national law alone, and 14 by both. All globally-threatened species are protected under the CBD (see Appendix 1), yet only half of them (n=12) are protected by national law. Of the 33 species which are likely to be threatened at national-level only, ten are protected by national law (Fig 1b).

Figure 1. Species assessment results

- (a) Proportion of taxa meeting priority criteria. 18% of amphibians (16 out of 88 species), 12% of reptiles (15 out of 122 species), 4% of birds (29 out of 693 species), and 23% of mammals (39 out of 166 species) met criteria 1-4a(i) in Table 1.



- (b) All species that are globally threatened are internationally protected under the CBD; certain are also protected by CITES and CMS in Gabon. Gabon's national law protects 12 (out of 25) globally-threatened species. We draw attention to the important proportion (38%) of threatened terrestrial vertebrates that are currently unprotected by law (23 species depicted by the red bar).



3.4.2 SPECIES DISTRIBUTION PATTERNS

The majority of species mapped had narrow distributions (Table 2), dependent on spatially-restricted resources. Of the species mapped by habitat suitability, one-third covered <1% of the

country, and another third between 1-5% (Fig 2a). Many species required lakes and lagoons in the coastal basin, or savanna/scrub habitats in the south (Appendix 3). Half the species were forest-dependent, yet all but five were biogeographically range-limited to particular parts of the country. The smallest mapped habitat area belonged to the Dja river warbler (*Bradypterus grandis*; 112 km²), a rarely-observed bird thought to favor particular forest clearings (Dowsett-Lemaire and Dowsett 2000), while the largest belonged to the leopard (*Panthera pardus*; 118,856 km²), a habitat-generalist whose distribution in Gabon is largely linked to prey availability (Henschel 2009).

3.4.3 COVERAGE AND GAPS IN PROTECTION

National parks protected part of the distributions of 39 out of the 45 priority species we were able to map. Five reptiles and one mammal were absent from parks (Table 2). About one-fifth of both suitable habitat and known locality distributions were located inside parks (20.1% and 22.7%, respectively). Replication in parks was relatively low, with 22% of distributions occurring only in one park (Fig. 2b).

Table 2. Area (km²) and number of presence localities [pres] of species distributions in the country, national parks, targets, gaps, and final solution.

	Species	Conservation assessment criteria (from Table 1)	In Gabon		In National Parks		Target		Gap	In Solution	
			km ² or [pres]	% of country	km ² or [pres]	% in parks	% target	km ² or [pres]	km ² or [pres]	% in solution	km ² or [pres]
1	Keeled hinged terrapin (<i>Pelusios carinatus</i>)	3, 4a	[6]		[-]	[-]	[60]	[4]	[4]	[67]	[4]
2	Maran's hinged terrapin (<i>Pelusios marani</i>)	4a, 4b	[10]		[1]	[10]	[60]	[7]	[6]	[70]	[7]
3	Nile crocodile (<i>Crocodylus niloticus</i>)	1a, 2b, 3	6,739	3	602	9	57	3,813	3,211	57	3,822
4	Chapin's chameleon (<i>Trioceros chapini</i>)	4a*	[4]		[-]	[-]	[60]	[3]	[3]	[75]	[3]
5	Ivindo dwarf gecko (<i>Lygodactylus sp.nov.</i>)	3, 4a, 4b, 4d	[1]		[1]	[100]	[100]	[1]	[-]	[100]	[1]
6	Omboué worm lizard (<i>Cynisca bifrontalis</i>)	4a, 4b	13,662	5	719	5	51	7,031	6,312	54	7,330
			[3]		[-]	[-]	[60]	[2]	[2]	[67]	[2]
7	Perret's worm snake (<i>Leptotyphlops perreti</i>)	4a, 4b	[1]		[-]	[-]	[100]	[1]	[1]	[100]	[1]
8	Pauwels' blind snake (<i>Letheobia pauwelsi</i>)	3, 4a, 4b, 4d	[1]		[-]	[-]	[100]	[1]	[1]	[100]	[1]
9	Ocellate water snake (<i>Hydraethiops laevis</i>)	3, 4a, 4b, 4d	[1]		[-]	[-]	[100]	[1]	[1]	[100]	[1]
10	Pink-backed pelican (<i>Pelecanus rufescens</i>)	1a*	1,758	0.7	285	16	66	1,166	881	67	1,173
	nesting sites		[9]		[6]	[67]	[60]	[6]	[-]	[78]	[7]
11	Yellow-billed stork (<i>Mycteria ibis</i>)	1a	4,197	2	492	12	60	2,519	2,027	60	2,519
12	Saddle-billed stork (<i>Ephippiorhynchus senegalensis</i>)	1a, 3	477	0.2	108	23	76	361	254	76	362
			[16]		[4]	[25]	[30]	[5]	[1]	[63]	[10]
13	Sacred ibis (<i>Threskiornis aethiopicus</i>)	1a*	[27]		[14]	[52]	[30]	[8]	[-]	[63]	[17]
14	African spoonbill (<i>Platalea alba</i>)	1a	1,933	0.7	297	15	66	1,268	972	66	1,281
			[21]		[12]	[57]	[30]	[6]	[-]	[100]	[35]
15	Peregrine falcon (<i>Falco peregrinus</i>) nesting sites	2b	[2]		[1]	[50]	[100]	[2]	[1]	[100]	[2]
16	Freckled nightjar (<i>Caprimulgus tristigma</i>)	4d	596	0.2	299	50	74	442	143	74	442
17	Black-and-white-casqued hornbill (<i>Bycanistes subcylindricus</i>)	4d	8,114	3	262	3	30	2,434	2,172	30	2,434
			[48]		[4]	[8]	[10]	[5]	[1]	[46]	[22]
18	African river martin (<i>Pseudochelidon eurystomina</i>) breeding sites	4a*, 4b, 4c	1,073	0.4	107	10	70	750	642	70	750
			[10]		[2]	[20]	[60]	[7]	[5]	[70]	[7]
19	Pale olive greenbul (<i>Phyllastrephus fulviventris</i>)	4d	340	0.1	53	16	78	266	213	91	308
			[2]		[-]	[-]	[100]	[2]	[2]	[100]	[2]
20	Rufous-tailed palm thrush (<i>Cichlادusa ruficauda</i>)	4d	148	0.1	4	3	80	118	114	84	125
			[6]		[-]	[-]	[60]	[4]	[4]	[83]	[5]

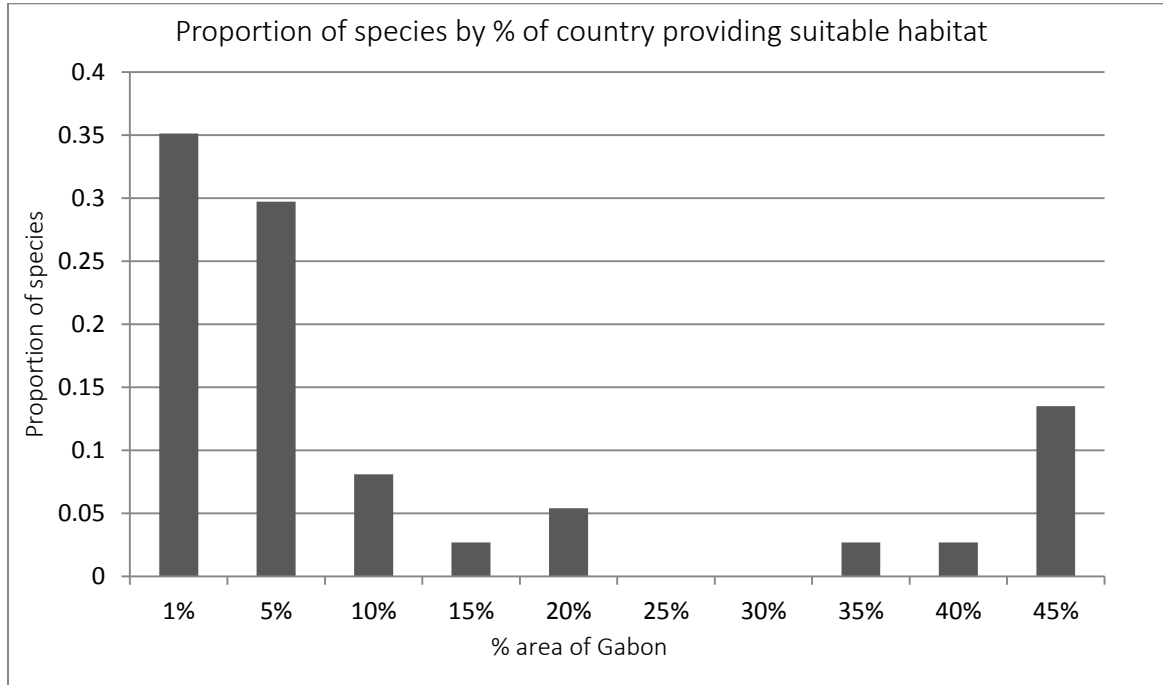
Table 2 continued

	Species	Conservation assessment criteria (from Table 1)	In Gabon		In National Parks		Target		Gap	In Solution	
			km ² or [pres]	% of country	km ² or [pres]	% in parks	% target	km ² or [pres]	km ² or [pres]	% in solution	km ² or [pres]
21	Dja river warbler (<i>Bradypterus grandis</i>)	4a, 4b, 4d	112	0.04	59	53	80	90	30	81	91
			[5]		[2]	[40]	[60]	[3]	[1]	[60]	[3]
22	Red-headed picathartes (<i>Picathartes oreas</i>)	1a, 2a, 2b, 4b, 4d	17,375	7	3,759	22	50	8,639	4,880	50	8,640
			[52]		[7]	[13]	[10]	[5]	[-]	[25]	[13]
23	Orange-tufted sunbird (<i>Nectarinia bouvieri</i>)	4d	3,062	1	273	9	30	919	645	43	1,303
24	Variable sunbird (<i>Nectarinia venusta</i>)	4d	6,538	2	274	4	30	1,961	1,687	31	2,030
25	Pink-footed puffback (<i>Dryoscopus angolensis</i>)	4d	[2]		[1]	[50]	[100]	[2]	[1]	[100]	[2]
26	Black-chinned weaver (<i>Ploceus nigrimentus</i>)	4a, 4d	8,440	3	1,507	18	55	4,638	3,131	56	4,754
27	Loango weaver (<i>Ploceus subpersonatus</i>)	2a, 4a*, 4b, 4d	365	0.1	62	17	78	284	222	78	286
			[37]		[5]	[14]	[10]	[4]	[-]	[38]	[14]
28	Grey waxbill (<i>Estrilda perreini</i>)	4d	11,503	4	1,783	16	53	6,063	4,280	53	6,065
29	Western lowland gorilla (<i>Gorilla gorilla</i>)	1a, 2a-c, 3, 4b	112,211	42	23,715	21	36	40,645	16,929	41	46,403
30	Chimpanzee (<i>Pan troglodytes</i>)	1a, 2a, 2b, 3, 4b	108,766	41	23,105	21	36	39,642	16,537	41	44,863
31	Black colobus (<i>Colobus satanas</i>)	2a, 3, 4a*, 4b	87,279	33	15,877	18	38	33,201	17,324	41	36,073
32	Mandrill (<i>Mandrillus sphinx</i>)	1a, 2a, 2b, 3, 4b	98,832	37	18,490	19	37	36,707	18,217	37	36,720
33	Red-capped mangabey (<i>Cercocebus torquatus</i>)	2a, 3, 4b, 4d	43,199	16	6,441	15	43	18,632	12,191	51	21,999
34	Sun-tailed monkey (<i>Cercopithecus solatus</i>)	1a, 2a, 3, 4a, 4b, 4d	15,423	6	4,952	32	51	7,802	2,849	51	7,803
35	Serval (<i>Felis serval</i>)	1a, 3, 4d	6,586	2	1,687	26	30	1,976	289	61	4,025
36	Golden cat (<i>Caracal aurata</i>)	2a*, 3, 4b	110,044	42	23,266	21	36	40,015	16,749	40	44,434
37	Leopard (<i>Panthera pardus</i>)	1a, 2a*, 2b, 3	118,856	45	25,547	21	36	42,557	17,010	43	51,198
38	West African manatee (<i>Trichechus senegalensis</i>)	1a, 2a, 2c, 3, 4b, 4d	1,694	1	390	23	67	1,128	737	71	1,204
39	African forest elephant (<i>Loxodonta cyclotis</i>)	1a, 2a, 2b, 3, 4b	116,392	44	24,980	21	36	41,851	16,871	42	49,158
40	Hippopotamus (<i>Hippopotamus amphibius</i>)	1a, 2a, 3, 4d	1,119	0.4	339	30	70	778	440	87	972
41	Giant forest hog (<i>Hylochoerus meinertzhageni</i>)	1a, 3	41,305	16	10,884	26	36	40,015	29,131	43	17,951
42	Defassa waterbuck (<i>Kobus ellipsiprymnus</i>)	1a, 3, 4d	453	0.2	202	45	76	345	143	79	358
43	Southern reedbuck (<i>Redunca arundinum</i>)	1a, 3, 4d	496	0.2	-	-	75	374	374	78	387
44	Grimm's duiker (<i>Sylvicapra grimmia</i>)	1a	4,856	2	1,502	31	30	1,457	-	72	3,486
45	Bongo (<i>Tragelaphus eurycerus</i>)	1a, 3, 4b	31,499	12	10,678	34	45	14,306	3,628	53	16,589

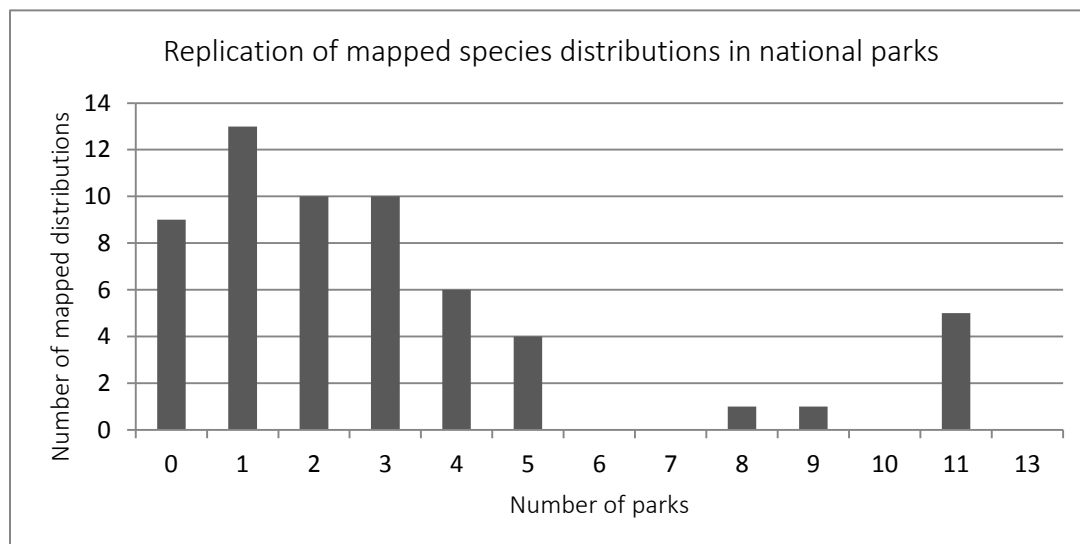
* denotes status that lowered in importance during the study period; for example, a species that was removed from protection during this period and is still unprotected.

Figure 2. Species distributions across Gabon and replication in national parks

- (a) Of the species mapped by habitat suitability, 35% covered <1% of the country, and nearly 30% more covered 1-5% of the country.



- (b) Replication of species distributions (confirmed localities and suitable habitat) in the 13 national parks. Six species (represented by 9 distributions) were missing from parks. Over one-fifth (22%) of distributions were represented in a single park. The 5 most widespread species – those covering >45% of the country in Figure 2a above – occurred in 11 parks

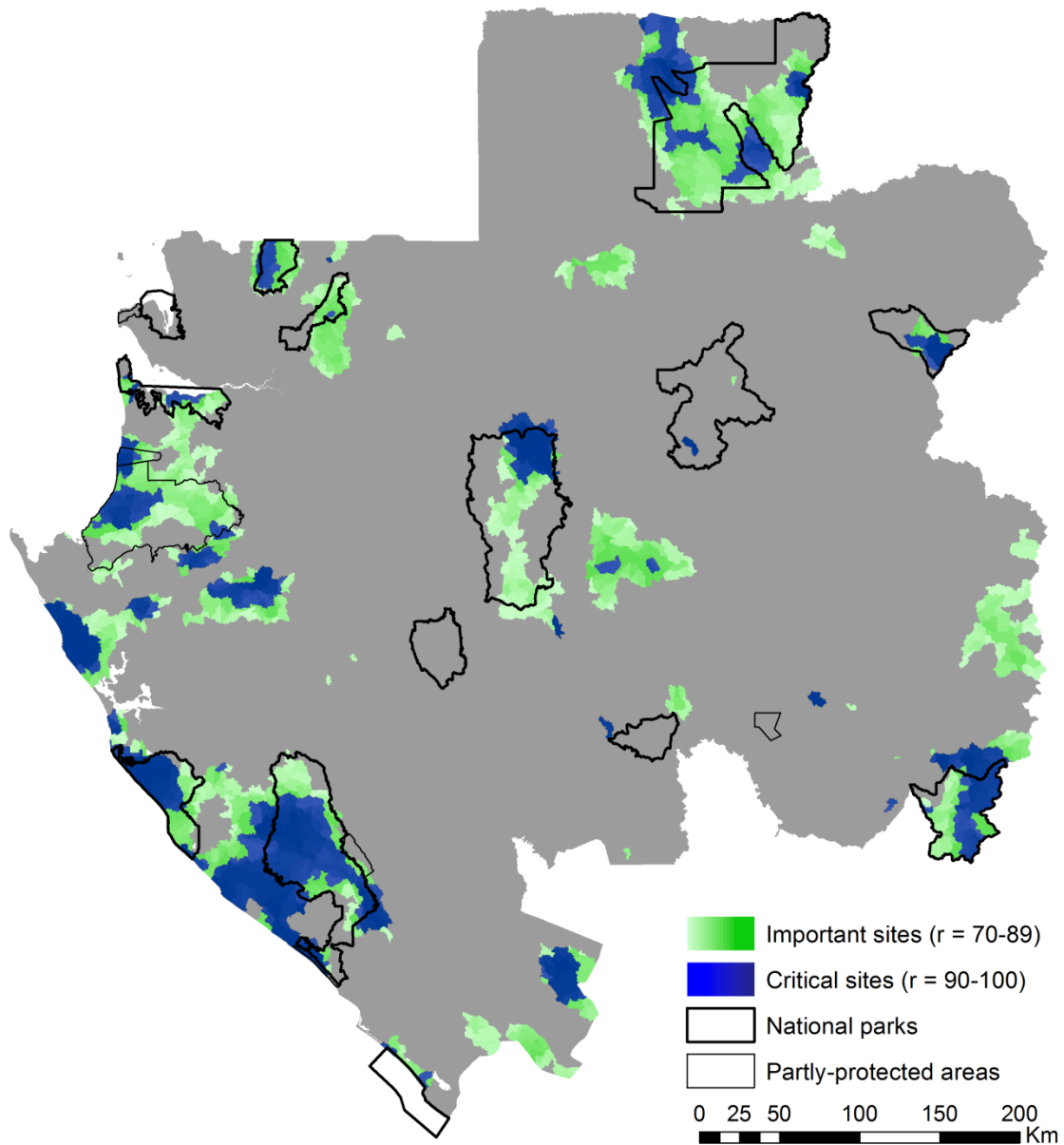


Parks met only 12% of species conservation targets (Table 2, Fig 4b). Targets met included confirmed localities of an endemic gecko, a mountain forest bird, four coastal water birds, and suitable habitat for a savanna antelope. Larger parks contained more suitable habitat summed across species but did not necessarily contribute more to the proportion of that habitat conserved (Appendix 5), since representing small distributions depends more on location than sheer area. Moukalaba-Doudou National Park performed particularly well in representation.

3.4.4 PRIORITY AREAS FOR SPECIES – EXPLORATORY SCENARIO

Critical sites for the species-only scenario covered 6.1% of the country's land area (Fig 3). Nearly two-thirds of this area fell within (48.8%) and adjacent to (15.6%) protected land, even though protected land was not factored into this planning scenario. *Important sites* covered 10.5% of the country, often adjacent to critical sites and substantially covering seven (out of 13) parks and one (out of five) partly-protected area. Overall, these patterns suggest that existing protected land is fairly well-placed to protect critical and important sites for species, yet inefficiencies and gaps in protection exist.

Figure 3. Critical and important sites for the exploratory species-only scenario, which was run to investigate patterns between species priority areas and protected areas, without factoring protected areas into the planning scenario. Blue catchments are critical to the solution (selection frequency, $r = 90-100$). Green catchments are important to the solution ($r = 70-89$).

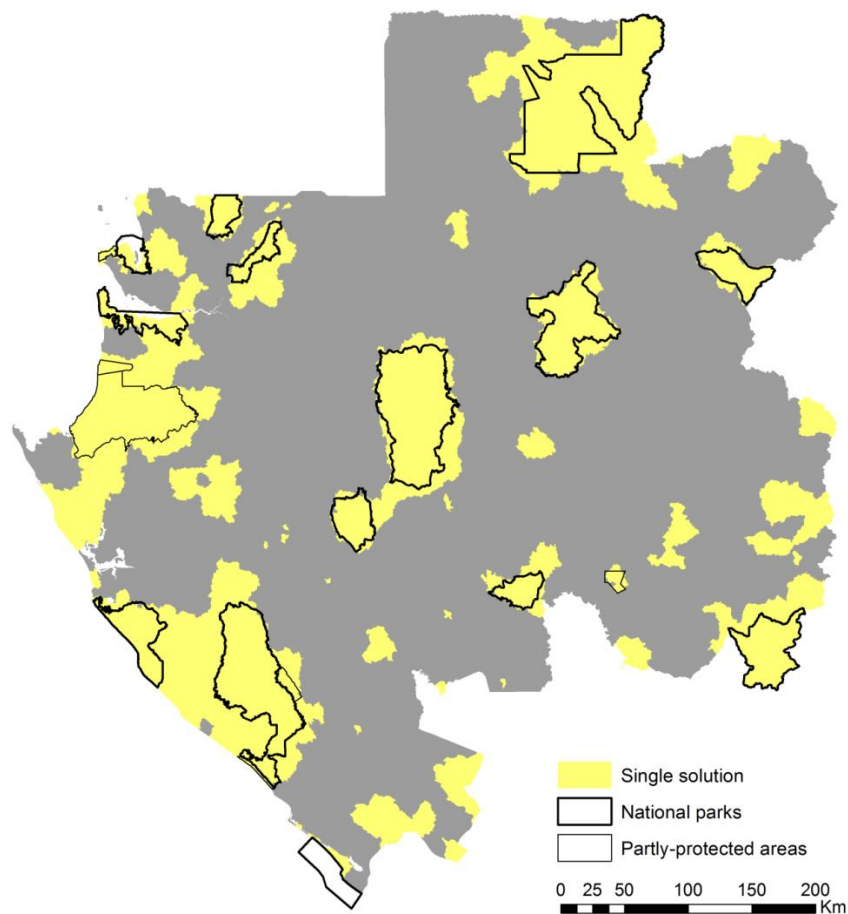


3.4.5 SITES THAT MEET SPECIES AND HABITAT CONSERVATION TARGETS – PLANNING SCENARIO

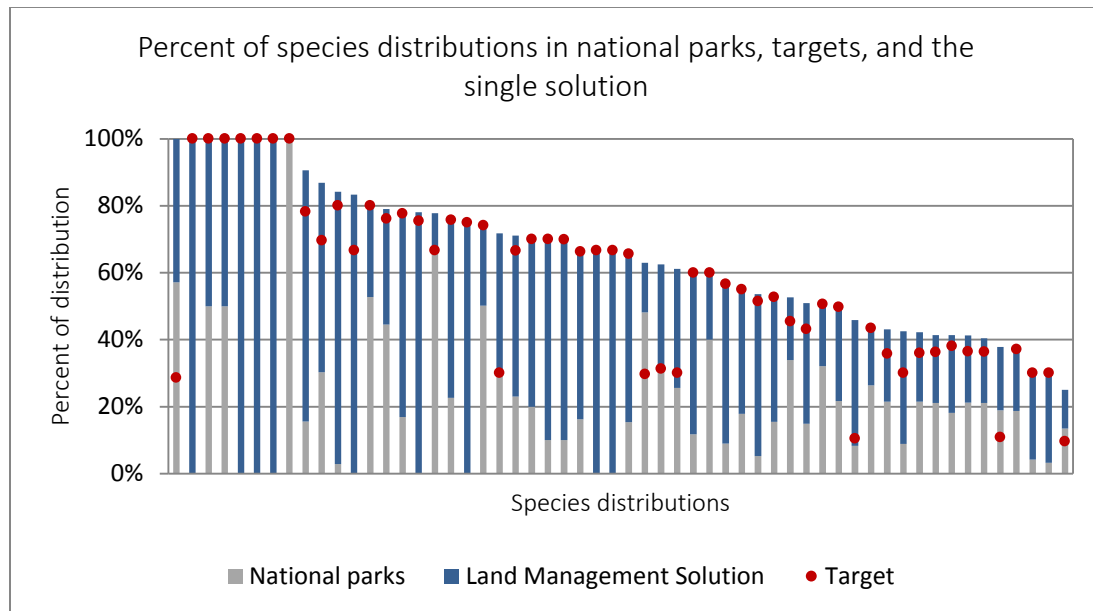
For the planning scenario, optimization identified a single solution that met 100% of targets for species and habitat types (Fig. 4a). National parks and partly-protected areas were locked into the solution from the outset to reflect existing target achievement, and additional areas identified, as close to them and clustered as possible, where outstanding targets could be met. Only 5.2% of this solution occurred within the settlement halo, assuring minimal impact on land used primarily for local livelihoods.

Figure 4. Single solution meeting all targets efficiently.

- (a) National parks cover 10.8% of Gabon and contain 18% of the overall proportion of species and habitats in this study. This single, optimal solution covers an additional 17.7% of Gabon (including partly-protected areas), and more than triples the overall proportion, to 60%.



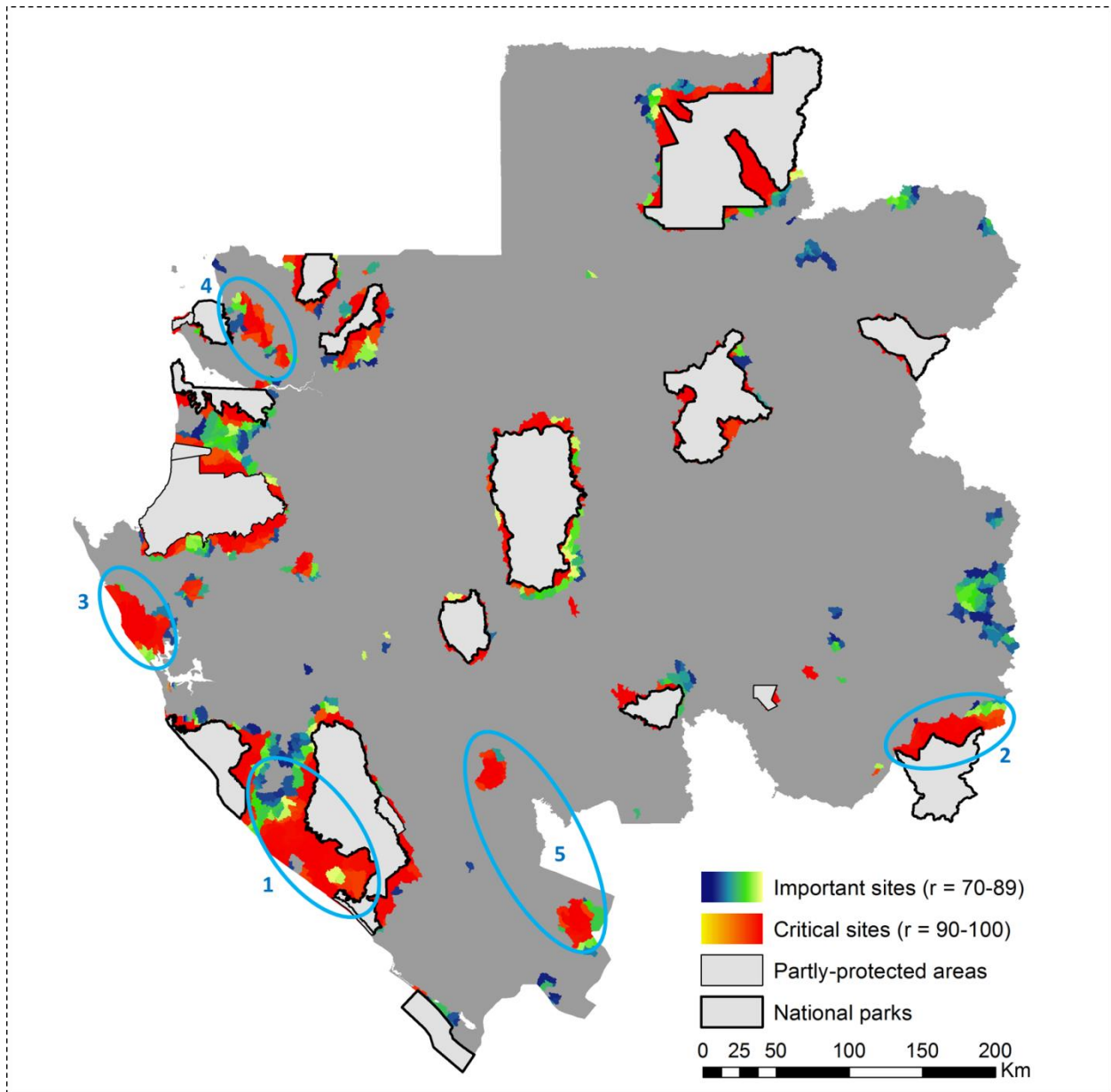
- (b) Percent of species distributions represented in national parks, in targets, and in the single, optimal solution (referred to as the land management solution below). National parks met only 12% of species conservation targets. The single solution built upon the park network, meeting all targets and exceeding 30 of them.



Within this solution, we focused on *critical* and *important* sites (Fig. 5). *Critical* sites covered 5.5% of the country outside of protected areas, mostly extending protection adjacent to them. *Important* sites covered an additional 3.5%. Although all critical sites are necessary to meet targets, we highlight five which cover only 2.3% of land and together address most gaps in species and habitat representation. Importantly, less than 7% of these five critical sites occur within settlement halos. We highlight: 1) south/west of Moukalaba-Doudou NP – exceptionally diverse, with 19 priority species (10 restricted range) and five habitat types (1 rare grass type needed to meet targets); 2) north of Plateaux Bateke NP – distinctive for bai habitat (a key resource for elephants (*Loxodonta cyclotis*) and other wildlife like the Dja river warbler (*Bradypterus grandis*)), one of two of the country’s known nesting sites for the Peregrine falcon

(*Falco peregrinus*), eight priority species (half savanna specialists), and five habitat types; 3) Ozouri on the central coast – remarkable for its mix of coastal, wetland and forest species and habitats at the mouth of the Ogooué River; 4) east of Akanda NP – Gabon’s only example of hyperhumid rugged forest, a relatively restricted, unprotected habitat type, and associated species; and 5) the savannas north and/or south of Ndendé – important for representing savanna habitats and species, which are currently under-protected in Gabon.

Figure 5. Species and habitat planning scenario. Protected land, locked into this scenario, is complemented by priority areas to meet targets efficiently. We highlight five critical sites in particular: 1) south/west of Moukalaba-Doudou NP; 2) north of Plateau Bateke NP; 3) Ozouri, 4) east of Akanda NP; and savannas 5) north and/or south of Ndendé.



3.5 DISCUSSION

We conducted the first formal conservation assessment and spatial prioritization for the country of Gabon, putting in place a vital information base for protected area and land use decisions. We discovered that 9% of terrestrial vertebrates met criteria for conservation attention (Fig 1a), many of them unrecognized by species' protection laws (Fig 1b). Most species were narrowly distributed (Fig 2a) and thus may be easy to overlook and unlikely to persist under increased development without explicit management (Groves 2003). We found that although many critical and important sites for these species are already protected (Fig 3), coverage was far from sufficient – national parks met only 12% of species' conservation targets (Fig 4b). We generated a solution that met 100% of targets efficiently (Fig. 4a), identifying a suite of key areas to protect and manage, with minimal inclusion of land used primarily for local livelihoods. We draw particular attention to a handful of critical sites to protect (Fig. 5) which cover only 2.3% of the country. More broadly, this study establishes a systematic approach and planning platform that can serve other purposes in a country whose political commitments include both conservation and development (Republique Gabonaise 2012) .

With an extremely low rate of deforestation (Sannier et al. 2013), some of Africa's greatest remaining populations of forest megafauna (Blake et al. 2008), and a substantial network of national parks (Anonymous 2002), Gabon is already considered by many to be a conservation success. Yet prior to this study, the performance of its protected areas in representing biodiversity had never been critically or systematically examined. Furthermore, a plan to complete them by filling conservation gaps – part of the original protected area vision (Anonymous 2002) – remains undrafted. By articulating a set of conservation goals and condensing a wealth of expert knowledge to map and account for the country's existing conservation achievements, this study offers sound guidance for future protection decisions.

While some priority sites we identified had already been identified before (IUCN 1990, Kamdem Toham et al. 2006), many were new. Importantly, for the first time, each site can now be traced to the species and habitats it protects, for transparent decision-making. This biodiversity planning platform can also be used for other purposes, such as to inform field surveys or environmental impact assessments, which is particularly relevant as the country expands its industrial activities in sectors like agriculture and mining (Republique Gabonaise 2012).

Managing impacts of development on biodiversity is a great challenge in places like Gabon, where wildlife managers are severely hampered by lack of information, such as population trends and distributions of the species in their charge. Today, only two studies documenting population trends for two species exist for the country, both of them revealing precipitous declines – between 1983 and 2000, Gabon lost over half of its gorilla population to Ebola and commercial hunting (Walsh et al. 2003), and approximately 60% of its elephants to hunting-related pressures in the last decade (Maisels et al. 2013). Loss of these large forest architects from Central African landscapes is alarming, as it is thought to indicate faunal erosion and changes in ecosystem function at other levels (Abernethy et al. 2013). However, outside of hunting control and national park management, little is known or done to target species-level protection in Gabon for the majority of wildlife species. By drawing attention to a wider (but manageable) set of species that merit conservation attention, this study convinced the National Parks Agency and Wildlife Department to adopt a transparent, criteria-based procedure to assess species' status based on biology, distribution and threat, and to use a decision tree to help determine which species meet criteria for national protection (K. Jeffery, pers. comm.). The revised species protection lists provide clear justification to law-makers or others who might challenge, need to defend, or otherwise seek rationale for protection decisions.

Putting biodiversity on the map is an important step in preempting its loss (Rodrigues et al. 2004, Brooks et al. 2006), but is still largely untackled at a practical level in many places that need it most (Meijaard and Sheil 2012). We demonstrate that, even in one of the most data-poor regions of the world, a wealth of existing information can be harnessed to generate and evaluate conservation scenarios at scales relevant to land management and decision-making (Possingham 2012). Admittedly, we faced important limits in assembling and mapping information, which compromised the objectivity and repeatability of the work (see Appendix 3). We relied heavily on expert knowledge, which was often the only source of information, but inevitably incurs error due to limits in any expert's knowledge, objectivity or accuracy (Kuhnert et al. 2010). However, we believe our errors would have been greater had we relied on existing data without refining them with local expert knowledge. For example, to map mammals we started with global distribution models (Rondinini et al. 2011) and refined them based on field observation and natural history knowledge (Appendix 3). In this process, 88% of all Extents of Occurrence mapped at a global scale changed based on local knowledge (44% of range polygons increased in area, 44% decreased), and 100% of the Areas of Occupancy (suitable habitat within a range) changed, most of them decreasing to reflect hunting pressure that had not been taken into account in the global models (Rondinini et al. 2011). In general, relying on existing suitable habitat models would have overestimated the area thought to be occupied by species, increasing commission error (false presences), whereas using only existing point locality records would have underestimated the distribution of key locations for species, increasing omission error (false absences; Rondinini et al. 2006). Reducing these errors through expert mapping increased confidence in both the planning process and its results. However, clearly there is room for improving distribution maps in the future, by including more empirical

data, greater treatment of expert information (Martin et al. 2005, Kuhnert et al. 2010), and explicitly and robustly accounting for uncertainty (Regan et al. 2002, Burgman et al. 2005).

Most countries have policies protecting their biological resources, but without taking concrete steps to prioritize the species, habitats and locations that need attention, “conserving biodiversity” will remain an unclear and therefore elusive goal. This is especially important in tropical forest areas, which are susceptible to the “empty forest” syndrome (Redford 1992, Galetti and Dirzo 2013) and cannot rely on indirect measures of conservation performance used elsewhere, such as the extent of forest cover, to evaluate biodiversity on the ground (Geldmann et al. 2013). An instructive finding from this study was that many priority species were naturally restricted to fairly discrete distributions within the relatively intact, continuous forested landscape. This implies that a handful of land managers operating at few sites may have a disproportionate impact on the persistence of priority species in Gabon. This pattern is important because currently, wildlife surveys on production lands focus primarily on apes and elephants because they are highly valued and conspicuous to survey. Far less attention is paid to the vast number of less-iconic species that currently risk being overlooked, but might be possible to save, if the scientific community uses its collective knowledge to put them on the map and work with decision-makers and managers to improve conservation policy and actions on the ground.

3.6 SUPPORTING MATERIAL FOR CHAPTER 3 – PUTTING BIODIVERSITY ON THE MAP: CONSERVATION PRIORITIES IN GABON

APPENDIX 1. CONSERVATION ASSESSMENT CRITERIA

We sought criteria that were simple, understandable, defensible, quick to use, possible to apply even with few data, and compatible with those used by established conservation efforts and organizations.

Criteria were either 1) legal or 2) scientific, although these are often linked. Legal criteria reflected species protected under national laws or international conventions recognized by Gabon. Scientific criteria included measures commonly used to evaluate extinction threat for species, such as range restriction, rarity, special distributions or small or declining populations.

We drew heavily on four established conservation assessment schemes: IUCN Red List assessments at the global (IUCN 2012b) and regional (IUCN 2012a) levels, Important Bird Areas (Stattersfield et al. 1998) and Key Biodiversity Areas (Eken et al. 2004). Potential criteria were first identified through a literature review, then refined through an internal review among conservation scientists in Gabon to tailor their feasibility with the local level of knowledge.

In the end we used 12 conservation assessment criteria (Table 1 in main text), explained in detail below.

Criteria 1-2 address legal protection at national and international levels.1. Nationally protected

Gabon's national species protection law, Decree n° 0164/PR/MEF dated 19/01/2011 (Annexes 1 & 2), fully protects 21 mammal species (one marine), two mammal genera, seven reptile species (four marine) and one bird species, prohibiting their hunting, capture, detention, commercialization or transport. It partly protects six mammal species, two reptile species and five bird species, regulating the above actions.

2. Internationally protected

Gabon's fauna is protected under four international conventions:

- a. *Convention on Biological Diversity (CBD)*. Gabon ratified the CBD in 1997. Parties to the CBD are legally-bound to protect globally threatened species (Art. 7, Annex 1, CBD), defined as those listed as Critically Endangered (CR), Endangered (EN) or Vulnerable (VU) on the IUCN Red List of Threatened Species (IUCN 2014). All species listed as CR, EN and VU were taken into consideration in this study.
- b. *Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES)*. Gabon is party to CITES since 1989, and is legally-bound to control the commerce of species listed in its Appendices. In this study, we considered only species on CITES Appendix 1 as part of our assessment, since they are "species threatened with extinction" (Art. II, Appendix 1).
- c. *Convention on the Conservation of Migratory Species of Wild Animals (CMS)*. Gabon is party to the CMS since 2008, and is legally-bound to protect the species listed in Appendix 1, which are considered endangered migratory species, as well as those protected under two specific Agreements: the "African Eurasian Waterbird Agreement" (AEWA) and the "Agreement on the

Conservation of Gorillas and their Habitats.” In this study, we considered species on CMS Appendix 1; species given highest priority under the AEWA Action Plan (those in Annex 3, Table 1, Column A requiring action for populations in Gabon); and the western lowland gorilla (*Gorilla gorilla*) for the “Agreement on the Conservation of Gorillas and their Habitats” (Art. IV (3)).

- d. *African Convention on the Conservation of Nature and Natural Resources (Algier’s Convention)*. Gabon ratified the Algier’s Convention in 1998. Parties to the Convention are legally-bound to protect species listed in the Convention. However, the species list dates to 1968, thereby not reflecting recent conservation status. Therefore, we did not consider species on the 1968 list in our criteria, even though it is still in force. (In 2003, the Convention was revised to provide additional protection to species listed as CR, EN or VU on the IUCN Red List of Threatened Species. However the 2003 revision has not yet entered into force).

Criterion 3 addresses range restriction and small or declining populations.

The assessment procedure was similar to that of a national Red List review (IUCN 2012a), but abbreviated due to constraints on time and participation. We considered criteria A-D only. In each case, we applied criteria at the Vulnerable (VU) level of threat only, to avoid the tendency to overrate species in a low data situation. Many species lacked data for complete evaluation, so experts applied best estimations, annotated with explanations where possible. For these reasons, we consider species meeting any of these criteria as *potentially or likely to be* threatened at national level, indicating a need for further study.

3. Likely to be threatened at national level

- a. *Population size reduction.* $\geq 30\%$ population decline observed, estimated, inferred or suspected in the past 10 years or 3 generations. The causes of reduction may not have ceased, be understood, or be reversible (modified after IUCN criterion A2 for VU). *Note:* IUCN criterion A has 4 sub-categories for assessing population decline. We only applied criterion A2. We did not apply criterion A1 because we considered that most causes of reduction may not have ceased (since hunting or harvest are among the biggest threats to species with population decline in Gabon, and these activities are ongoing). We did not apply criterion A3 or A4 because we were not confident stating projections into the future.
- b. *Small declining or fluctuating range.* A species whose range is very globally restricted ($< 20,000 \text{ km}^2$ EOO) and/or occupies a small area ($< 2000 \text{ km}^2$ AOO), and is either severely fragmented or known from ≤ 10 locations, or has continuing decline or extreme fluctuations in range or occupation (IUCN criterion B for VU).
- c. *Small population size and decline.* Population of $< 10,000$ mature individuals declining at 10% (within 10 years or 3 generations). Or population of $< 10,000$ mature individuals in a continuing decline, and either all individuals are in one subpopulation, or experience extreme fluctuation in population (Modified after IUCN criterion C for VU status). *Note:* we did not apply criterion C2ai due to lack of population data.
- d. *Very small range or restricted population.* A species globally known to occupy $< 20 \text{ km}^2$ (AOO) or known from ≤ 5 locations in Gabon, presumably due to actual rarity, versus low survey effort (modified after IUCN criterion D2 for VU status). *Note:* we did not apply criterion D1 due to lack of population data. We modified D2 slightly by recognizing species known from ≤ 5 locations *in Gabon*, as we did not have adequate information on localities outside Gabon. Also, because there

are many species known from ≤ 5 locations due to lack of survey effort, experts were asked only to report those believed to actually occur rarely.

For any species likely to be threatened at national level, we collected information about the influence of surrounding populations, if it was known:

- *Face risk from outside Gabon.* A species whose conspecific populations in surrounding/migratory countries increase the extinction risk for the population in Gabon (modified after IUCN 2012a). This is the case where populations thought to be declining nationally are not isolated from surrounding populations, and conditions for surrounding populations increase the risk of extinction for populations in Gabon. For migratory species, it is the case where population risk is increased by threats in other countries where it spends part of its distribution.
- *Isolated from conspecific populations in surrounding countries.* This is the case where populations thought to be declining nationally are either endemic, or are so isolated from conspecific populations that they 'act' as an endemic (IUCN 2012a). In this case they cannot be 'rescued' by other populations immigrating from other areas.

Criterion 4 addresses important populations or distributions in Gabon.

4. Important populations or distributions

- a. *Endemic or near-endemic.* We define endemism by political borders to be compatible with species' checklists and national records in many countries. We consider a species 'endemic' if its only known occurrence is in Gabon, and 'near-

endemic' if is known to occur in ≥ 3 contiguous countries including Gabon (modified after Anderson 2002).

- b. *Important population in Gabon.* A species whose range is globally-limited with an important proportion of its global population occurring in Gabon regularly (modified after IBA criterion A2, or KBA criterion 2).
- c. *Migratory with a large congregation in Gabon.* Migratory species with at least 1% of the global population congregating in Gabon at a given time, for breeding, foraging, roosting, or other bottleneck activities (modified after IBA criterion A4, and KBA criterion 3).
- d. *Rare or special distribution for a species with national scientific importance.* A species with a rare, special or notable distribution within Gabon, the location or configuration of which may be especially relevant to protect or manage in order to assure the species' persistence in Gabon.

APPENDIX 2. SPECIES ASSESSMENT AND PRIORITIZATION

The first list of amphibians, reptiles, birds and mammals in Gabon was published in 2008, documenting known occurrences of 1076 species in each national park and in the country (Christy et al. 2008). We systematically evaluated the terrestrial species on this list, as well as aquatic and semi-aquatic species whose habitats are embedded in a terrestrial context that would be affected by land use. This included a few introductions, visiting taxa (non-breeding in Gabon) and vagrant taxa (occasional visitors). We did not include marine species. Database searches were conducted by species name (versus by country, etc.) since some species on the national list are not recognized as occurring in Gabon in global databases, and some species recognized as occurring in Gabon on global lists are not (or no longer) confirmed in-country.

Evaluations were performed by a small team of biologists and taxonomic specialists with careers based largely in Gabon. All species were first evaluated by a literature review, including global, regional, national and local species' information (see References). We then conducted one-on-one interviews with specialists covering each species, which generally revealed additional specialized sources of information including published and unpublished field observations. Specialists were advised to reply only when they had justification or confidence in their answer, and to note uncertainties. Species' evaluations were conducted in 2008-2009 and periodically updated since. Therefore, a few cases exist of species' status changing over time (for example, a species that was protected under national law in 2009 but removed from protection in 2011); such changes are noted in Supplementary Table 1.

In this study, we defined priority species as those meeting any of the criteria 1, 2a-c, 3a-d, and 4a endemic only. Given what we know at this time, we consider these to be the primarily-terrestrial birds, mammals, amphibians and reptiles whose conservation prioritization in Gabon is most reasonably defensible by legal and scientific criteria, and whose long-term global survival may depend strongly on conditions in Gabon, for which targeted management is justified. In addition, species meeting criteria 4b-d may be especially important to take into consideration in spatial planning.

APPENDIX 3. MAPPING SPECIES DISTRIBUTIONS

We collated information on species' locality records, geographic ranges and habitat preferences from the literature and expert knowledge for reptiles, birds and mammals in Supplementary Table 1 (Mbina [no year] , Malbrant and Maclatchy 1949, Caballé 1978, Emmons et al. 1983, Tutin and Fernandez 1984, Lahm 1986, Blom et al. 1992, Lahm 1993, Oliver 1993, White 1994,

Barnes et al. 1995, Garcia and Mba 1997, Kingdon 1997, Brugière 1998, Brugière and Gautier 1999, East 1999, Gautier-Hion et al. 1999, Istituto di Ecologia applicata 1999, Fay 2000, Blake et al. 2001, Borrow and Demey 2001, Abernethy et al. 2002, Anonymous 2002, Sinclair et al. 2003, Walsh et al. 2003, Fisher ed. 2004, Starkey 2004, Brugiere 2005, Brugière et al. 2005, Henschel et al. 2005, Latour 2005, Maran and Pauwels 2005, Nicolas et al. 2005, Abitsi 2006, Alonso et al. 2006, Burger et al. 2006, Henschel 2006, Keith et al. 2006, Laurance et al. 2006b, O'Brien et al. 2006, Pauwels et al. 2006, Telfer 2006, Aba'a Nseme and Bezangoye Ndoukoue 2007, Blake et al. 2007, Blanc 2007, Christy et al. 2007, Croes et al. 2007, Lahm et al. 2007, Maisels et al. 2007, Morgan and Lee 2007, Pauwels and Maran 2007, Pauwels and Rödel 2007, Blake et al. 2008, Henschel 2008, Pauwels and Vande weghe , Abernethy and Ndong Obiang 2009, Morgan 2009, Keith 2011, Coad et al. 2013). Amphibians were not possible to map due to constraints on time and information. Information was sought from published and unpublished literature, online databases, museum collections, field reports and observations, and screened by considering the quality, age and source of data, taxonomic and geographic precision, and spatial extent of sampling (Boitani et al. 2011).

Our objective was to produce distribution maps to inform spatial planning at a national scale.

Two types of distribution maps were produced depending on the information available:

- 1) maps of point localities, recording confirmed observation sites or locations important for a species;
- 2) maps of relative habitat suitability in two classes, suitable and less-suitable, for species with more observations and information about range limits, ecology and habitat preferences in Gabon.

In some cases, both kinds of maps were prepared for the same species, complementing each other in information, so as to account both for known localities – which may be limited in number or spatially-biased, but are sure to represent important occurrences – and for larger areas of potential suitable habitat which would be likely but not guaranteed to contain the species.

To map point localities, we assembled records and plotted them in a GIS. Many records had not been taken with a GPS, so were plotted by planning unit, often by the observer. If a mobile species was known to inhabit a particular habitat at a site – such as a bird observed frequently in wetlands surrounding a lake – all planning units containing the habitat at the site were recorded.

To map relative habitat suitability, we followed the method in Rondinini et al. (2011). Each species' geographic range (Extent of Occurrence) was first determined from the literature or online databases (such as IUCN 2014) and plotted in a GIS. Mammal range polygons for this exercise were provided by the Global Mammal Assessment (Boitani et al. 2010). Global range limits were then adjusted if point locality data or local knowledge confirmed newer or more accurate limits of distribution within Gabon.

Within these ranges, suitable habitat (Area of Occupancy) was mapped deductively based on knowledge of species' habitat preferences with respect to four factors: 1) land cover; 2) elevation, topography or landform; 3) proximity to water; and 4) proximity to roads or human settlement.

- 1) Land cover

To represent land cover we used the Globcover data set (300m resolution) (Bicheron et al. 2008). For each species whose distribution is determined by vegetative cover, we reclassified each landcover type as either suitable or less-suitable. In addition, one species' distribution (Dja river warbler, *Bradypterus grandis*) is determined by a particular type of forest clearing which could not be detected in the landcover dataset. We approximated these forest clearings by assembling field-collected GPS localities for baobabs (Fay 2000, Mve Mebia 2007, Bout 2011) and applying a 1km buffer around points.

2) Elevation, topography or landform

To represent elevation, topography and landform we used the Shuttle Radar Topographic Mission (SRTM) elevation model (90m resolution) (Jarvis et al. 2008). Few species' distributions were determined by elevation, topography or landform. For one species whose distribution is thought to be related to altitude (Dja river warbler, *Bradypterus grandis*), we reclassified the elevation model as either suitable or less-suitable at expert-specified elevations. For one species whose distribution is related to topographic ruggedness (Red-headed mountain picathartes, *Picathartes oreas*), we used the grid of rugged terrain developed from (Jarvis et al. 2008) in Chapter 2 of this thesis. Finally for one species whose distribution is related to rocky outcrops or inselberg landforms (Freckled nightjar, *Caprimulgus tristigma*), we identified areas of exceptional variability in local relief using the Topographic Position Index (TPI) (Jenness 2006) in a 15-cell radius based on the elevation model. We calculated the standard deviation of TPI in R (R Core Team 2013) and classified areas of >2.5 std. as having considerable variability in local elevation, as they reflected our field observations in different places around the country. Of these areas, we distinguished isolated formations from contiguous ridges by inspecting the layer in Google Earth. Isolated points were retained and a 500m buffer applied to approximate inselberg landforms.

3) Water

To represent water, we used the surface water dataset developed in Chapter 2 of this thesis to represent lakes, lagoons and large rivers. To represent smaller rivers we used the digital river network corresponding to catchments developed as planning units in this study (see 3.3.2.1 in main text). For species whose distribution is related to water we created buffers around these water sources at distances used for each species, as dictated by experts.

4) Roads, railways and human settlements

We applied buffers around road, railway, rail station and human settlement datasets to represent hunting pressure (primarily) and anthropogenic habitats. We used the Gabon national dataset to represent primary and secondary roads, railways, rail stations, villages and cities (available from World Resources Institute 2009). To account for the effects of roads and human settlements of neighboring countries within Gabon, we used datasets for roads and villages for Cameroon (World Resources Institute 2005), Congo (World Resources Institute 2007) and Equatorial Guinea (World Resources Institute 2006).

We used these datasets as a proxy for hunting pressure and anthropogenic habitats. Commercial hunting pressure in Central Africa has a well-documented relationship with access to markets and hunting controls along roads (see References, especially Henschel et al. 2005, Laurance et al. 2006b, Buij et al. 2007, Blake et al. 2008, Coad 2008, Laurance et al. 2008, Van Vliet and Nasi 2008). We modified the Gabon datasets to reflect local, field-based observations of hunting pressure in different areas of the country by: 1) identifying roads with low hunting pressure due to poor access or presence of hunting / road management; 2) adding new roads, taken from GPS tracks, with high hunting pressure; and 3) distinguishing villages and rail stations as having

either high or low market access, depending on road or river connections to a major population center. We then distinguished 11 human-use types related to hunting pressure: 1) the capital city, Gabon's largest population center; 2) large cities; 3) market villages; 4) non-market villages; 5) primary and secondary roads with hunting pressure; 6) primary and secondary roads with low hunting pressure; 7) rail stations with hunting pressure; 8) rail stations with low hunting pressure; 9) railroad track; 10) human settlements in neighboring countries; and 11) roads in neighboring countries. For species whose distribution is determined by hunting pressure, we applied buffers to each type per species at appropriate distances, following expert knowledge. For species whose distribution is determined by anthropogenic habitats, we used the original datasets and created buffers around the features as appropriate per species, based on expert knowledge.

We combined these features to distinguish suitable and less-suitable areas for each species within its geographic range, following the GIS processing methods used in the Global Mammal Assessment (Rondinini et al. 2011). All polygon features were converted to raster format. Raster datasets were resampled to 300m (the resolution of the landcover dataset) using a bilinear resampling technique. For each species, each relevant layer was reclassified as either 1 or 0, representing suitability or non-suitability, respectively. We then combined these layers using the "Map algebra" function in ArcGIS (ESRI 2011), and clipped the resulting raster to the species' range polygon.

Preliminary maps of species' localities and suitable habitat distributions were circulated among field biologists and wildlife specialists with knowledge of different parts of the country for

verification. Based on this feedback, maps were iteratively corrected to better reflect expert field observations. We were obliged to use this expert verification approach due to limits in data. Since model accuracy is therefore unquantifiable, and in many cases unknown, we advise caution in the use of the models (especially at finer spatial scales than were intended). However, many of these models have also been used provisionally to inform or prepare field surveys in different parts of the country, and have matched field observations well. We consider these maps to be a preliminary benchmark of information, and recommend they be used to guide field evaluations and target land management attention, versus to enact actual land use decisions without further field verification.

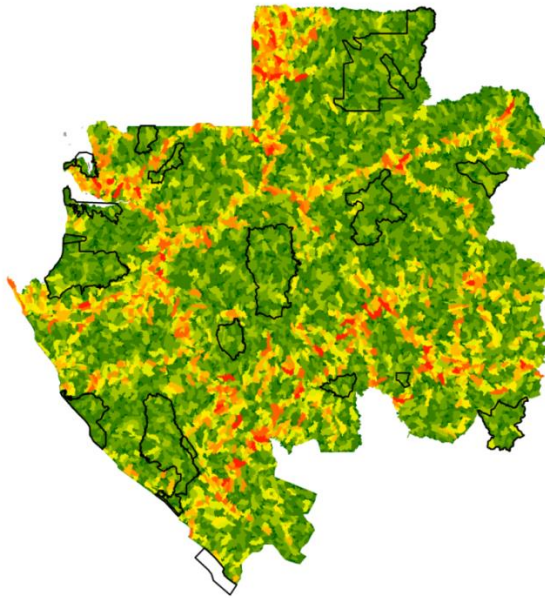
APPENDIX 4. LAND USE CONSTRAINTS

Protected areas (or “protected land”) in this study included all 13 fully-protected national parks, and five partly-protected areas: the Wonga-Wongé Presidential Reserve, the Plaine Ouanga and Moukalaba faunal reserves, the Lekedi hunting domain, and the Rapondah Walker arboretum. We did not represent other existing partly-protected areas that are currently being considered for status change (the Sette Cama, Ngové-Ndogo and Iguéla hunting domains), or others, so that we could evaluate the level of importance that their species and habitats offer to the network independent of their protection status.

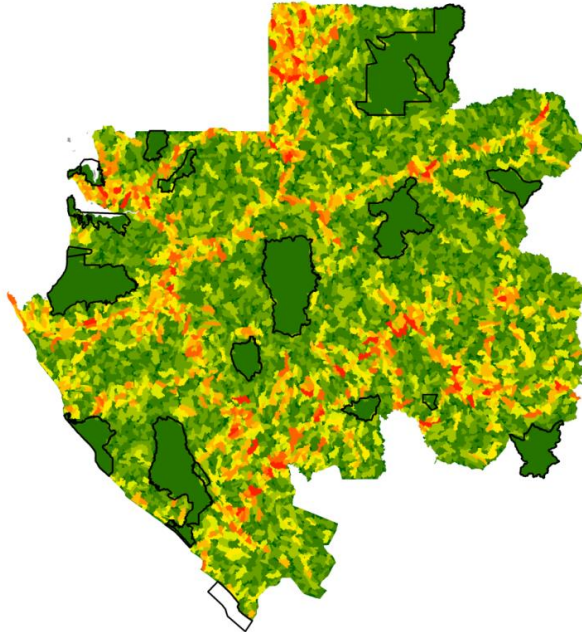
Settlement halos were represented by buffers around villages, towns and cities in the national GIS dataset (available from World Resources Institute 2009).

These land use data were represented as costs calculated at the catchment level for (a) the species-only scenario and (b) the species and habitat scenario.

(a) *Species-only scenario*. Catchment base cost was equal to area (ha), except for any area within the settlement halo, which was multiplied by ten. Warmer colors are relatively more costly. Protected land is outlined in black for reference.



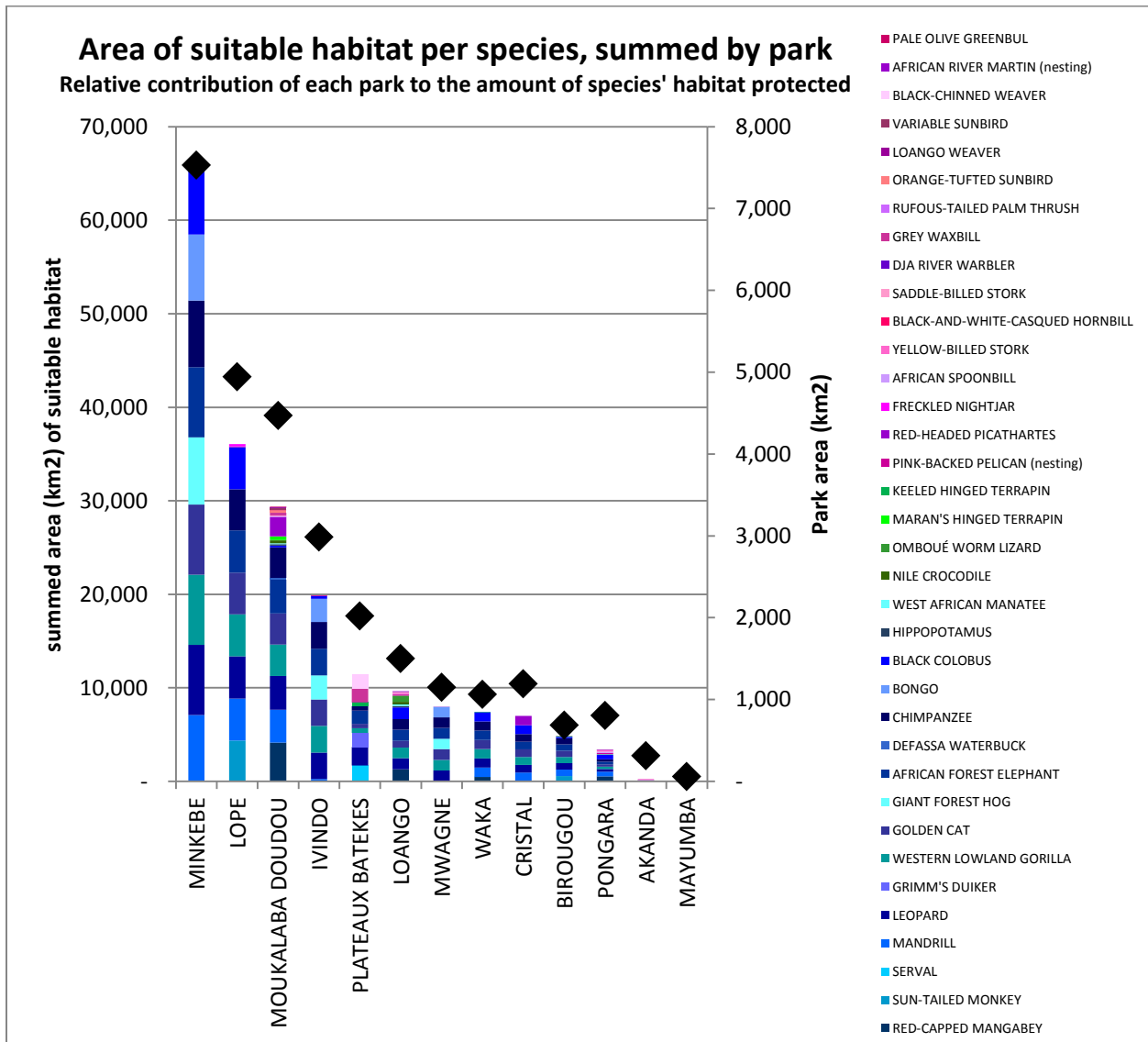
(b) *Species and habitat scenario*. Catchments with $\geq 50\%$ of their area on protected land were locked into the solution, in darkest green. For catchments with 10-49% of their area on protected land, cost was equal to area (ha). For catchments $< 10\%$ on protected land, cost was handled as in the species-only scenario. Warmer colors are relatively more costly.



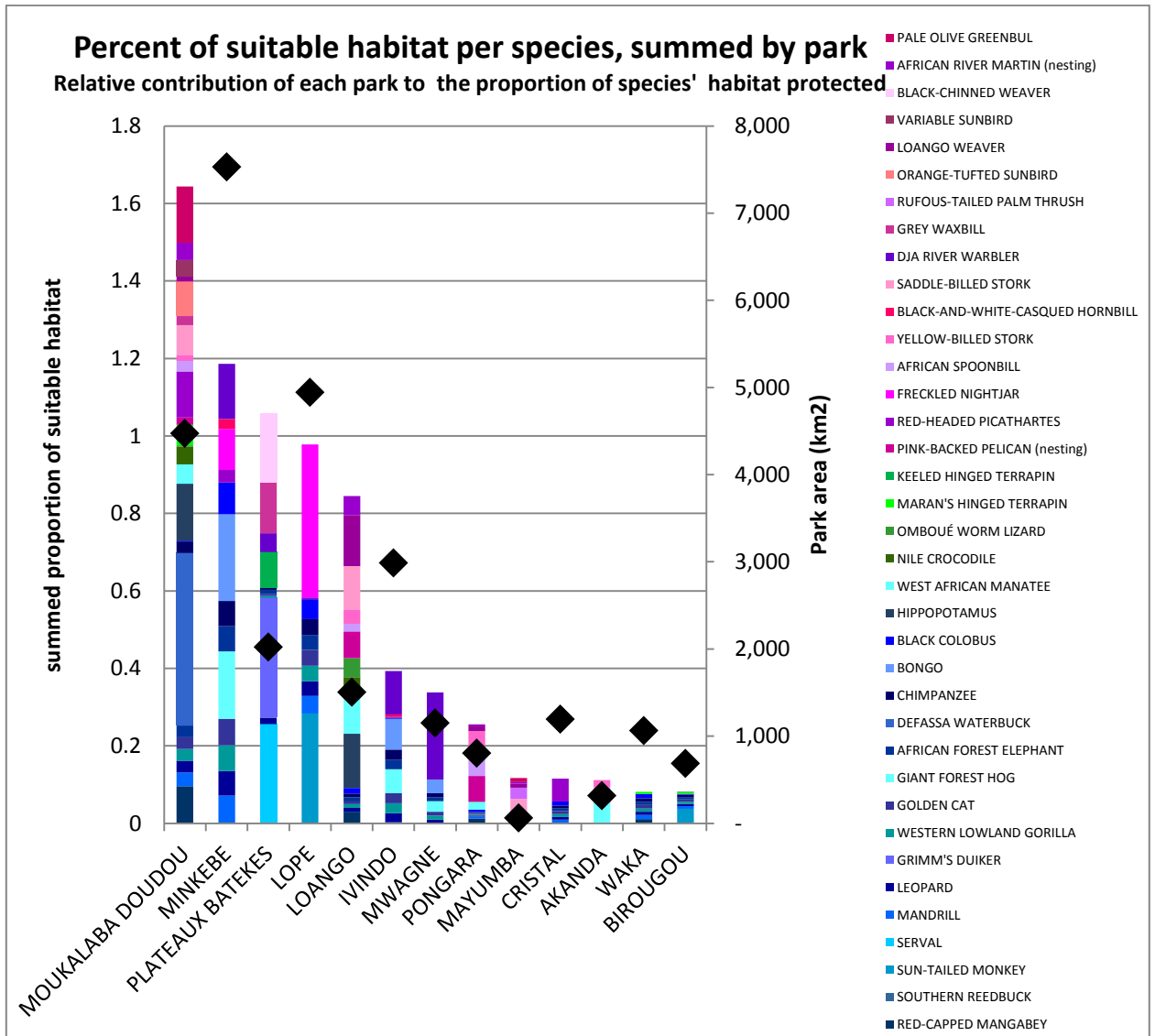
APPENDIX 5. SPECIES REPRESENTATION BY NATIONAL PARK

Area and percent of suitable habitat per species, summed by park. Mammals are represented in blue, reptiles in green, birds in pink. Black diamonds indicate park area (km^2).

Area (km²) of suitable habitat per species, summed by park. Summed area of suitable habitat tends to reflect park size for species with extensive distributions, notably large mammals, with larger parks containing more area of suitable habitat than smaller parks.



Percent of suitable habitat per species, summed per park. Summed proportion of suitable habitat reflects the contribution of each park to overall representation of species' suitable habitat. Larger parks do not necessarily contribute a higher proportion of suitable habitat than smaller parks. Rather, the park's coverage of restricted species' distributions mattered.



Supplementary Table 1: Conservation assessment of primarily-terrestrial vertebrates in Gabon, with notes below.

			Criteria in Table 1:	2a	3a-d	4a	1a	2b-c	4b	4c	4d
Genus	Species	Common name		Globally threatened CR EN VU	Potentially nationally threatened	Endemic to Gabon Near-endemic	Nationally protected Fully Partially	Internationally protected CITES CMS	Important population in Gabon	Important congregation in Gabon	Rare or special distribution
AMPHIBIANS	Arthroleptis	adelphus	FOULASSI SCREECHING FROG								
	Cardioglossa	gratiosa	ONGOT LONG-FINGERED FROG								
	Leptodactylodon	blanci	BLANC'S STREAM FROG		1						
	Leptodactylodon	stevarti	STÉVART'S STREAM FROG	2							
	Trichobatrachus	robustus	HAIRY FROG								
	Amietophrynus	funereus	ANGOLA TOAD								3
	Amietophrynus	superciliaris	GIANT AFRICAN TOAD					4			
	Nectophryne	batesii	BATES'S TREE TOAD								
	Werneria	iboundji	IBOUNDJI WATERFALL TOAD	5							
	Hemisus	perreti	PERRET'S SHOVELNOSE FROG								
	Acanthixalus	spinusus	WARTY TREE FROG								
	Afrixalus	laevis	YELLOW BANANA FROG								6
	Alexteroon	hypsiphonus	EKOMTOLO FRILLED TREE FROG								
	Alexteroon	obstetricans	COMMON FRILLED TREE FROG								
	Chlorolius	koehlerii	KOHLER'S TREE FROG								7
	Cryptothylax	greshoffii	GRESHOFF'S WAX FROG								
	Hyperolius	mosaicus	SOUTH CAMEROON REED FROG								8
	Kassina	sp. nov.	DOUDOU MOUNTAINS REED FROG		9						
	Leptopelis	crystallinoron	CRYSTAL MOUNTAINS TREE FROG		10						
	Leptopelis	viridis	RUSTY TREE FROG		11						
Opisthothylix	immaculatus	GREY-EYED TREE FROG									
Phlyctimantis	boulengeri	BOULENGER'S STRIPED TREE FROG			12						
Petropedetes	palmipes	EFULEN ROCKY RIVER FROG	13								
Petropedetes	parkeri	PARKER'S ROCKY RIVER FROG		14							
Petropedetes	vulpiae	FUCH'S ROCKY RIVER FROG								15	
Phrynobatrachus	batesii	BATES'S PUDDLE FROG								16	
Phrynobatrachus	ogoensis	OGOUE PUDDLE FROG			17						
Hymenochirus	feae	GABON DWARF CLAWED FROG			18						
Xenopus	andrei	ANDRE'S CLAWED FROG								19	
Xenopus	petersii	PETER'S PLATANNA								20	
Hylarana	amnicola	FOREST WHITE-LIPPED FROG									
Aubria	subsigillata	BROWN FISHING FROG									
Ptychadena	pumilio	MEDINE RIDGED FROG			21						
Pelusios	carinatus	KEELED HINGED TERRAPIN			22						
Pelusios	marani	MARAN'S HINGED TERRAPIN									

REPTILES	Cycloderma	aubryi	AUBRY'S SOFTSHELL TURTLE		23					
	Trionyx	triunguis	NILE SOFTSHELL TURTLE		24					
	Croodylus	niloticus	NILE CROCODILE		25					
	Mecistops	cataphractus	SLENDER-SNOUTED CROCODILE	28						
	Osteolaemus	tetraspis	DWARF CROCODILE	27						
	Trioceros	chapini	CHAPIN'S CHAMELEON			28				
	Hemidactylus	angulatus	GABON HALF-TOED GECKO		29					
	Hemidactylus	kamdemtohami	KAMDEM TOHAM'S HALF-TOED GECKO		30					
	Lygodactylus	sp.nov.	IVINDO DWARF GECKO		31					
	Urocootyledon	palmata	WEBBED TAIL-PAD GECKO			32				
	Feylinia	boulengeri	BOULENGER'S LIMBLESS SKINK			33				
	Varanus	ornatus	ORNATE MONITOR				34			
	Cynisca	bifrontalis	OMBOUE WORM LIZARD							
	Cynisca	haugi	LAMBARENE WORM LIZARD							
	Monopeltis	galeata	GABON HELMETED WORM LIZARD			35				
	Leptotyphlops	perreti	PERRET'S WORM SNAKE							
	Letheobia	pauwelsi	PAUWELS'S BLIND SNAKE		36					
	Python	sebae	SEBA'S PYTHON				37			
	Polemon	fulvicollis	FRANCEVILLE SNAKE-EATER			38				
	Bothrophthalmus	brunneus	BROWN LOREAL-PITTED WOLF SNAKE			39				
Hydraethiops	laevis	OCELLATE WATER SNAKE		40						
Spheniscus	demersus	JACKASS PENGUIN	41							
Phaeton	aethereus	RED-BILLED TROPICBIRD						42		
Sula	capensis	CAPE GANNET	43							
Pelecanus	rufescens	PINK-BACKED PELICAN					44			
Fregata	aquila	ASCENCION FRIGATEBIRD	45							
Ixobrychus	minutus	LITTLE BITTERN							46	
Mycteria	ibis	YELLOW-BILLED STORK								
Ephippiorhynchus	senegalensis	SADDLE-BILLED STORK		47						
Threskiornis	aethiopicus	SACRED IBIS					48			
Platalea	alba	AFRICAN SPOONBILL								
Haliaeetus	vocifer	AFRICAN FISH EAGLE					49			
Gypohierax	angolensis	PALM-NUT VULTURE								
Trigonoceps	occipitalis	WHITE-HEADED VULTURE	50							
Stephanoaetus	coronatus	CROWNED EAGLE					51			
Polemaetus	bellicosus	MARTIAL EAGLE							52	
Falco	naumanni	LESSER KESTREL						53		
Falco	vespertinus	RED-FOOTED FALCON						54		
Falco	cherrug	SAKER FALCON	55	check						
Falco	peregrinus	PEREGRINE FALCON						56		
Sarothrura	lugens	CHESTNUT-HEADED FLUFFTAIL							57	
Sarothrura	boehmi	STREAKY-BREADED FLUFFTAIL						58		
Rallus	caenulescens	AFRICAN WATER RAIL							59	
Aenigmatolimnas	marginalis	STRIPED CRAKE						60		

BIRDS

Glareola	cinerea	GREY PRATINCOLE					81			
Charadrius	marginatus	WHITE-FRONTED PLOVER					82			
Pluvialis	squatarola	GREY PLOVER							83	
Vanellus	lugubris	LESSER BLACK-WINGED LAPWING					84			
Calidris	canutus	RED KNOT					85			
Calidris	minuta	LITTLE STINT							86	
Calidris	ferruginea	CURLEW SANDPIPER							87	
Gallinago	media	GREAT SNIPE					88			
Numerius	arquata	EURASIAN CURLEW					89			
Sterna	caspia	CASPIAN TERN					90			
Sterna	albifrons	LITTLE TERN					91			
Sterna	balaenarum	DAMARA TERN					92			
Rynchops	flavirostris	AFRICAN SKIMMER					93			
Psittacus	erithacus	GREY PARROT	74							
Musophaga	rossae	ROSS'S TURACO								75
Otus	icterorhynchus	SANDY SCOPS OWL								76
Bubo	shelleyi	SHELLEY'S EAGLE OWL		77						
Caprimulgus	tristigma	FRECKLED NIGHTJAR								78
Bycanistes	subcylindricus	BLACK-AND-WHITE-CASQUED HORNBILL								79
Melignomon	zenkeri	ZENKER'S HONEYGUIDE								80
Mesopicos	goertae	GREY WOODPECKER								81
Pitta	reichenowi	GREEN-BREASTED PITTA								82
Pitta	angolensis	AFRICAN PITTA								83
Pseudochelidon	eurystomina	AFRICAN RIVER MARTIN				84				
Phyllastrephus	fulviventris	PALE OLIVE GREENBUL								85
Cichladusa	ruficauda	RUFIOUS-TAILED PALM THRUSH								86
Zoothera	camaronensis	BLACK-EARED GROUND THRUSH								87
Zoothera	princei	GREY GROUND THRUSH								88
Bradypterus	grandis	DJA RIVER WARBLER								89
Batis	minima	GABON BATIS				90				
Picathartes	oreas	RED-HEADED PICATHARTES	91							
Nectarinia	bouvieri	ORANGE-TUFTED SUNBIRD								92
Nectarinia	venusta	VARIABLE SUNBIRD								93
Dryocopus	angolensis	PINK-FOOTED PUFFBACK								94
Ploceus	nigrimentus	BLACK-CHINNED WEAVER				95				
Ploceus	subpersonatus	LOANGO WEAVER				96				
Mandingoa	nitidula	GREEN TWINSPOUT								97
Estrilda	perreini	GREY WAXBILL								98
Gorilla	gorilla	WESTERN LOWLAND GORILLA	99					CMS		
Pan	trogodytes	CHIMPANZEE	100							
Colobus	satanas	BLACK COLOBUS				101				
Colobus	guereza	GUEREZA COLOBUS								102
Mandrillus	sphinx	MANDRILL	103							
Cercocebus	torquatus	RED-CAPPED MANGABEY	104							

MAMMALS

Cerocebus	agilis	AGILE MANGABEY								105
Miopithecus	ogouensis	NORTHERN TALAPOIN						108		
Cercoopithecus	solatus	SUN-TAILED MONKEY	107	?						
Perodicticus	potto	POTTO								
Arctocebus	aureus	GOLDEN POTTO								
Euticus	elegantulus	ELEGANT GALAGO								
Galagoides	demidoff	DWARF GALAGO								
Galagoides	thomasi	THOMAS'S DWARF GALAGO								
Sciurocheirus	gabonensis	GABON GALAGO								
Hipposideros	caffer	SUNDEVALL'S ROUNDLEAF BAT								108
Rhinolophus	silvestris	FOREST HORSESHOE BAT		109						
Suncus	remyi	GABON DWARF SHREW			110					
Epixerus	ebii	WESTERN PALM SQUIRREL						111		
Funisciurus	duchailui	DU CHAILLU'S ROPE SQUIRREL			112					
Canis	adustus	SIDE-STRIPED JACKAL		113						
Aonyx	congius	CONGO CLAWLESS OTTER							114	
Bdeogale	nigripes	BLACK-LEGGED MONGOOSE							115	
Herpestes	ichneumon	EGYPTIAN MONGOOSE								116
Crossarchus	platyocephalus	FLAT-HEADED CUSIMANSE								117
Crocuta	crocuta	SPOTTED HYAENA		118						
Poiana	richardsoni	AFRICAN LINSANG							119	
Leptailurus	serval	SERVAL		120						
Caracal	aurata	GOLDEN CAT	121							
Panthera	pardus	LEOPARD	122	?						
Phataginus	tricuspis	TREE PANGOLIN	123							
Smutsia	gigantea	GIANT PANGOLIN	124	?						
Uromanis	tetradactyla	LONG-TAILED PANGOLIN	125							
Orycteropus	afer	AARDVARK								
Dendrohyrax	dorsalis	WESTERN TREE HYRAX								
Trichechus	senegalensis	WEST AFRICAN MANATEE	126							
Loxodonta	cyclotis	AFRICAN FOREST ELEPHANT	127							
Hippopotamus	amphibius	HIPPOPOTAMUS	128							
Hylochoerus	meinertzhageni	GIANT FOREST HOG		129						
Potamochoerus	porcus	RED RIVER HOG							130	
Hyemoschus	aquaticus	WATER CHEVROTAIN							131	
Cephalophus	callipygus	PETER'S DUIKER							132	
Cephalophus	dorsalis	BAY DUIKER							133	
Cephalophus	leucogaster	WHITE-BELLIED DUIKER							134	
Cephalophus	nigrifrons	BLACK-FRONTED DUIKER							135	
Cephalophus	ogilbyi	OGILBY'S DUIKER							136	
Cephalophus	silvicultor	YELLOW-BACKED DUIKER							137	
Kobus	ellipsiprymnus	DEFASSA WATERBUCK		?	138					
Neotragus	batesi	DWARF ANTELOPE							139	
Redunca	arundinum	SOUTHERN REEDBUCK		?	140					

Sylvicapra	grimmia	GRIMM'S DUIKER							
Syncoerus	caffer	AFRICAN FOREST BUFFALO		?	141				
Tragelaphus	eurycerus	BONGO						142	
Tragelaphus	scriptus	BUSHBUCK		?	143				?
Tragelaphus	spekii	SITATUNGA							

Notes:

1. *Leptodactylodon blanci*, endemic to Gabon. Thought to have extremely restricted distribution. Known from 2 localities. Rare.
2. *Leptodactylodon stevarti*, IUCN Red List EN B1ab(iii). Thought to have extremely restricted distribution. Estimated >50% of global population in Gabon. Known from 1 locality in Gabon. Rare.
3. *Amietophrynus funereus*, ranges in Central Africa, but in Gabon appears limited to west.
4. *Amietophrynus superciliaris*, CITES Appendix I.
5. *Werneria iboundji*, IUCN Red List CR B1ab(iii)+2ab(iii). Endemic to Gabon.
6. *Afraxalus laevis*, ranges in Central Africa, but in Gabon appears limited to NE (Mpassa).
7. *Chlorolius koehleri*, ranges in Central Africa, but in Gabon appears limited to north.
8. *Hyperolius mosaicus*, limited to neighboring countries. In Gabon, appears just in north. Requires trees for breeding.
9. *Kassina* sp. nov., unconfirmed taxonomic status. Only known from female specimens within Gabon.
10. *Leptopelis crystallinoron*, endemic to Gabon. Known from 1 locality.
11. *Leptopelis viridis*, ranges widely in Africa. Gabon distribution may be isolated from other populations.
12. *Phlyctimantis boulengeri*, disjunct range in Africa. Gabon distribution may be isolated from other populations.
13. *Petropedetes palmipes*, IUCN Red List EN B1ab(iii). Est. <25% of global population in Gabon. Gabon population small. Believed to be isolated from other pops. Habitat specialist (forest torrents).
14. *Petropedetes parkeri*, known Gabon population is small. Believed to be isolated from other populations. Fragile habitat specialist (forest torrents).
15. *Petropedetes vulpiae*, habitat specialist (river torrents).
16. *Phrynobatrachus batesii*, ranges in Central Africa, but in Gabon appears limited to north.
17. *Phrynobatrachus ogoensis*, known only from type locality near Lambarene.
18. *Hymenochirus feae*, known only from type locality near Lambarene.
19. *Xenopus andrei*, previously known from only 2 localities in Gabon (Mekambo, Makokou); in 2013 also recognized in Cameroon, CAR. Not habitat restricted.
20. *Xenopus petersii*, ranges in Central Africa, but in Gabon appears limited to SW.
21. *Ptychadena pumilio*, ranges widely in Africa. Gabon distribution may be isolated from other populations.
22. *Pelusios carinatus*, estimated VU in Gabon due to limited geographic range.
23. *Cycloderma aubryi*, estimated 70% of population in Gabon. Threatened by hunting.
24. *Trionyx triunguis*, ranges widely in Africa. Threatened by hunting.
25. *Crocodylus niloticus*, estimated VU in Gabon due to hunting. CITES Appendix I.
26. *Mecistops cataphractus*, IUCN Red List A2acde+3code+4acde. CITES Appendix I. Gabon population globally important. Occurs widely in medium rivers (2nd or 3rd order) covered in forest.
27. *Osteolaemus tetraspis*, IUCN Red List VU A2od. Estimated <25% of global population occurs in Gabon. Widespread in Gabon.
28. *Trioceros chaini*, thought to be near-endemic at original assessment (GA, DRC). Since then, also recognized in EG and CG.
29. *Hemidactylus angulatus*, estimated VU in Gabon. Introduced, not thought to be conservation concern. Known from 2 locations in cities.
30. *Hemidactylus kamdentohami*, known from <5 locations in Gabon. Seems rare, although may have a wide distribution within mid-altitudinal ranges.
31. *Lygodactylus* sp. nov, thought to be endemic to Gabon (although unconfirmed taxonomic status). Estimated VU in Gabon. Known from <5 locations. Rare.
32. *Urocotyledon palmata*, only known from Gabon and Cameroon. Canopy dependent.
33. *Feylinia boulengeri*, only known from 2 locations in Gabon. Digging species.
34. *Varanus niloticus*, partly-protected by national law. Widespread.
35. *Monopeltis galeata*, known in Gabon and Equatorial Guinea. Restricted to coastal sedimentary basin.
36. *Letheobia pauwelsi*, known from <5 locations in Gabon. Rare.
37. *Python sebae*, partly-protected by national law. Widespread.

38. *Polemon fulvicollis*, known from Gabon and Congo. Ground species. Likely to be in riverine forest in savannas.
39. *Bothroptalmus brunneus*, near-endemic, but thought to occur widely within that range. Habitat generalist.
40. *Hydraethiops laevis*, known from < 5 locations in Gabon. Rare.
41. *Spheniscus demersus*, IUCN Red List EN A2ace+3ce+4ace. Vagrant in Gabon. Not thought threatened in Gabon.
42. *Phaeton aethereus*, CMS AWEA (Table 1, Col A).
43. *Sula capensis*, IUCN Red List VU A2acde+3cde+4acde;B2ab(iii,iv,v). CMS AWEA (Table 1, Col A). Rare visitor in Gabon. Not thought threatened in Gabon.
44. *Pelicanus rufescens*, was fully-protected by national law; now unprotected.
45. *Fregata aquila*, IUCN Red List VU D2. Vagrant in Gabon. Not thought threatened in Gabon.
46. *Ixobrychus minutus*, CMS AWEA (Table 1, Col A).
47. *Ephippiorhynchus senegalensis*, estimated VU in Gabon. May face hunting outside national parks.
48. *Threskiornis aethiopicus*, was partly-protected by national law; now unprotected.
49. *Haliaeetus vocifer*, was fully-protected by national law; now unprotected.
50. *Trigoniceps occipitalis*, IUCN Red List VU C1+2a(ii). Rare visitor in Gabon. Faces threats throughout its range.
51. *Stephanoaetus coronatus*, was fully-protected by national law; now unprotected. Considered relatively common.
52. *Polemaetus bellicosus*, large territory and distribution in the Plateaux Bateke. Rare to observe.
53. *Falco naumanni*, CMS Appendix I.
54. *Falco vespertinus*, CMS Appendix I.
55. *Falco cherrug*, IUCN Red List VU A2bode+3cde+4bcde. CMS Appendix I. Vagrant in Gabon.
56. *Falco peregrinus*, CITES Appendix I.
57. *Sarothrura lugens*, known from 4 localities in Gabon. Global and local distributions appear patchy but widespread. Difficult to observe.
58. *Sarothrura boehmi*, CMS AWEA (Table 1, Col A).
59. *Rallus caerulescens*, observed once in Gabon (Ivindo River, Makokou). Rare.
60. *Aenigmatolimnas marginalis*, CMS AWEA (Table 1, Col A). Ranges widely, but in Gabon appears limited. Rare. 6 dispersed localities known. Breeds in Bateke area.
61. *Glaucoceryx cinerea*, CMS AWEA (Table 1, Col A).
62. *Charadrius marginatus*, CMS AWEA (Table 1, Col A).
63. *Pluvialis squatarola*, migratory, nonbreeding in Gabon.
64. *Vanellus lugubris*, CMS AWEA (Table 1, Col A).
65. *Calidris canutus*, CMS Appendix I.
66. *Calidris minuta*, migratory, nonbreeding in Gabon.
67. *Calidris ferruginea*, migratory, nonbreeding in Gabon.
68. *Gallinago media*, CMS AWEA (Table 1, Col A).
69. *Numenius arquata*, CMS AWEA (Table 1, Col A).
70. *Sterna caspia*, CMS AWEA (Table 1, Col A).
71. *Sterna albifrons*, CMS AWEA (Table 1, Col A).
72. *Sterna balaenarum*, CMS AWEA (Table 1, Col A).
73. *Rynchops flavirostris*, CMS AWEA (Table 1, Col A).
74. *Psittacus erithacus*, IUCN Red List VU A2abcd+3bcd+4abcd due to trade, habitat loss. Gabon's population may be the last very large population in Africa, and most important population globally. Not thought threatened in Gabon.
75. *Musophaga rossae*, ranges widely, but in Gabon limited to a few sightings at Makokou (despite searches). Rare, an anomaly in Gabon.
76. *Otus icterorhynchus*, known from 3 localities in Gabon. Believed rare.
77. *Bubo shelleyi*, may be VU D for Gabon population (unsure). Largest forest owl, probably needs large areas. Extremely rarely observed globally.
78. *Caprimulgus tristigma*, not widespread, spotty distribution tied to habitat requirements. Not rare where it exists. In Gabon 4 localities known.
79. *Bycanistes subcylindricus*, not rare but known from few places.
80. *Melignomon zenkeri*, ranges widely, but in Gabon, known from few observations. Appears to be naturally rare, small territory.

81. *Mesopicos goertae*, ranges widely, but in Gabon, only known from savanna near Mouila.
82. *Pitta reichenowi*, ranges widely, but in Gabon, appears to have very limited distribution. Very secretive, few observations.
83. *Pitta angolensis*, ranges widely, but in Gabon, appears limited. Observed a few times in Gabon. Naturally rare.
84. *Pseudochelidon eurystomina*, documented in small areas of 5 countries, but mostly exists in Gabon, Congo, DRC. Largest population in Gabon. Widespread in Gabon, but nesting grounds exclusive to coast (perhaps 50,000km²). Also nests in Congo, but threatened there, whereas not thought threatened in Gabon. Susceptible to habitat disturbance by fishermen.
85. *Phyllastrephus fulviventris*, limited global range, not mentioned to exist in Gabon in published sources. Only known from the Gamba area in Gabon.
86. *Cichladusa ruficauda*, in Gabon, limited to southwest.
87. *Zoothera camaronensis*, in Gabon, known from 5 dispersed localities. Apparently at low densities. Difficult to observe.
88. *Zoothera princei*, ranges widely, but in Gabon known from 7 dispersed localities. Apparently at low densities. Difficult to observe.
89. *Bradypterus grandis*, requires bai habitats.
90. *Batis minima*, moderately small global range (>50,000km²), very patchy distribution within it. Recorded in 4 countries. Gabon holds most important population (25-50% of total).
91. *Picathartes oreas*, IUCN Red List VU C2a(i). CITES Appendix I. Estimated 25-50% of global population in Gabon. Small population (1000-10000), but not thought to be declining, threatened, or isolated from surrounding populations. Requires rock and cave habitats; widespread where these habitats exist. Can persist despite logging, since preferred habitats are difficult to access. Adaptable.
92. *Nectarinia bouvieri*, ranges widely but spotty. Limited distribution in Gabon.
93. *Nectarinia venusta*, ranges widely, but spotty. Limited distribution in Gabon.
94. *Dryoscopus angolensis*, ranges widely, but spotty. Limited distribution in Gabon. Thought rare, known from 2 localities.
95. *Ploceus nigrimentus*, reported from 3 countries but may occur more widely. Gabon's small population, limited to Bateke area, is part of a much wider distribution.
96. *Ploceus subpersonatus*, IUCN Red List VU C2a(i). Estimated 75% of global population in Gabon. Reported from 4 countries. Restricted to small area along coast. Not declining, threatened, or isolated from populations in other countries. Adaptable.
97. *Mandingoa nitidula*, ranges widely, but spotty. Known from 7 localities in Gabon at forest edge.
98. *Estrilda perreini*, ranges widely, but spotty. Limited distribution in Gabon, thought rare.
99. *Gorilla gorilla*, IUCN Red List CR A4code. Estimated VU in Gabon due to disease, hunting, habitat loss. CITES Appendix I. CMS Gorilla Agreement. Endemic to Central Africa.
100. *Pan troglodytes*, IUCN Red List EN A4cd. Estimated VU in Gabon due to disease, hunting, habitat loss. CITES Appendix I. Endemic to West and Central Africa.
101. *Colobus satanas*, IUCN Red List VU A2cd. Recorded in 4 countries, but Gabon may hold 75-80% of global population. Estimated VU in Gabon due to hunting, habitat loss. Requires primary forest.
102. *Colobus guereza*, endemic to Central Africa. In Gabon, restricted to extreme NE. Can be locally abundant.
103. *Mandrillus sphinx*, IUCN Red List VU A2cd. Estimated VU in Gabon due to hunting, habitat loss. Endemic to western Central Africa. Gabon may hold largest remaining population. CITES Appendix I.
104. *Cercocebus torquatus*, IUCN Red List VU A2cd. Estimated VU in Gabon due to hunting. Restricted to parts of the coastal sedimentary basin.
105. *Cercocebus agilis*, endemic to equatorial Africa. In Gabon, restricted to extreme NE. Can be locally abundant.
106. *Miopithecus ogoouensis*, endemic to Central Africa. Most of global distribution in Gabon. Not thought threatened.
107. *Ceropithecus solatus*, IUCN Red List VU B1ab(v). May be VU in Gabon due to hunting and habitat loss. Endemic to Gabon (mostly in Forêt des Abeilles).
108. *Hipposideros caffer*, ranges widely in Africa, but an exceptionally large population (500,000 individuals) documented roosting in a cave in NE Gabon.
109. *Rhinolophus silvestris*, IUCN Red List DD. Known from Gabon and Congo. Most of global population believed to be in Gabon, declining. Estimated VU in Gabon due to restricted population. 4 known localities globally (Benga, Bellinga, Lastoursville, and 1 locality in Congo). Requires cave habitats.
110. *Suncus remyi*, known from Gabon, CAR and Congo. Estimated 1/3 of global distribution occurs in NE Gabon. Rare.
111. *Epixerus ebi*, comprised of 3 disjunct distributions, the Central African distribution largely in Gabon. Uncommon. Requires primary forest.
112. *Funisciurus duhaillui*, IUCN Red List DD. Endemic to Gabon. Very restricted to central Gabon.
113. *Canis adustus*, ranges widely in Sub-Saharan Africa. May be VU in Gabon due to restricted range and/or small population in Gabon (known from 2 localities, likely < 500 individuals).
114. *Aonyx congicus*, endemic to Central Africa. Gabon thought to harbor large proportion of global population. Requires undisturbed rainforest, lowland swamp.
115. *Bdeogale nigripes*, endemic to Central Africa. Gabon thought to harbor large proportion of global population. Prefers undisturbed forest.
116. *Herpestes ichneumon*, ranges widely, but in Gabon, limited to riparian areas in SW.
117. *Crossarchus platyocephalus*, endemic to Gulf of Guinea region. Thought uncommon. In Gabon, restricted to north, rare, known from 1 locality.
118. *Crocuta crocuta*, ranges widely in Sub-Saharan Africa. May be VU in Gabon due to restricted range and/or small population in Gabon (occasionally recorded at 1 locality, likely < 20 individuals).
119. *Poiana richardsoni*, endemic to Central Africa. Gabon thought to harbor large proportion of global population.
120. *Leptailurus serval*, ranges widely in Sub-Saharan Africa. May be VU in Gabon due to restricted range and/or small population in Gabon (known from 2 localities, likely <100 individuals).

121. *Caracal aurata*, IUCN Red List NT. Was partly-protected by national law at time of original assessment. Now unprotected by national law.
122. *Panthera pardus*, IUCN Red List NT. May be VU in Gabon due to hunting pressure upon prey base. CITES Appendix I.
123. *Phataginus tricuspis*, IUCN Red List VU. Endemic to West and Central Africa. Threatened by hunting.
124. *Smutsia gigantea*, IUCN Red List VU. Endemic to West and Central Africa. May be VU in Gabon due to hunting. Important population may exist in Gabon.
125. *Uromanis tetradactyla*, IUCN Red List VU. Endemic to West and Central Africa.
126. *Trichechus senegalensis*, IUCN Red List VU A3cd; C1. Estimated VU in Gabon due to hunting and small, fragmented range. Gabon has one of highest densities remaining.
127. *Loxodonta cyclotis*, IUCN Red List VU A2a globally, however the Central African Regional Assessment is EN A2a. Estimated VU in Gabon due to hunting. CITES Appendix I.
128. *Hippopotamus amphibius*, IUCN Red List VU A4cd. Estimated VU in Gabon due to hunting and small, fragmented population (estimated 250 individuals).
129. *Hylochoerus meinertzhageni*, endemic to West and Central Africa. Estimated VU in Gabon due to restricted distribution, specific habitat requirements, and natural occurrence at low densities.
130. *Potamochoerus porcus*, widespread but patchily distributed in Central and West Africa. Threatened by hunting.
131. *Hyemosochus aquaticus*, endemic to West and Central Africa. Threatened by hunting. Requires riparian habitats in closed-canopy forest.
132. *Cephalophus callipygus*, endemic to western Central Africa, but most of distribution is in Gabon. Globally declining. Threatened by hunting.
133. *Cephalophus dorsalis*, endemic to West and Central Africa. Globally declining. Prefers primary, undisturbed forest. Threatened by hunting.
134. *Cephalophus leucogaster*, endemic to Central Africa. Gabon has population stronghold. Globally declining. One of the ungulates most threatened by hunting.
135. *Cephalophus nigrifrons*, endemic to Central Africa. Globally declining. Requires swamp forest and watercourses. Threatened by hunting.
136. *Cephalophus ogilbyi*, largest part of the subspecies *crusalbum* thought to occur in Gabon. Threatened by hunting.
137. *Cephalophus silvicultor*, globally declining. Ranges widely across West and Central Africa. Threatened by hunting.
138. *Kobus ellipsiprymnus*, wide but patchy distribution across Sub-Saharan Africa. Estimated VU in Gabon due to restricted range, hunting, habitat loss.
139. *Neotragus batesi*, three separate populations exist in Africa, but largest part of distribution is in Gabon.
140. *Redunca arundinum*, distributed across Southern Africa. Estimated VU in Gabon due to restricted range. Presence to be confirmed in Gabon.
141. *Syncerus caffer*, forest subspecies *nanus* may be VU in Gabon due to hunting, even though it is widely distributed in Gabon and can be locally abundant. Restricted to grassy areas near/in forest.
142. *Tragelaphus eurycerus*, IUCN Red List NT. Globally declining. Endemic to West and Central Africa. Estimated VU in Gabon due to restricted distribution (at edge of global range), specific habitat requirements, and natural occurrence at low densities (species rarely encountered). Threatened by hunting.
143. *Tragelaphus scriptus*, ranges widely in Sub-Saharan Africa. May be VU in Gabon due to restricted habitat (does not favor closed forest) and hunting (thought to be resilient, but still under pressure).

Chapter 4

BUILDING NATURE INTO INDUSTRIAL DEVELOPMENT IN GABON, CENTRAL AFRICA³

4.1 ABSTRACT

Under the Convention on Biological Diversity, nations have pledged to mainstream biodiversity into industrial development on production lands, but commonly lack a strategic framework for planning and coordinating conservation efforts across landscapes and operators to achieve biodiversity targets efficiently. A recent study in the country of Gabon identified a set of critical biodiversity sites that need to be protected for the country to meet national biodiversity targets efficiently for priority terrestrial vertebrates and habitats. We examine the feasibility of protecting these sites where they overlap with permits in four industrial sectors. We found that critical biodiversity sites overlap with 23% of onshore oil permits, 9% of mining permits, 3% of logging permits, and no agro-industrial permits, but that nearly all of the land area to be managed is in logging permits, mostly in the buffer zones of national parks. Drilling down to the species and permit level, we specify management actions needed by

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different sectors and operators to conserve the priority species and habitats on their lands. The spatial structure of biodiversity and land uses in Gabon dictates that for the country to achieve international conservation targets, biodiversity management on production lands must be stepped up. By unpacking high-level policy targets to identify the species, habitats, locations and actions needed to meet them, we illustrate one way that tropical countries might begin to align science, policy and industry in a more coordinated approach to land management.

4.2 INTRODUCTION

4.2.1 TRANSFORMING HIGH-LEVEL CONSERVATION TARGETS INTO ACTIONS ON THE GROUND

The Convention on Biological Diversity (CBD) – the world’s foremost biodiversity policy – is based on targets, to measure progress towards global goals (Secretariat of the Convention on Biological Diversity 2011). However, despite the fact that most nations are bound to respect the targets, many consistently fall short (Butchart et al. 2010). How can countries improve biodiversity performance? In this study we focus on Targets 1, 2 and 4 of the CBD, which aim to mainstream biodiversity into government and society, and Targets 11 and 12, which aim to safeguard it (Table 1). We suggest that an important step in achieving these high-level policy targets is unpacking them at national and local levels (Opdam et al. 2013) – identifying *what* needs to be protected, *where* it can be achieved, what actions are needed (*how*), and *who* will dedicate the

expertise and means to see them through. We illustrate the beginnings of such a process through a case study of the Central African nation of Gabon.

Tropical countries like Gabon face particular challenges meeting biodiversity targets: little of their rich biota is even catalogued or mapped (Dirzo and Raven 2003); natural systems and the consequences of management actions are poorly-understood (Meijaard and Sheil 2012); and capacity to effectively act to stem extinctions and safeguard ecosystems is often lacking (Melick et al. 2012). In addition, in many countries, land use decisions are devolved to local administrative units or sites, whose objectives and concerns may differ from nations, let alone international bodies (Pierce et al. 2005), or who may not even be aware of such larger objectives or legal obligations. Tropical countries need practical solutions for transforming the broad visions and targets espoused in global policy forums into concrete actions that scientists, politicians and land managers can realize on the ground.

Table 1. Main goals and targets of the Convention on Biological Diversity addressed in this study.

<i>Strategic Goal A : Address the underlying causes of biodiversity loss by mainstreaming biodiversity across government and society.</i>	
1	By 2020, at the latest, people are aware of the values of biodiversity and the steps they can take to conserve and use it sustainably.
2	By 2020, at the latest, biodiversity values have been integrated into national and local development and poverty reduction strategies and planning processes and are being incorporated into national accounting, as appropriate, and reporting systems.

4	By 2020, at the latest, Governments, business and stakeholders at all levels have taken steps to achieve or have implemented plans for sustainable production and consumption and have kept the impacts of use of natural resources well within safe ecological limits.
<i>Strategic Goal C : To improve the status of biodiversity by safeguarding ecosystems, species and genetic diversity.</i>	
11	By 2020, at least 17 per cent of terrestrial and inland water, and 10 per cent of coastal and marine areas, especially areas of particular importance for biodiversity and ecosystem services, are conserved through effectively and equitably managed, ecologically representative and well connected systems of protected areas and other effective area-based conservation measures, and integrated into the wider landscapes and seascapes.
12	By 2020, the extinction of known threatened species has been prevented and their conservation status, particularly of those most in decline, has been improved and sustained.

4.2.2 MAINSTREAMING BIODIVERSITY ON INDUSTRIAL LANDS IN CENTRAL AFRICA

Protected areas are the world's core conservation strategy (Chape et al. 2008), but cover less than 13% of land and miss many species threatened with extinction – they are not enough to meet targets for adequately conserving biodiversity (Venter et al. 2014). Preserving biodiversity therefore requires conserving it not only in protected areas, but also across a matrix of other lands (Fischer et al. 2006), as outlined in the CBD. The last decade has seen considerable growth in efforts to mainstream biodiversity – a concept which implies not only integrating biodiversity into sectors and societies, but “has the added meaning of modifying that into which it is integrated” (Redford 2013, p.4). While it is necessary to be realistic about what can be conserved on land primarily dedicated to other uses (Meijaard and Sheil 2012), mainstreaming biodiversity on production lands has the potential to contribute considerable effort and investment to conservation. This may be especially important in production-oriented

forested landscapes, since industrial activities often determine much of quality, quantity and location of nature that they retain (Laurance and Balmford 2013).

In Central Africa, protected areas cover about 14% of land (de Wasseige et al. 2012) in a matrix dominated by industrial-scale natural resource production permits – oil, mining, agriculture and logging – laced with human settlements, roads and informal land uses. Common mainstreaming mechanisms include species protection laws, national environmental protection laws and impact assessment processes, and sector-specific regulations and guidelines. However, implementation can be highly variable. In addition, some companies seek voluntary environmental certifications, such as from the Forest Stewardship Council (FSC) or Roundtable on Sustainable Palm Oil (RSPO). Such certifications aim to maintain High Conservation Values in particular permits or operations, where these values are guided by general principles (Jennings et al. 2003) but ultimately depend on country-specific criteria that are defined through a national interpretation process.

Multiplied across permits and sectors, mainstreaming mechanisms like these have the potential to significantly complement and bolster the core strategy of protected areas. In fact, a growing body of evidence from Central Africa suggests that tropical production lands can maintain conservation benefits if carefully managed (Clark et al. 2009, Stokes et al. 2010, Eggert et al. 2014). However, current mainstreaming efforts are piecemeal, permit-based and individual, making it difficult to account for the contributions made by different land management units to overall targets, and to

strategically guide management so that individual efforts achieve more than the sum of their parts. This is important because countries are limited in land and resources at different levels, and need to leverage, encourage, coordinate and account for the contributions of each actor – government, private or civil society – to national goals, to make the most of conservation efforts.

4.3 METHODS

4.3.1 CONSERVATION ACROSS INDUSTRIAL SECTORS IN THE CONTEXT OF GABON

Using the country of Gabon as a case study, we apply a systematic method to plan biodiversity management on production lands, to complement what is already conserved in national parks. Gabon is a sparsely-populated, politically-stable, upper-middle income country in Central Africa, historically reliant on hydrocarbon development, and currently engaged in an economic diversification program aimed to double its GDP by 2020, largely based on natural resource production, yet committed to doing so in 'green' or sustainable ways (Bongo Ondimba 2011, Oxford Business Group 2011). Gabon's landscapes are remarkably intact, harboring some of the highest forest cover in the world (Saatchi et al. 2011), half of Africa's remaining forest elephants (Maisels et al. 2013), and a large share of all great ape habitat (Junker et al. 2012). National parks, the backbone of conservation efforts, cover 11% of land. Yet parks alone do not achieve conservation targets for species or habitats, and with over five times more land in industrial-scale production than in parks, many species that are threatened with extinction depend on production lands to survive (Chapters 2 and 3, this thesis). For Gabon to achieve its sustainable development vision will require,

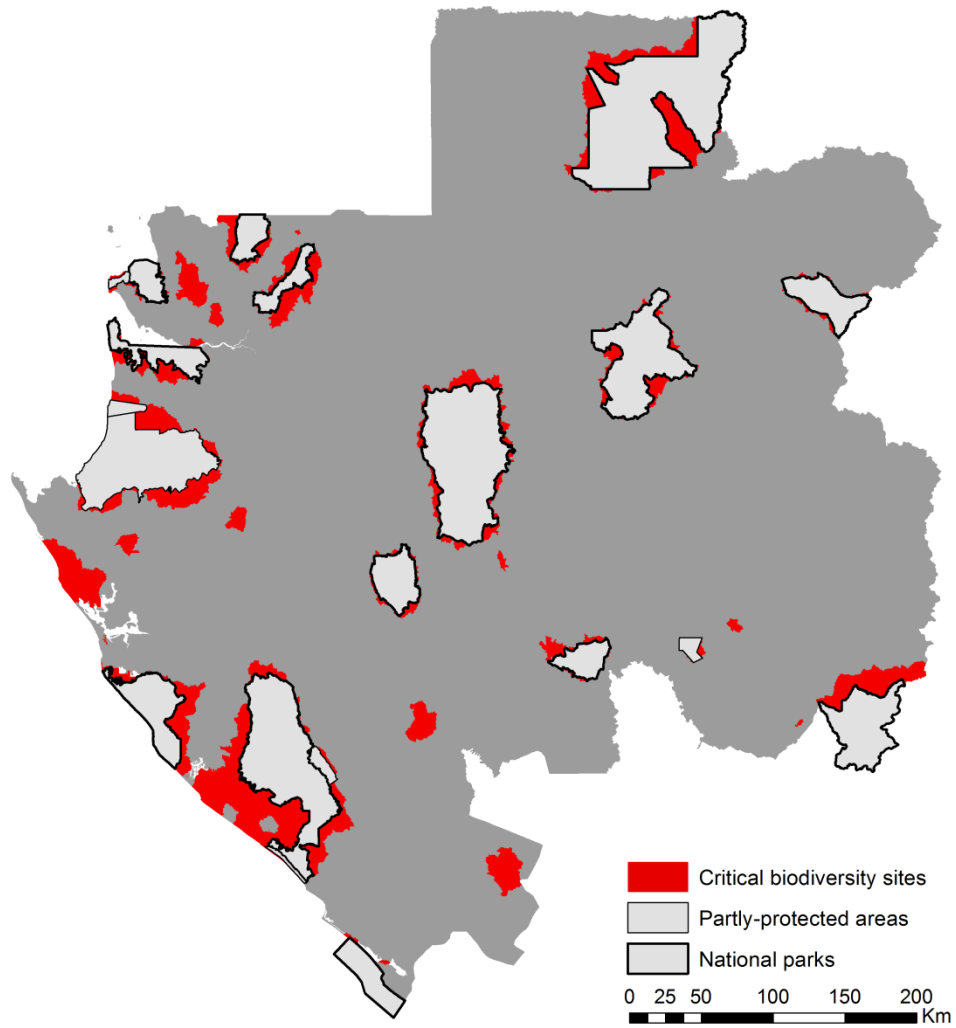
among other things, creating a simple but effective system of directing, protecting, and reporting on biodiversity within industrial operations.

4.3.2 OVERLAPPING BIODIVERSITY AND PRODUCTION LAND USES

This study builds on previous work that laid a foundation for conservation and land use planning in Gabon by identifying a set of sites that complemented existing protected area to efficiently meet conservation targets for 45 priority species and 30 habitat types – henceforth called “critical biodiversity sites” (Figure 1, Chapter 3, this thesis). Critical biodiversity sites represent the top tier of conservation priorities for this suite of features (species and habitats) in Gabon. They take into account national parks and partly-protected areas that are already central to conservation in the country, complementing them with other sites that are the most irreplaceable, least negotiable locations that could be protected to meet national targets with the least impact on land used for local livelihoods (Chapter 3, this thesis).

In this study, we overlay critical biodiversity sites with land use permits in four industrial sectors – oil, mining, agriculture and logging – to evaluate their overlap. For each species in an industrially-managed critical biodiversity site, we investigate its susceptibility to four threats, based on the literature and expert knowledge: tree canopy disturbance, ground-level disturbance, water disturbance (sedimentation or pollution), and hunting pressure. We pinpoint key contributions that different permits and sectors make to national biodiversity targets, and specify the actions needed to maintain these species and habitats on the ground.

Figure 1. Critical biodiversity sites located outside of protected areas that were examined in this study. These sites were identified in Chapter 3 of this thesis by first having taken the distribution of species and habitats within protected areas into account, then using optimization to efficiently complement them to meet international conservation targets.



4.4 RESULTS

4.4.1 CRITICAL BIODIVERSITY SITES IN INDUSTRIAL PERMITS

The results of this study are summarized in Table 2 (at the end of the chapter), which provides metrics for all features occurring in critical biodiversity sites, giving their overall national distribution, their representation in national parks, and their distribution in four types of production permits – oil, mining, agriculture, logging – that occur within critical biodiversity sites. Spatial management or preventative actions are listed for each feature, based upon its distribution and main known susceptibilities in Gabon.

We found that critical biodiversity sites overlap in area with 23% of onshore oil extraction permits, 9% of mineral extraction permits, 3% of logging permits, and no agricultural permits (Table 3, Figs 2-5). However, in terms of land area to manage, nearly all land occurs within the logging sector (4,744 km²), with relatively minor amounts in mining (752 km²) and oil (308 km²). In total, parts of 63 permits operated by 48 companies overlap to some degree (although often marginally) with critical biodiversity sites.

Table 3. Land use allocation by sector in Gabon, and overlap of industrial permits with critical biodiversity sites (referred to as CBS).

	Oil	Mining	Agriculture	Logging
Total permit area in Gabon (km ²)	1358	8638	1881	144,832
% of country in sector land use	0.5	3.3	0.9	54.1
Permit area in CBS (km ²)	308	752	0	4,744
% of sector land in CBS	23	9	0	3
# of permits overlapping with CBS	9	3	0	51
Number of companies in CBS	3	3	0	42

In terms of biodiversity, 73% of the species used to identify critical biodiversity sites (Chapter 3, this thesis) occur in industrially-managed critical biodiversity sites – six species of reptile, 14 birds and 13 mammals (Table 2). Four of these are discrete presence localities, two are small nesting sites, and 27 are for more widely distributed species. Despite the small extent of onshore oil permits, almost two-thirds of species occur in them. One-third of species occur in mining permits, and one species (Omboué worm lizard, *Cynisca bifrontalis*) is predicted to occur in agricultural permits. All but one species (Perret's worm snake, *Leptotyphlops perreti*) are predicted to occur in logging permits. Around half the species require hunting control (n=19), and about one-third require road management (n=11). Many require protection of important habitat resources such as wetlands, outcrops or fruiting trees within the larger landscape (n=16), while some rely exclusively on discrete localities (n=8).

Of the 30 habitat types considered, 27 occur in industrially-managed critical biodiversity sites (Table 2). Similar to species patterns, all but two habitat types occur within logging permits. Nine habitat types occur in oil permits, six in mining permits, and two in agricultural permits.

Next, we draw attention to three notable cases of biologically-important features occurring on production lands in critical biodiversity sites.

4.4.1.1 Globally-exceptional features that occur only in Gabon's production

permits

First, we discovered that some production lands harbor species that are unique or exceptional at a global level – species that are not known to exist anywhere else in the world – which could easily go unnoticed if not targeted for attention. For example, one oil permit holds the only known localities in the world for the endemic Omboué worm lizard (*Cynisca bifrontalis*), a burrowing reptile believed to require intact forest. A single logging permit holds the only known localities in the world for the endemic, nationally-threatened Pauwels' blind snake (*Letheobia pauwelsi*), and another holds one of two known localities in the world for the near-endemic, nationally-threatened ocellate water snake (*Hydraethiops laevis*). One site holds the only known locality in Gabon for the near-endemic Perret's worm snake (*Leptotyphlops perreti*) and a relatively rare type of unprotected savanna. Although it is possible that these species occur elsewhere, at present these are the only known records that exist in the world – they merit attention.

4.4.1.2 Key sites for securing global populations in production permits

This analysis also revealed the importance of Gabon's production lands in maintaining key sites for the global survival of more widespread species. We found that oil permits hold an important proportion of the total distribution of the globally-threatened, near-endemic Loango weaver (*Ploceus subpersonatus*), a coastal bird with approximately 75% of its global population in Gabon (Chapter 3, this thesis). Oil permits also cover part of the most important nesting grounds in the world for the globally-threatened leatherback sea turtle (*Dermochelys coriacea*, Witt et al. 2009) and the African river martin (*Pseudochelidon eurystomina*; Chapter 3, this thesis). In addition, a handful of

logging permits in critical biodiversity sites harbor threatened species with restricted national distributions – such as the endemic, globally-threatened sun-tailed monkey (*Cercopithecus solatus*), the globally-threatened red-capped mangabey (*Cercocebus torquatus*), and the nationally-threatened giant forest hog (*Hylochoerus meinertzhageni*) and bongo (*Tragelaphus euryceros*). How these logging permits are managed may influence the global survival of these species outside of protected areas.

4.4.1.3 Features that occur in production lands but not national parks in Gabon

Finally, we discovered cases in which production lands contribute solely or importantly to national targets, because the features do not occur, or barely occur, in national parks. Confirmed localities for three species (Chapin's chameleon, *Trioceros chapini*; Pauwel's blind snake, *Letheobia pauwelsi*; and the ocellate water snake, *Hydraethiops laevis*) are only known from logging permits in Gabon, and one species (Perret's worm snake, *Leptotyphlops perreti*) from a mining permit. Four habitat types are also missing from parks, but occur in critical biodiversity sites in production permits (hyperhumid rugged forest; flat and rugged well-drained grasslands of Wonga-Wongé; mixed terrain savanna near Franceville). In other cases, critical biodiversity sites in production permits provided far more habitat than parks, such as for the Rufous-tailed palm thrush (*Cichladusa ruficauda*) and Pale olive greenbul (*Phyllastrephus fulviventris*) in oil permits. Maintaining these populations on production lands is vital, since existing parks largely miss them.

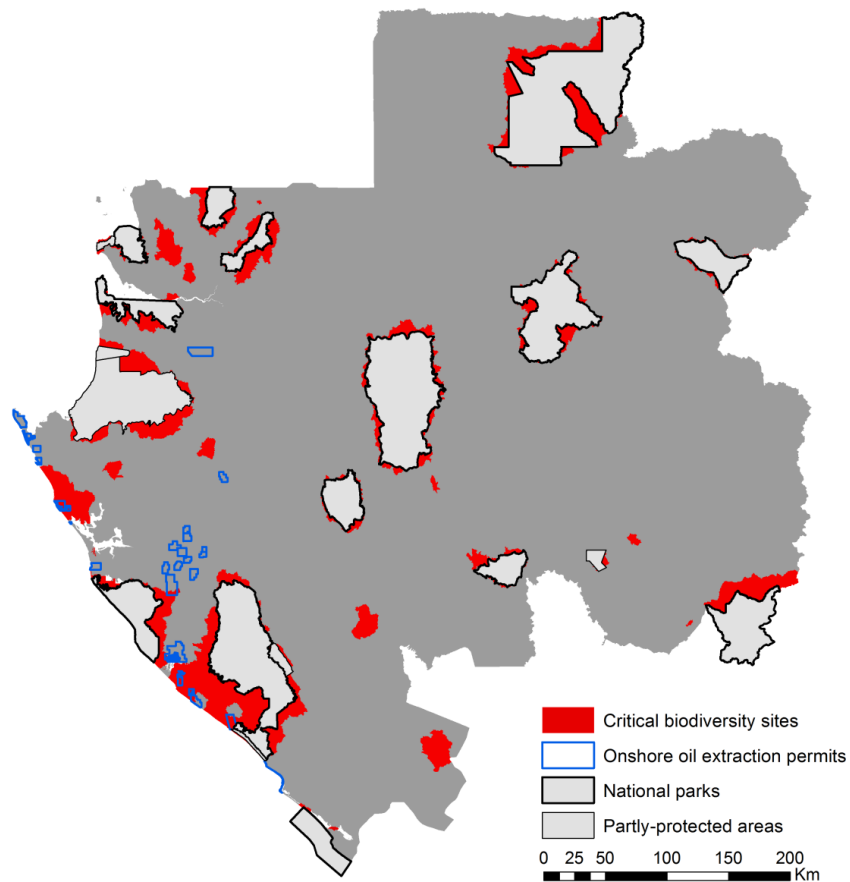
4.4.2 SECTOR-SPECIFIC MANAGEMENT CONSIDERATIONS

The research that laid the foundation for this study found that species, habitats and land uses are highly spatially-structured across Gabon (Chapters 2 and 3, this thesis). These patterns have implications for sector-specific management.

4.4.2.1 Oil and biodiversity

Gabon's oil deposits, associated with geological formations in the coastal sedimentary basin (Chevallier et al. 2002), are concentrated in areas of high habitat heterogeneity (Chapter 2, this thesis). Onshore oil extraction permits are small, covering 0.5% of national land (Chapter 2, this thesis). Thus, although critical biodiversity sites overlap with a relatively small extent of oil permits (308 km²), they occur in nearly one-quarter (23%) of terrestrial permits. These sites are biologically diverse, with nine wetland or coastal habitat types, five of them rare (Chapter 2, this thesis), and contribute particularly to wetland and coastal wildlife populations, including eight water or coastal-scrub birds, the globally-threatened hippopotamus (*Hippopotamus amphibius*) and West African manatee (*Trichechus senegalensis*), and the Nile crocodile (*Crocodylus niloticus*). The sensitivities of these features to human impacts (Table 2) suggest that main conservation actions for the oil sector should include controlling conversion, pollution, hunting and net-fishing in wetlands, waterways and coastal habitats.

Figure 2. Critical biodiversity sites, protected areas, and onshore oil extraction permits.

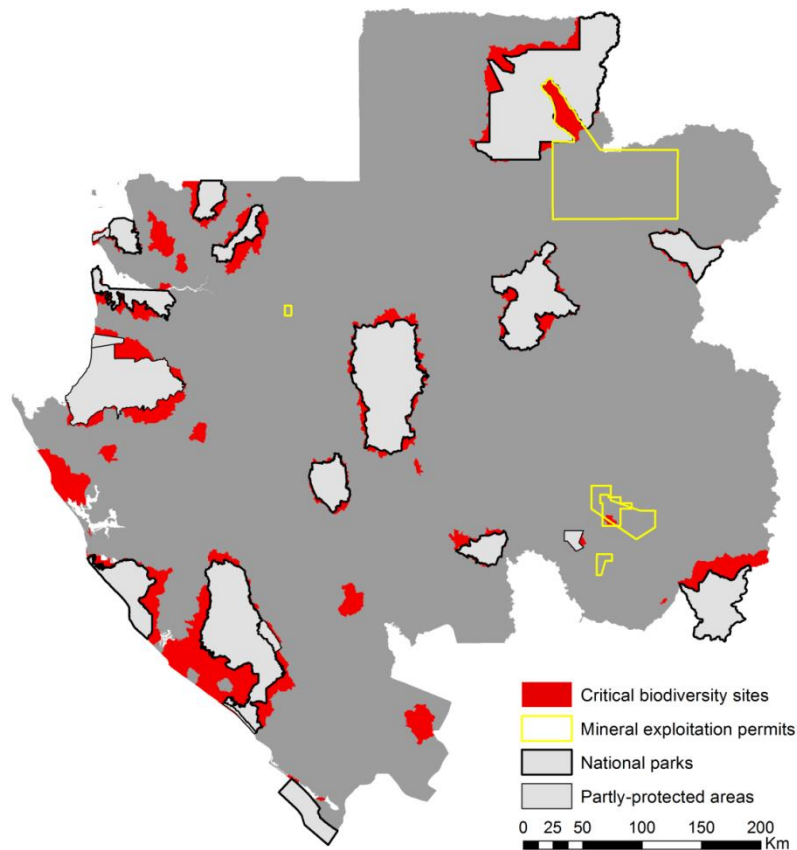


4.4.2.2 Mining and biodiversity

Like oil, mineral deposits tend to be fairly localized. The most important critical biodiversity site in a mineral extraction permit overlapped with a deposit of iron ore and gold which forms a mountain complex covered in submontane and subhumid forest on Gabon's northeastern plateau (Chapter 2, this thesis). This site – which has long been prospected but is not yet developed – provides particularly remote habitat for globally-threatened, highly-legislated species such as the critically endangered western lowland gorilla (*Gorilla gorilla*), the endangered chimpanzee (*Pan troglodytes*), and the

threatened black colobus (*Colobus satanas*), mandrill (*Mandrillus sphinx*), African forest elephant (*Loxodonta cyclotis*) and Red-headed picathartes (*Picathartes oreas*). In light of the economic importance of this mineral resource, it seems prudent to anticipate and proactively plan the conservation of representative samples of these species and habitats (*in situ* and *ex situ*), and develop innovative ways, adapted to the local context, to minimize (or perhaps offset) foreseeable, negative primary and secondary impacts due to mineral development.

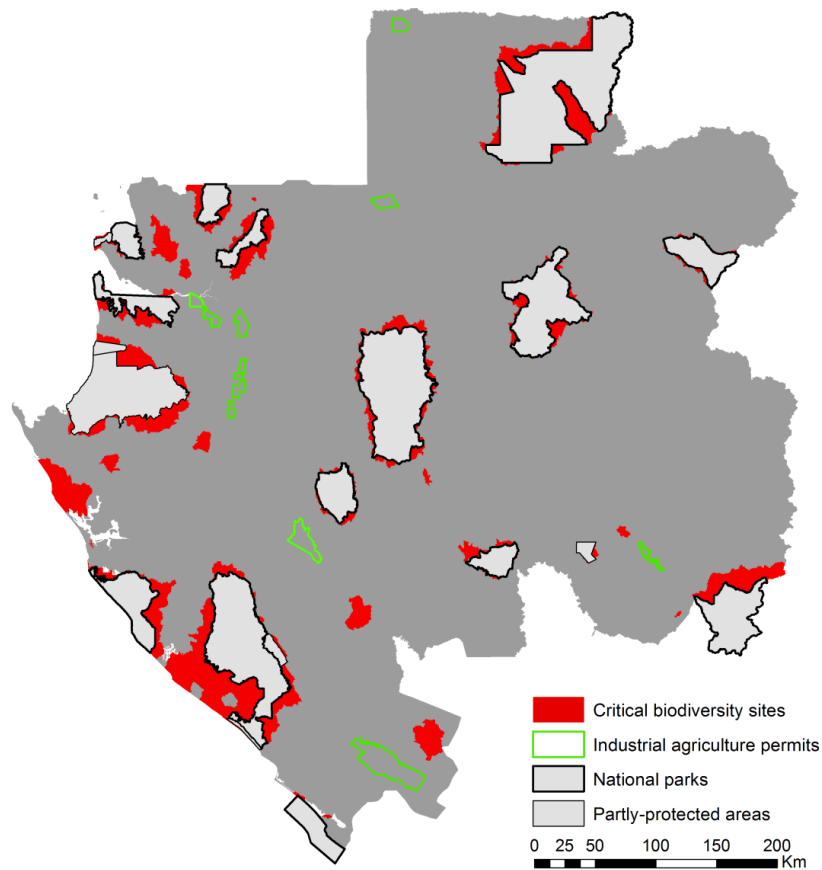
Figure 3. Critical biodiversity sites, protected areas, and mineral extraction permits.



4.4.2.3 Agriculture and biodiversity

Monocultures can devastate tropical biodiversity (Fitzherbert et al. 2008), and may be one reason why no critical biodiversity sites were found in existing agriculture permits. However, a small amount (61 km²) of critical biodiversity sites overlapped with areas being studied for their agronomic potential. Agro-industry currently occupies a fraction of Gabon (0.9% of the country; Chapter 2, this thesis), but is committed to grow (Republique Gabonaise 2012). Unlike oil or mineral deposits, the location of plantations is more spatially flexible – carefully siting them to deliver societal benefits without eroding valuable natural areas is key (Phalan et al. 2011), especially given Gabon’s relative intactness. Existing biodiversity knowledge (such as gathered in Chapter 3, this thesis) can already be used to prevent encroachment on rare or highly localized features. In addition, our results (Table 2) suggest that siting future agricultural areas in such a way as to maintain connections between critical biodiversity sites, important habitat resources, and other conservation areas will be important for the survival of many wide-ranging species.

Figure 4. Critical biodiversity sites, protected areas, and industrial agriculture permits.

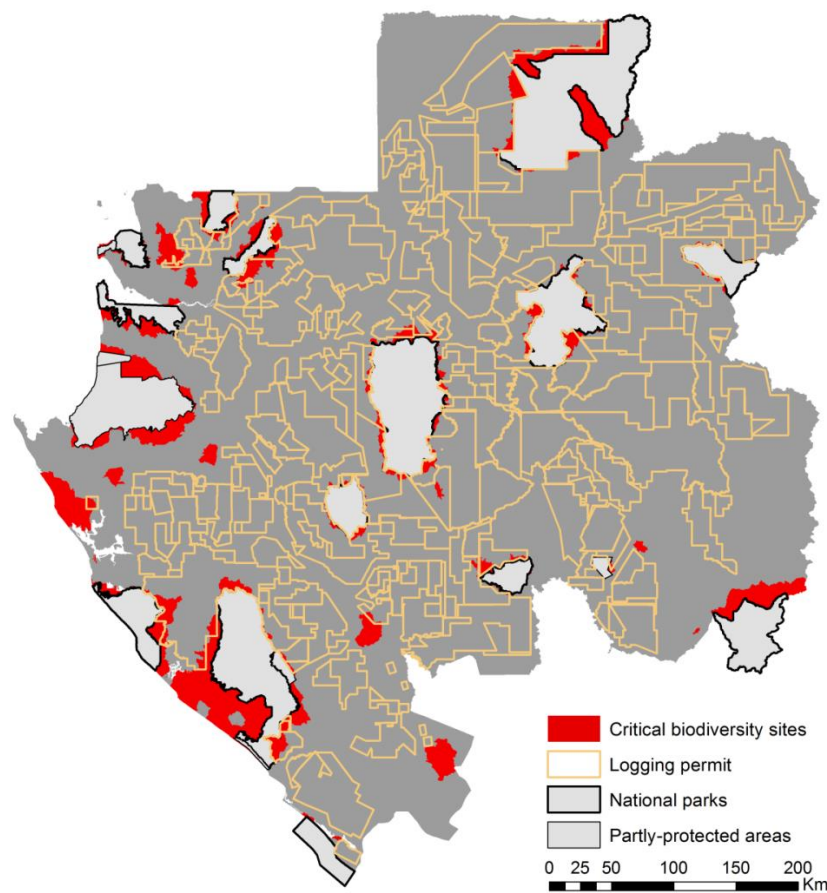


4.4.2.4 Logging and biodiversity

Of the four sectors investigated in this study, most critical biodiversity sites occurred in logging permits. However, since critical biodiversity sites were designed to be clustered near existing protected areas for compactness (Chapter 3, this thesis), all but nine permits are situated at least partly within national park buffer zones, which already require stricter environmental management by law. These sites are dominated by 12 wide-ranging forest mammals – apes, elephants, large carnivores and ungulates – many of which are globally threatened by habitat loss and over-harvest (Schipper et al. 2008). Gabon’s populations therefore make an essential contribution to the global

survival of the species, and the logging sector in particular plays a crucial role, since its lands extend over half (54.1%) the country (Chapter 2, this thesis). Key actions to combat overharvest include controlling illegal hunting, wildlife trafficking, and the proliferation and use of roads (Maisels et al. 2013). To combat habitat loss, in addition to maintaining the quality and quantity of overall habitat, our results (Table 2) suggest that ensuring connectivity across the land use matrix is crucial, by controlling roads and access (Buij et al. 2007, Blake et al. 2008), and ensuring functional connections between important habitat resources (such as wetlands, sand banks, salines, outcrops, fruiting trees, etc.) that anchor species' survival in the wider landscape.

Figure 5. Critical biodiversity sites, protected areas, and logging permits.



4.5 DISCUSSION

4.5.1 A TACTICAL APPROACH TO CONSERVATION ACROSS LAND USES

Of the 20 biodiversity targets set by the Convention on Biological Diversity, only one (Target 11) mentions protected areas. All the other targets explicitly aim to mainstream biodiversity into different facets of society. Indeed, protected areas should remain a core conservation strategy where they are effective, but under the CBD, countries have pledged to go beyond protected areas and take actions in the wider landscape. We suggest that the effect of these actions could be strengthened by taking a coherent, tactical approach to planning and organizing them across the land use matrix by aligning environmental management across sectors around national goals, and holding managers accountable for the biological resources in their care. A tactical approach is consistent with the top-down framework of financial accounting that governments are increasingly required to apply to report on environmental performance (McDonald-Madden et al. 2009), and would build biodiversity conservation more firmly into industrial land management.

Adopting the wider scope of a tactical approach may benefit government and industry in several ways throughout a project lifecycle. For example, prior to development, knowing what and where national priorities lie may reduce the uncertainty and risk of unnecessary environmental harm. Prior to and during development, it may clarify an operator's responsibility for contributing to national targets, and increase confidence of due diligence in managing specific features. During production, it may allow greater efficiency in actions and costs of sharing the burden of management across different

land units or for multiple activities at the same site. It may also help streamline regulatory and monitoring processes, helping auditors focus on the sites and features that respond to national goals. However, it is important to note that the wider scope of such an approach could guide and complement, but should not replace, management practices that are best identified and implemented at the permit-level.

4.5.2 BUILDING CONSERVATION INTO INDUSTRIAL DEVELOPMENT IN CENTRAL AFRICA

Central African forests represent about one-fifth of the world's tropical rainforest area and harbor a wealth biodiversity (Mayaux et al. 2013) – their conservation and management is such a monumental task that it must be shared. Planning biodiversity conservation across protected areas *and* production lands may help achieve this more efficiently, and be a relevant strategy in the region for several reasons. First, with extensive tracts of forest managed for production, widening the geographic scope could achieve substantially higher targets than from the limited coverage of protected areas alone. Second, rural land is largely held by the State. If used to its advantage, this administrative centralization could facilitate coordinated conservation policy and practice across large management units, compared to landscapes fragmented by multiple private smallholdings. Third, whereas protected areas in the region are often poorly resourced (Blom 2004), support from the industrial sector could dramatically increase the human and financial resources that could be engaged in managing some part of biodiversity. Finally, diversification may act like a well-balanced financial investment portfolio, to guard against risk of natural or human-induced loss to species, habitats, or locations, bringing greater stability over time. This may be especially

important in less stable socio-political contexts or places that may not be able to respond appropriately to catastrophic events – spreading the eggs among many baskets may reduce risk.

Pursuing such an approach will clearly depend on finding new ways to mainstream biodiversity in the private sector. Currently, one of the main mechanisms being developed for this in Central African production landscapes is the concept of High Conservation Values (HCV; Jennings et al. 2003), which is applicable to companies pursuing international environmental certification. Under this concept, six general themes (or values) address conservation of biological resources or environmental services, and each country is responsible for defining its own specific interpretation of the values and how to conserve them during development (Brown et al. 2013).

Operationalizing this concept therefore depends on defining meaningful and measurable conservation goals and targets for each country – a task that is currently hampering credible application of the HCV concept at least in Gabon, where because of its relative intactness, much of the country arguably fits criteria that would preclude development elsewhere (Stewart and Rayden 2008). The approach outlined in this study is compatible with the High Conservation Value framework and has indeed been trialed in case studies in the logging and agricultural sectors in country (M. Lee, unpublished data) to attempt to guide operations to areas with lower environmental risk. We encourage further testing and development, as well as greater scientific, government and civil society involvement in Gabon's national HCV interpretation, and biodiversity mainstreaming efforts in the private sector in general.

International biodiversity policy sets clear goals and targets for mainstreaming (Secretariat of the Convention on Biological Diversity 2011), and little by little, conservation is being incorporated into industrial operations on the ground (Redford 2013), but without focusing those efforts on context-relevant interpretations and actions that matter, well-intended policy targets will continue to be missed. We illustrate one way that tropical countries might begin to direct and harness local actions into larger, national or international conservation results, and align science, policy and industry (Macdonald et al.) in a more coordinated approach to land management.

Table 2. Species and habitats occurring in critical biodiversity sites: overall distribution in Gabon, distribution among five land uses within critical biodiversity sites, and management actions for their conservation.

	In Gabon		CRITICAL BIODIVERSITY SITES															Spatial management or preventative action:
	km ² or pres	% country	Nat'l Park			Oil			Mining			Agriculture			Logging			
			km ² or pres	% in park	# permits	km ² or pres	% in oil	# permits	km ² or pres	% in mining	# permits	km ² or pres	% in agriculture	# permits	km ² or pres	% in logging		
Species: confirmed presence localities																		
Chapin's chameleon (<i>Trioceros chapini</i>)	4													1	1	25	Map and protect known location near Monts de Cristal NP, at least until confirmed elsewhere including in a park.	
Perret's worm snake (<i>Leptotyphlops perreti</i>)	1							2*	1	100							Map and protect known location near Mounana, at least until confirmed elsewhere including in a park.	
Pauwels' blind snake (<i>Letheobia pauwelsi</i>)	1													1	1	100	Map and protect known location on Mt Iboundji, at least until confirmed elsewhere including in a park.	
Ocellate water snake (<i>Hydraethiops laevis</i>)	1													1	1	100	Map and protect known location near Birougou NP, at least until confirmed elsewhere including in a park.	
Species: suitable habitat																		
Nile crocodile (<i>Crocodylus niloticus</i>)	6,739	3	602	9	7	157	2							4	85	1	Control hunting in and around large waterbodies like lakes and lagoons.	
Omboué worm lizard (<i>Cynisca bifrontalis</i>)	13,662	5	719	5	3	47	0.3				1	4	0.03	7	526	4	Map and protect known locations, east of Loango NP, at least until confirmed elsewhere including in a park.	
Pink-backed pelican nesting sites (<i>Pelecanus rufescens</i>)	1,758	1	285	16	5	101	6							2	18	1	Map and protect nesting sites (large trees) around large lagoons and lakes. Control hunting and pollution.	
Yellow-billed stork (<i>Mycteria ibis</i>)	4,197	2	492	12	4	83	2							5	61	1	Map and protect open marsh, mudflats and wetlands, especially areas with shallow water for feeding and sandbanks or trees for roosting. Control hunting and pollution.	

Saddle-billed stork (<i>Ephippiorhynchus senegalensis</i>)	477	0.2	108	23	2	32	7					3	34	7	Map and protect large fresh and brackish wetlands, marshes and lagoons, especially areas with roosting trees. Control hunting and pollution.
African spoonbill (<i>Platalea alba</i>)	1,933	1	297	15	1	19	1					3	36	2	Map and protect large waterbodies, especially in non-forested areas like river mouths. Control hunting and pollution.
Freckled nightjar (<i>Caprimulgus tristigma</i>)	596	0.2	299	50								5	89	15	Map and protect areas of bare or savanna-covered rocky habitat.
Black-and-white-casqued hornbill (<i>Bycanistes subcylindricus</i>)	8,114	3	262	3								3	72	1	Map and protect old dead trees and fruiting trees along large rivers, flooded forest, plantations and roadsides. Control hunting.
African river martin nesting sites (<i>Pseudochelidon eurystomina</i>)	1,073	0.4	107	10	5	67	6					1	4	0.4	Map and protect breeding grounds, where it digs nests in sandbars along large forested rivers, grassy sand plains and islands with sandy shores. Control inundation.
Pale olive greenbul (<i>Phyllastrephus fulviventris</i>)	340	0.1	53	16	4	83	24					1	4	1	Map and control disturbance to gallery and dense bush.
Rufous-tailed palm thrush (<i>Cichladusa ruficauda</i>)	148	0.1	4	3	4	42	28						4	3	Restricted to palm forest around villages and cities in the southwest of Gabon; anthropogenic disturbance tolerated but control large-scale habitat conversion.
Red-headed picathartes (<i>Picathartes oreas</i>)	17,375	7	3,759	22				1	421	2		16	1,102	6	Map and protect rocky outcrops with sheer rockfaces and overhangs.
Orange-tufted sunbird (<i>Nectarinia bouvieri</i>)	3,062	1	273	9								1	52	2	Restricted to savanna near Tchibanga and Mourindi. Control habitat conversion.
Variable sunbird (<i>Nectarinia venusta</i>)	6,538	2	274	4								2	60	1	Restricted to savanna and anthropogenic habitats in the southwest. Control large-scale habitat conversion.
Loango weaver (<i>Ploceus subpersonatus</i>)	365	0.1	62	17	3	45	12					1	4	1	Restricted to bush, Phoenix scrub and mangrove along the coastal fringe, as well as villages. Control habitat conversion.
Grey waxbill (<i>Estrilda perreini</i>)	11,503	4	1,783	16								1	52	0	Restricted to savanna in southern Gabon. Control habitat conversion.

Western lowland gorilla (<i>Gorilla gorilla</i>)	112,211	42	23,715	21	2	71	0	1	688	1			34	3,309	3	Map and protect critical habitat areas, especially forest with dense herbaceous cover and swamp forest. Control hunting, road impacts, and contact with humans for disease.
Chimpanzee (<i>Pan troglodytes</i>)	108,766	41	23,105	21	2	71	0	1	683	1			37	3,283	3	Map and protect critical habitat areas, especially closed-canopy and swamp forest. Control hunting, road impacts, and contact with humans for disease.
Black colobus (<i>Colobus satanas</i>)	87,279	33	15,877	18	3	79	0	1	683	1			34	2,867	3	Map and protect critical habitat areas, especially high-canopy, dense primary forest and swamp forest. Control hunting and road impacts.
Mandrill (<i>Mandrillus sphinx</i>)	98,832	37	18,490	19	1	34	0.03	1	683	1			34	2,634	3	Map and protect critical habitat areas, especially primary forest, secondary areas with fruiting trees, riparian areas. Control hunting and road impacts.
Red-capped mangabey (<i>Cercocebus torquatus</i>)	43,199	16	6,441	15	4	87	0						13	1,346	3	Map and protect critical habitat areas, especially swamp and valley forest. Control hunting and road impacts.
Sun-tailed monkey (<i>Cercopithecus solatus</i>)	15,423	6	4,952	32									10	595	4	Map and protect critical habitat areas, especially densely-shaded forest. Control hunting and road impacts.
Golden cat (<i>Caracal aurata</i>)	110,044	42	23,266	21	2	51	0	1	687	1			35	3,242	3	Control hunting and road impacts.
Leopard (<i>Panthera pardus</i>)	118,856	45	25,547	21	2	74	0	1	688	1			37	3,315	3	Control hunting and road impacts.
West African manatee (<i>Trichechus senegalensis</i>)	1,694	1	390	23	2	18	1						2	61	4	Map and protect large lakes, lagoons, rivers and wetlands, especially in the rainy season. Control hunting.
African forest elephant (<i>Loxodonta africana</i>)	116,392	44	24,980	21	2	75	0	1	688	1			35	3,316	3	Map and protect critical habitat, especially salines, fruiting trees, and wetlands especially in the dry season. Control hunting and road impacts.
Hippopotamus (<i>Hippopotamus amphibius</i>)	1,119	0.4	339	30	5	73	7						2	52	5	Map and protect critical habitat areas, especially large surface waters of rivers, lakes and lagoons with herbaceous cover. Control hunting.

Giant forest hog (<i>Hylochoerus meinertzhageni</i>)	41,305	16	10,884	26			1	684	2			12	934	2	Map and protect critical habitat areas, especially along rivers. Control hunting and road impacts.
Bongo (<i>Tragelaphus eurycerus</i>)	31,499	12	10,678	34			1	684	2			12	856	3	Map and protect critical habitat areas, including edge habitats and rivers. Control hunting and road impacts.
Habitat types															
Hyperhumid flooded forest	397	0.1	106	27								1	20	5	Manage wetlands along the coast, particularly those supporting Akanda and Pongara NPs and human livelihoods near Libreville.
Hyperhumid flat forest	3,974	2	112	3					1	61	2	6	130	3	Currently underprotected - protect from urban sprawl near Libreville. Manage seasonally-flooded areas.
Hyperhumid rugged forest	357	0.1							1	48	13	5	77	21	Currently unprotected - needs protection. Manage erosion under steep, high rainfall conditions.
Mangrove	1,815	1	751	41	1	39	2								Manage upstream impacts to aquatic systems and wood harvesting.
Flat well-drained grassland, Wonga-Wongé	1,037	0.4			1	12	1					?	9	1	Protect in the Presidential Reserve. Manage development on erosive valleys. Manage fire.
Rugged well-drained grassland, Wonga-Wongé	316	0.1			1	3	1					?	11	4	Protect in the Presidential Reserve. Manage development on erosive valleys. Manage fire.
Flooded alluvial forest, coastal basin	7,076	3	586	8	5	156	2					5	221	3	Manage wetlands, conversion or draining, and upstream impacts.
Flooded alluvial grassland, coastal basin	846	0.3	53	6	3	47	6					?	3	0.4	Manage wetlands, conversion or draining, and upstream impacts.
Well-drained forest, coastal basin	5,321	2	809	15	5	121	2					3	182	3	Manage fire maintaining forest-savanna mosaics along the coast. Manage erosion in white sand forests.
Well-drained grassland, coastal basin	564	0.2	50	9	3	32	6					1	5	1	Manage fire maintaining forest-savanna mosaics along the coast. Manage erosion in sandy grasslands.
Surface water (lakes, lagoons, major rivers)	2,937	1	289	10	6	92	3					1	60	2	Manage direct and upstream impacts to water bodies and wetlands at the catchment level.

Flat forest, sed. basin & Ikoundou plateau	30,807	12	1,186	4	2	36	0.1					7	639	2	Protect remnants of mature forest in the coastal basin, and the mountain gradient. Manage seasonally-flooded areas.
Rugged forest, sed. basin & Ikoundou plateau	5,568	2	1,332	24								3	163	3	Protect remnants of mature forest in the coastal basin and the mountain gradient. Manage erosion on steep areas.
Subhumid flat forest, Nyanga plains	5,541	2	333	6								2	135	2	Currently underprotected - new protection area is needed. Protect mountain gradient.
Subhumid rugged forest, Nyanga plains	4,444	2	544	12								2	145	3	Protect mountain gradient. Manage erosion on steep areas.
Humid calcareous grassland	1,854	1	27	1								2	59	3	Currently underprotected - new protection area is needed, especially given expanding agriculture.
Subhumid calcareous grassland	6,790	3	232	3								1	40	1	Currently underprotected - new protection area is needed, especially given expanding agriculture.
Rugged forest, Doudou-Mayombe mountains	2,793	1	779	28								3	87	3	Protect mountain gradient. Manage erosion on steep areas.
Flat forest, Cristal-Chaillu mountains	17,342	7	616	4								14	329	2	Currently underprotected. Protect mountain gradient.
Rugged forest, Cristal-Chaillu mountains	35,148	13	5,571	16								23	1,519	4	Protect mountain gradient. Manage erosion on steep areas.
Submontane	5,182	2	1,158	22				1	18	0.3		14	300	6	Protect sensitive habitat. Manage erosion on steep areas.
Flat forest, central inland plateau	53,591	20	2,856	5				2	11	0.02		9	477	1	Control habitat conversion.
Rugged forest, central inland plateau	16,192	6	962	6				2	12	0.1		8	274	2	Manage erosion on steep areas.
Mixed terrain savanna, Lopé	681	0.3	370	54								5	113	17	Manage fire and habitat conversion.
Mixed terrain savanna, Franceville	2,121	1						2	42	2					Currently unprotected - need to protect a representation that is in good condition
Subhumid flat forest, northeastern plateau	36,899	13.9	7,992	22				1	364	1		8	578	2	Manage habitat conversion.
Subhumid rugged forest, northeastern plateau	4,078	1.5	684	17				1	421	10		3	42	1	Manage erosion on steep areas.

Chapter 5

TARGETING FIELD SURVEYS TO REDUCE UNCERTAINTY IN PROTECTED AREA PRIORITIES⁴

5.1 ABSTRACT

Decision-makers selecting protected areas are often faced with uncertain maps of the distribution of species. Given limited funds to gather new information, how and where should they search? Not all survey information yields equal return on investment. The best information not only reduces uncertainty in the data, but more importantly, has the maximum potential to change a decision that would have been made without it. We present a method to identify where surveys are most likely to improve decisions about protected area expansion, illustrated by a case study in Gabon. Dividing Gabon into 25-km² planning units, we mapped the value of surveying each unit to confirm the presence of bird and reptile species that are targets of protected area expansion. We then used a site selection algorithm to identify a benchmark set of protected areas that represented both known and likely distributions of these species, and to determine

⁴ Manuscript in preparation. Potential authors include: Michelle Lee, Edward Game, Josie Carwardine, Daniel Segan, Olivier Pauwels, Patrice Christy, David Macdonald, Hugh Possingham. Statement of authorship: ML, EG, JC, DS, HP designed the study; ML, OP, PC contributed data and mapped species; ML, DS analysed data; EG, JS, DS, HP advised with spatial analysis; DM, HP oversaw the work; ML wrote the first draft document and all authors contributed to revisions.

relative conservation priority of units based on our current knowledge. We combined survey value with relative conservation priority to determine the potential impact on protected area decisions of surveying each planning unit. We found that preferentially surveying localities of uncertain conservation priority was likely to reveal additional options where species could be protected, potentially changing the location of the protected area network by almost 15%. In contrast, surveying localities of known conservation priority would only change the location of the protected area network by <1%. Improving knowledge of species' distributions mattered more when it revealed new places to protect them that were unlikely to be included in a protected area network otherwise. Uncertainty is only important to the extent it might change a decision. Uncertainty in species' distributions can never be completely removed, so effort to reduce uncertainty should target actions that are most likely to make a difference to the decision. This is particularly relevant to conservation decisions in little-studied regions like Central Africa, where field surveys will always improve scientific knowledge but possibly fail to impact decisions.

5.2 INTRODUCTION

Protected areas form the foundation of most nations' efforts to conserve biodiversity, particularly rare or threatened species. However, the process of selecting areas to protect species is commonly hampered by a paucity of species-level distribution data (Gaston and Rodrigues 2003). Knowledge of species' distributions can be improved through field surveys, yet they are expensive, difficult, and ultimately limited in geographic coverage. To overcome these geographic gaps, predictive models are

commonly used to relate field data on species' occurrence to environmental conditions and statistically predict species' distributions in unsampled areas (Guisan and Zimmermann 2000, Elith et al. 2006). The accuracy of these models can be improved by gathering more field data at sites that reduce the most overall uncertainty in these distributions (Hirzel and Guisan 2002). Such optimal survey designs recognize that not all information has the same value, and that limited resources for new data collection should be spent where uncertainty can be reduced most efficiently.

However, reducing uncertainty in knowledge of species' distributions alone will not maximize our ability to make informed decisions about the location of protected areas. Species' distributions are only one of many factors in protected area design, whose outcome is often more influenced by other opportunities and constraints (Possingham et al. 2005). Some sites, for instance, may be too expensive to protect. Others may be critical to protect for another reason, so surveying them to improve knowledge of species' distributions is unlikely to change our decision to prioritize that planning unit. Uncertainty in a species' distribution will never be completely removed, so it is reasonable to prioritize the points of uncertainty whose reduction will be most influential on the eventual decision. If the distributional information is being used to inform protected area decisions, optimal surveying should target sites that not only reduce uncertainty about distributions, but also reduce uncertainty about the best sites for a protected area network. This distinction, between surveying to improve species' predictive models (which may be applied to protected area decisions), versus surveying to improve the protected area expansion decision itself, is rarely made but should not be confused; efficient solutions for meeting these two different objectives

are unlikely to be the same. This concept is consistent with recent research on the “Value of Information” in applied ecology (Grantham et al. 2008, McDonald-Madden et al. 2010, Wintle et al. 2010, Runge et al. 2011).

We develop a method to identify locations to survey that maximizes return on survey investment, where return is defined by the reduction in uncertainty about where to expand protected areas to conserve target species. We contrast two novel survey strategies: both reduce uncertainty in the distribution of species, one in places of known conservation priority, and the other in places of uncertain conservation priority. Through a case study, we demonstrate how survey effort could best be directed to inform priorities for protected area designation.

5.3 METHODS

5.3.1 STUDY CONTEXT

Our goal was to design a method to identify field survey priorities for protected area expansion which leveraged existing biodiversity data and land use knowledge, and which could reasonably be implemented in data-poor contexts – arguably those needing advice on how to spend limited resources for conservation the most. We used Gabon as a case study, a sparsely-populated, heavily-forested country the size of Italy (26.7M ha) on the Atlantic coast of central Africa. Gabon has relatively high species diversity for Africa, but knowledge of diversity and distributions is far from complete. About 4700 of an estimated 7000 plant species have been documented (Sosef et al.

2006), along with 163 species of non-marine mammals, 693 birds, 88 amphibians and 122 reptiles (Christy et al. 2008). Species numbers continue to increase with survey effort, even in higher order taxa (Fisher ed. 2004, Alonso et al. 2006). For example, a 12-week survey by a three-person team in one area of the country increased the national amphibian list by 25% (Burger et al. 2006). Currently, 11% of Gabon is allocated to national parks. This study was designed as a precursor to a project to survey areas to expand the park network.

5.3.2 SPECIES MAPPING

We used ten bird and ten reptile species of conservation concern, distributed widely across the country, to illustrate our approach (Table 1). We divided the country into 11,027 planning units of 25-km², and mapped known and probable distributions for each species. First, we synthesized and geo-referenced specimen or sighting records, and assigned a value of one to each unit with certain presence for that species. Then, since no species had enough geographically-precise records for inductive species-habitat modeling, we elicited expert ornithologist and herpetologist knowledge in Gabon to deductively map probable distributions based on field observations, species' ranges and habitat preferences. For each species, experts assigned units a 0.7 value if they were confident of finding the species there 70% of the time in a survey due to it having suitable habitat and/or a verified observation nearby, and a 0.3 value if they were confident of finding the species there 30% of the time due to less suitable habitat and/or no verified observation nearby (Polasky et al. 2000, Strange et al. 2007). All other units were assigned a zero for that species, indicating our assumption of species'

absence. These expert-mapped predictions attempted to make the most of what was known in a data-poor situation, and were treated as initial hypotheses which could be verified by surveying.

Table 1. Species, conservation rationale, data sources used to map distributions and targets

	Species	Conservation information	Source	% Target (known, probable)
1	Pink-backed Pelican <i>Pelecanus rufescens</i> Nesting sites	In Gabon, restricted to sedimentary basin (a). Nests colonially in tall trees, re-using sites annually (b). Nesting sites inadequately represented in parks (c).	c	100, 50
2	African Spoonbill <i>Platalea alba</i>	Partly-protected (d). In Gabon, restricted to north / coast. Needs large waters, lagoons, estuaries (b).	a, c	50, 50
3	Freckled Nightjar <i>Caprimulgus tristigma</i>	Localized in Gabon (c). Restricted to north-center of country (a).	a, c	No data, 20
4	African River Martin <i>Pseudochelidon eurystomina</i> Nesting sites	Central African endemic (b). Equatorial migrant with important congregation nesting on coast (a). Nests colonially on riverine sandbars or grassy sand plains near coast (b). Nesting sites inadequately represented in parks (c).	a, c	100, 50
5	Pale Olive Greenbul <i>Phyllastrephus fulviventris</i>	In Gabon, known from 1 observation in 1991 (e). Not recorded in a park (f).	c, e	100, 50
6	Dja River Warbler <i>Bradypterus grandis</i>	Near Threatened. Near-endemic. Important proportion of a globally-restricted species. Known from few localities (a).	a, c	100, 50
7	Red-headed Picathartes <i>Picathartes oreas</i>	Fully-protected (d). Vulnerable VU C2a(i). Important proportion of a globally-restricted species (a).	a, c, g	50, 20
8	Variable Sunbird <i>Cinnyris venustus</i>	In Gabon, restricted to southwestern savannas (a). Known from very few sites (c).	a, c	20, 20
9	Black-chinned Weaver <i>Ploceus nigrirostris</i>	Near-endemic. In Gabon, restricted to southeast (a).	a, c	50, 20
10	Loango Weaver <i>Ploceus subpersonatus</i>	Vulnerable VU C2a(i). Important proportion of a globally-restricted species. In Gabon, restricted to coastal scrub (a).	a, c	50, 50

11	Keeled Hinged Terrapin <i>Pelusios carinatus</i>	Vulnerable VU B in Gabon (h, i). Near-endemic. In Gabon, restricted to southeast (j). Not recorded in a park (f).	h, k	100, 20
12	Maran's Hinged Terrapin <i>Pelusios marani</i>	Near-endemic (j). Important proportion of globally-restricted species (l).	h, j, k, l	100, 20
13	Nile Crocodile <i>Crocodylus niloticus</i>	Fully-protected (d). Vulnerable VU in Gabon (h, i). Decline due to hunting. In Gabon, restricted to large water bodies along coast (j).	h, j	50, 20
14	Chapin's Chameleon <i>Chamaeleo chapini</i>	Near-endemic. Known from few localities (j). Not recorded in a park (f).	h, j, m	100, 20
15	Ivindo Dwarf Gecko <i>Lygodactylus sp. nov.</i>	Vulnerable VU in Gabon (h, i). Endemic. Known from 1 locality (j). In a park (f).	h, j	100, No data
16	Omboué Worm Lizard <i>Cynisca bifrontalis</i>	Endemic (j). Known from 2 localities. Restricted to central sedimentary basin (j). Not recorded in a park (f).	h, j, n	100, 20
17	Lambaréné Worm Lizard <i>Cynisca haugi</i>	Endemic (j). Known from 1 locality. Restricted to central sedimentary basin (j). Not recorded in a park (f).	h, j, n	No data, 20
18	Perret's Worm Snake <i>Leptotyphlops perreti</i>	Near-endemic (j). Known from 1 locality (j). Not recorded in a park (f).	h, j	100, No data
19	Pauwels' Blind Snake <i>Letheobia pauwelsi</i>	Vulnerable VU in Gabon (h, i). Endemic. Known from 1 locality (j). Not recorded in a park (f).	h, j, o	100, 100
20	Ocellate Water Snake <i>Hydraethiops laevis</i>	Near-endemic (j). Known from 1 locality (j). Not recorded in a park (f).	h, j	100, 20

Sources: a- IUCN Red List of Threatened Species (IUCN 2014); b- (Keith et al. 1992); c- P. Christy, unpublished data; d- Decree n° 164/PR/MEF, 19 Jan. 2011; e- (Sargeant 1993); f- (Christy et al. 2008); g- R. Oslisly, unpublished data; h- O.S.G. Pauwels, unpublished data; i- Evaluated according to IUCN criteria (IUCN 2012b); j- (Pauwels and Vande weghe 2008); k- (Pauwels and Maran 2007); l- (Maran and Pauwels 2005); m- (Knoepffler 1967); n- (Branch et al. 2003); o- (Pauwels et al. 2006).

5.3.3 MAPPING SURVEY VALUE

We defined the value of information that could be obtained through surveying a planning unit based on the extent to which surveys would be likely to confirm the presence of species we wanted to conserve. When expanding a protected areas network, confirming a species presence is more useful than increasing confidence in its absence. Surveying units with confirmed presence (1) or assumed absence (0) conferred no value since species occupancy was already known. Other units (0.3 or 0.7) contained uncertain information which could be improved by surveying. Units with higher probabilities of confirming a species (i.e. 0.7) contributed more valuable information than those with lower probabilities (i.e. 0.3) because they are more likely to be included in a reserve network. Each species' probability was treated as a non mutually-exclusive independent event, the union of which gave the probability of confirming a species in each unit:

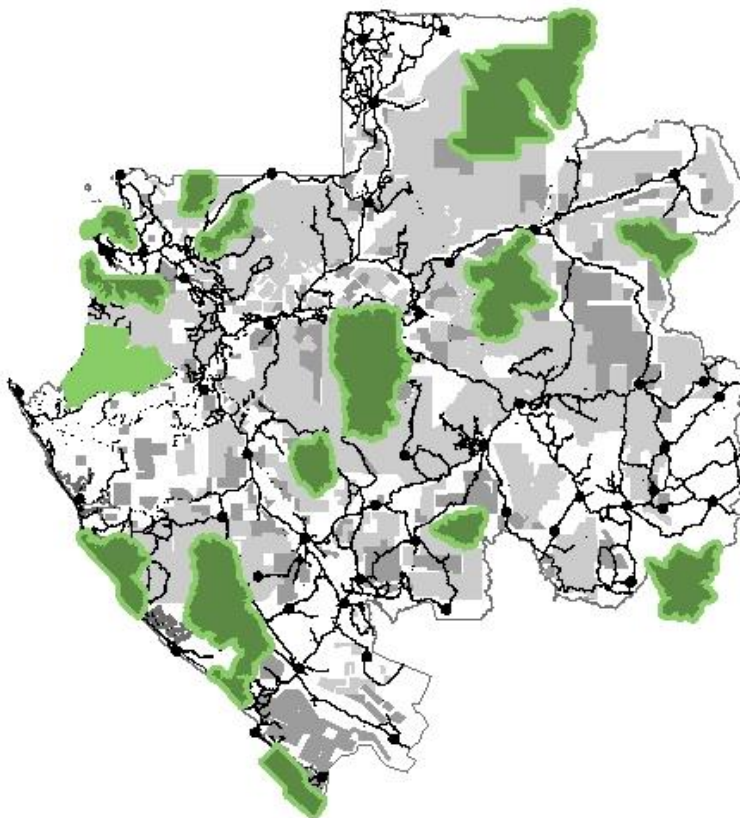
$$P(A \cup B) = P(A) + P(B) - P(A \cap B) \quad \text{eqn 1}$$

where A and B are probabilities of species A and B occurring in the unit. Probabilities were combined for all 20 species per unit, giving an overall survey value, p_i , for unit i . Units with high combined species' probabilities had multiple species where the likelihood of confirming their presence was high (0.7) but still uncertain; those with low values contained fewer species or species that were less likely to be present (0.3).

5.3.4 CONSERVATION OPPORTUNITY IN DIFFERENT LAND USE TYPES

We divided the country into six land-use types (Fig. 1; data from World Resources Institute 2009) and assigned relative costs reflecting conservation opportunity, where lower costs indicated higher levels of existing protection or management for species. The site selection algorithm, Marxan, preferentially selects lower-cost units when meeting representation targets (Ball et al. 2009). Existing parks were locked into the protected area network. Park buffer zones, the Wonga-Wongé Presidential Reserve and the Mondah Forest Reserve were considered partly-protected areas favorable for conservation, and assigned a relatively low cost, 50. Logging concessions, which by law should be sustainably managed, were given medium costs; those with validated management plans, 300, and those without management plans, 400. Urban areas (5km from towns, 1km from villages or roads) were considered least favorable for conservation and given a high cost of 800. All other areas were presumed to be unallocated to another major use and therefore 'available' to be zoned for conservation fairly favorably, receiving a cost of 100.

Figure 1. Land use types, used as a proxy for conservation opportunity, were assigned relative costs representing different levels of management for species-level conservation. Dark green = national parks; light green = partly-protected areas; light grey = logging permits with management plans; dark grey = logging permits without management plans; black = 5km from towns, 1km from villages and roads; white = areas not used for settlement, logging or protection.



5.3.5 GENERATING THE BENCHMARK CONSERVATION NETWORK

Our two representation goals were (1) to protect areas of known occurrence for each species, and (2) to represent a portion of their predicted ranges. Therefore we set two targets per species – one for their known distribution, and one for their possible but uncertain distribution (Table 1). Setting the target for known occurrences assures that

at least some of the known distribution of each species is conserved – a risk averse strategy given the uncertainty inherent in predicted distributions. For known localities, we set a 100% target for species with relatively small distributions ($\leq 275 \text{ km}^2$) and/or absence in most parks, 50% targets for those with wider distributions and/or limited presence in parks, and a 20% target for one species thought to favor anthropogenic habitats (only ever observed in gardens in Gabon) so presumably less important for park protection. For probable distributions, we set a 100% target for one very narrow endemic (likely to occur in $\sim 150 \text{ km}^2$), 50% targets for species with modest distributions ($< 5000 \text{ km}^2$), and 20% for species with larger distributions. Two species lacked data that were geographically precise enough to map confirmed targets, but contained probable targets based on natural history knowledge; two others lacked probable targets due to their unknown natural histories, but contained confirmed targets from specimen records.

The site selection software Marxan (Ball and Possingham 2000) was used to identify units that met targets in areas as favorable for conservation as possible (those units with lower cost). We ran Marxan 100 times, with 1 million iterations per run.

Marxan generates one near-optimal solution per run, resulting in a total of 100 alternative network solutions that satisfied our objectives and are reasonably efficient. A decision-maker with no resources to survey, who wished to meet all targets in the most favorable land use types, could select any of these 100 configurations that made sense to implement. Of these 100 solutions, Marxan identifies the ‘best’ solution – that

with the lowest objective function value – which we used as our benchmark conservation network to compare with different survey strategies.

Patterns across solutions are summarized by selection frequency, which is the number of times a unit is selected as part of one of the 100 near-optimal solutions. Units with 100% selection frequency are critical to an efficient protected area network; units never chosen are decisively unimportant. Units with 50% selection frequency are included in the final solution half the time, so clearly the species they contain can also be protected elsewhere. Selection frequency can be considered indicative of the unit's substitutability in an efficient protected area network. Higher selection frequency means fewer equivalent planning units, and therefore would be considered higher conservation priority than units with lower selection frequencies.

We used selection frequency, r_i , to indicate the conservation priority of each unit, i , in the initial network. We also used selection frequency values to define the substitutability weight, w_i , indicating the spatial flexibility of unit i in a solution. Substitutability weight was calculated as the absolute difference between a unit's selection frequency and the selection frequency of the most uncertain planning unit in the solution, scaled so more uncertain units had higher weightings:

$$w_i = (0.5 * n) - |r_i - (0.5 * n)| \quad \text{eqn 2}$$

where w_i = substitutability weight of unit i , r_i = selection frequency of unit i , and n = the number of runs. The term $(0.5 * n)$ gives the selection frequency value of planning units

that were selected 50% of the time – those which would be included in one of every two reserve systems, and so are the most uncertain of being included in an efficient network. Substitutability weight places the most weight on planning units whose inclusion in the network is least certain.

5.3.6 DESIGNING SURVEYS TO IMPROVE PROTECTED AREA DESIGN

Our goal was to design surveys that efficiently improved knowledge of species' distributions in places where knowledge was most important for good decision-making. The benchmark conservation network represented what a protected area network would be *a priori*, without being able to update our knowledge through surveying. However, if surveying was possible, we argue that effort should be invested in generating new information that challenges or changes this outcome. The most valuable information is that which most alters the decision outcome, in our case, where to put new protected areas. The benefit of a survey is measured as the change in the *a priori* protected area network that results from the knowledge gained.

We compared two strategies to prioritize units to survey. Both strategies directed surveys to units most likely to confirm species' presence, by taking the combined species' probabilities, p_i , of planning unit i (equation 1), into account. The first strategy prioritized units with higher selection frequencies (those most likely to be important for the conservation network), estimating survey value by:

$$v_i = p_i * r_i \quad \text{eqn 3}$$

where v_i = value of surveying unit i , p_i = combined species' probabilities of unit i , and r_i = selection frequency of unit i . In contrast, the second strategy prioritized surveying units from the benchmark network whose conservation priority was most uncertain (or substitutable), and estimated survey value by:

$$v'_i = p_i * w_i \quad \text{eqn 4}$$

where v'_i = value of surveying unit i when conservation priority is unknown, p_i = combined species' probabilities of unit i (equation 1), and w_i = substitutability weight of unit i (equation 2).

We compared the map of relative survey value based on both strategies to the benchmark conservation network. Since the benchmark network contained 425 units, we selected the top (highest value) 425 units under each survey strategy, and calculated the difference between each strategy and the benchmark, using Jaccard's distance as a percent:

$$J'(C, D) = \frac{|C \cup D| - |C \cap D|}{|C \cup D|} * 100 \quad \text{eqn 5}$$

where C is a set of the 425 top units in one strategy, and D is the best solution.

5.3.7 SURVEY COST

To explore implementation of these two strategies in the field, we estimated costs of surveying the top 10% of units from both, which consisted of 146 and 147 units respectively, spread widely across the country. We considered that a survey locality

had to be comprised of at least 3 clustered units. Survey cost was estimated in two parts, the logistical cost of accessing the survey locality, and salary and field expenses. Team composition varied by locality, depending on the species and skills needed, but could include an expert ornithologist and/or herpetologist, 1-2 experienced but junior field technicians, and a local guide. Time spent surveying depended on the search requirements of the species, estimated from previous inventories (Alonso et al. 2006). Logistical costs were estimated for a team originating from the capital city and traveling by the most practical means (plane, train, vehicle, boat or foot) to each locality. Travel distances were estimated from the national road map and digital road coverage (World Resources Institute 2009). Salary, insurance, transport, food and accommodation costs were sourced in-country and used to build a budget for surveying localities adequately enough to find the species or reasonably presume its absence, given realistic time and distance constraints for fieldwork in Gabon.

5.3.8 COMPARING SURVEY STRATEGIES

We compared sets of survey localities based on cost, benefit, and cost-effectiveness. The cost of surveying, c_j , was calculated for each survey locality j as above. The decision benefit, b_j , of surveying locality j was defined as the number of units at locality j that were not in the benchmark network, that were likely to be added to the network after surveying (expressed as a percent of the total network). The cost-effectiveness of surveying locality j , e_j , was the ratio of decision benefit to locality cost, b_j / c_j . We calculated b_j for each survey set, and ranked the order of surveying each site per set three different ways, by cost, benefit, and cost-effectiveness. We also calculated

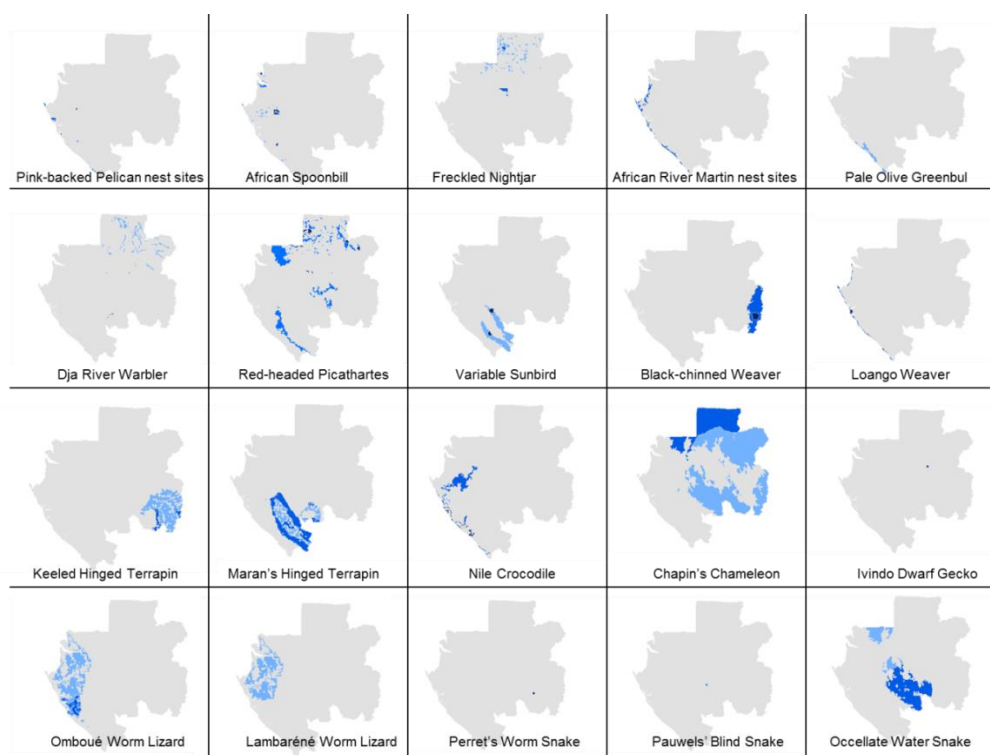
overall cost-effectiveness of surveying each set, as the ratio of overall decision benefit to overall cost.

5.4 RESULTS

5.4.1 SPECIES DISTRIBUTIONS

For all 20 species, confirmed presences occurred in 3.2% of units, based on 77 presence records (Fig 2). Only ten records were field-collected GPS points, among four species. Four species were known from single localities (Table 1, spp. 9, 15, 18, 19), and only one from >10 locations (sp. 12). Two species lacked mappable known localities, but are reliably documented in the country (spp. 3, 17). Mapping probable distributions increased the portion of units with non-zero values from 3.2% to 69.0%. Probable distributions were impossible to map for the least-known species (spp. 15, 18) for which no natural history information exists (Pauwels and Vande weghe 2008).

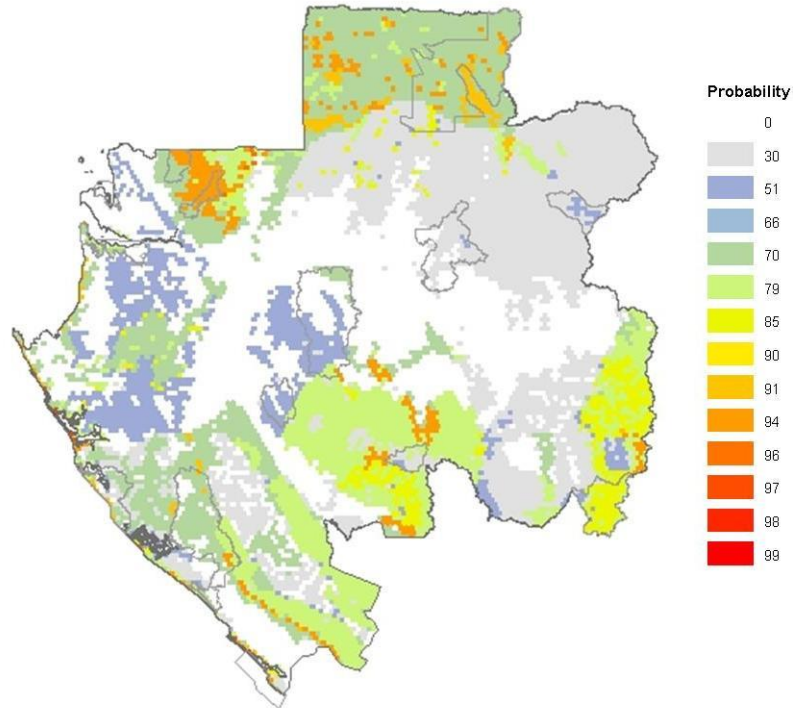
Figure 2. Distributions of species 1-20 in Table 1, top L to bottom R. Black = 100% confirmed presence; royal blue = 70% probable presence; light blue = 30% possible presence; grey = assumed absence



5.4.2 COMBINED SPECIES PROBABILITIES

Combined species' probabilities ranged from 0%, for units with only known (0,1) values, to 99.2% likely to confirm a presence, for units with four overlapping probable (0.7) values (Fig.3). Mapping combined species' probabilities helped to focus survey effort: just 0.31% of units had $\geq 95\%$ likelihood of confirming a species' presence, whereas over half the landscape (55.8% of units) had $\leq 30\%$ chance. If the purpose of survey is to document species' presence, the most expedient units to survey would be those with highest combined species' probabilities.

Figure 3. Combined species' probabilities for all 20 species. Warmer colors have higher probability of finding a species in survey.



5.4.3 GAPS IN THE EXISTING NATIONAL PARK NETWORK

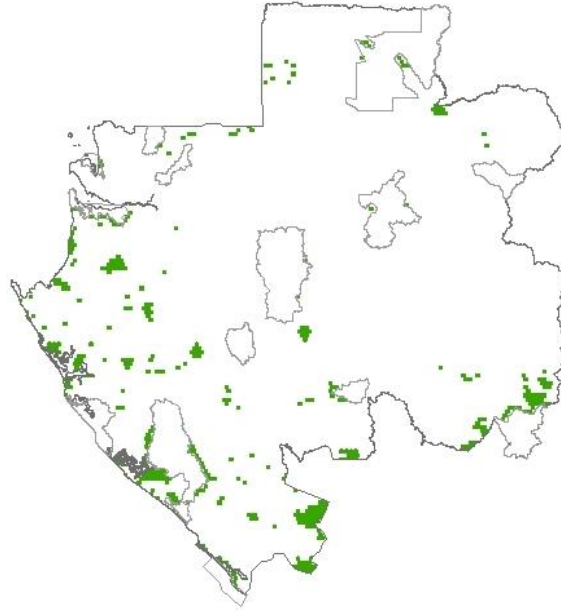
Existing parks exhibited large gaps in both presence targets and probable distributions. For confirmed occurrence, parks met targets for only one species (sp. 15). Known localities for half of the other 17 species fell entirely outside parks (spp. 5, 8, 9, 11, 14, 16, 18, 19, 20). For probable distributions, parks met targets for six relatively widespread species (spp. 3, 6, 7, 9, 14, 20), but missed targets for 12 of the 18 species with probability data. Of these 12, two distributions were entirely outside parks (spp. 17, 19), and ten were partially inside.

5.4.4 PRIORITY AND FLEXIBILITY IN CONSERVATION OPTIONS

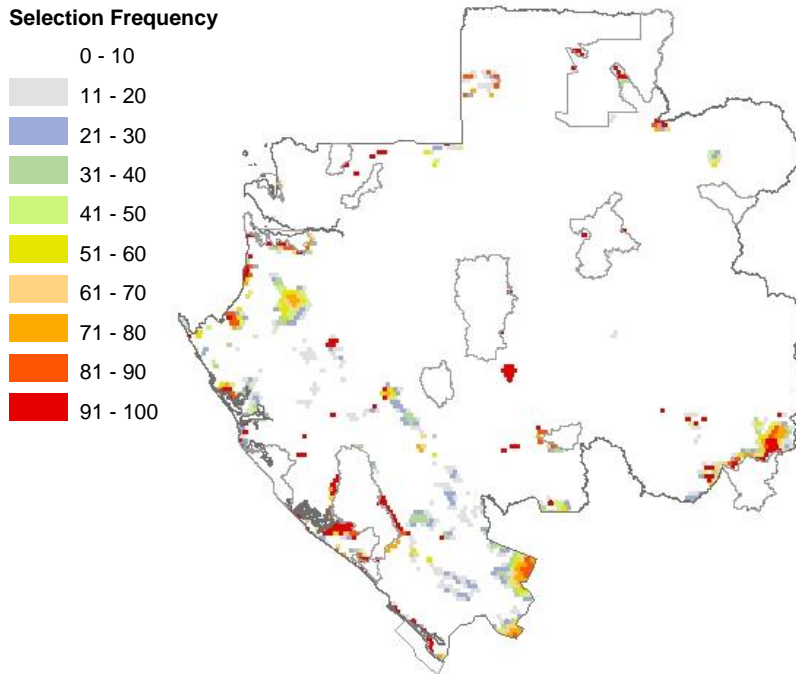
The benchmark conservation network, meeting all targets, is presented in Figure 4a, and patterns of priority and flexibility in Figure 4b. As indicated in the latter, most units were either very high or very low priority, giving a fairly decisive, spatially-restrictive, solution. Only about 1% of units were critical to meet targets, or high-priority ($r = 100$ for 0.9% of units; $r = 90-99$ for 0.5%). In contrast, most units added little-to-no value to the network ($r = 0-10$ for 92.5% of units). Half of the critical or high priority sites occurred in park buffer zones or reserves (53.1%). If no survey was possible, these critical or high-priority units would be a good preliminary set of expansion areas to propose, although not all targets would be met.

However, if survey was possible, effort should go towards seeking genuine alternatives to this preliminary set, giving decision-makers options for where to protect. We found that few (1.1%) units were highly substitutable ($40 \leq r \leq 60$). These are the few units which may provide good (although less obvious) alternatives for conservation.

Figure 4. (a) The benchmark conservation network, the solution meeting all targets most efficiently, was used to compare with both survey strategies.



(b) Selection frequency of initial conservation prioritization. Warmer colors were selected more often to meet targets in an efficient solution. Units that were critical ($r=100$) and high-priority ($r=90-99$) to meet targets comprised only 0.9% and 0.5% of all units. Most of the landscape had little to no value to survey, in white ($r=0-10$ for 92.5% of units). However, the most substitutable units are those with middle values of selection frequency ($40 \leq r \leq 60$).



5.4.5 COMPARING SURVEY STRATEGIES

The top 425 units in each survey strategy varied considerably with respect to the benchmark network. However, the strategy targeting uncertain conservation priority shared about half as many units with the benchmark network than the strategy targeting units of known priority ($J' = 71.0\%$ vs. 42.8%). In other words, it selected a considerably different set of units to survey (and potentially protect) than would be selected if no survey was possible. This uncertain priority strategy also targeted about 20% more units in 'available' land than the known priority strategy, orienting surveys to

places outside the current conservation landscape. In contrast, the known priority strategy selected about three-quarters more units in park buffer zones or reserves than the uncertain priority strategy – directing surveys to places where protection is already practiced to some degree. Both strategies had very few units in logging or urban areas, but some units in these land use types were critical to meet targets that could not be met elsewhere.

5.4.6 COST AND BENEFIT OF SURVEY PER LOCALITY AND SET

Sixteen localities were identified from the top subsets for each strategy, forming two survey sets, arrayed around the country (Fig 5, Table 2). Survey cost ranged from \$1,824 to \$14,488 per locality, depending on location and task. For example, the cheapest locality required a quick lake survey by technicians for a conspicuous species, versus the most costly, which required extensive travel and expert search in mountainous terrain for four elusive species. Certain localities were clearly important for each set, and eight were common to both. Surveying the full set identified by known priority would cost \$121,539, and the full set identified by uncertain priority would cost \$117,074.

Figure 5. Survey localities with known conservation priority (blue) and uncertain conservation priority (red). Each set contained 16 localities for which we compared survey cost and decision benefit. Surveying the known priority set would reduce uncertainty in species' distributions, verifying the importance of the locality for the species, but would have very little impact on land use decisions. Limited funds might instead be better spent on sites or species whose priority is less certain, yielding more options for conservation.

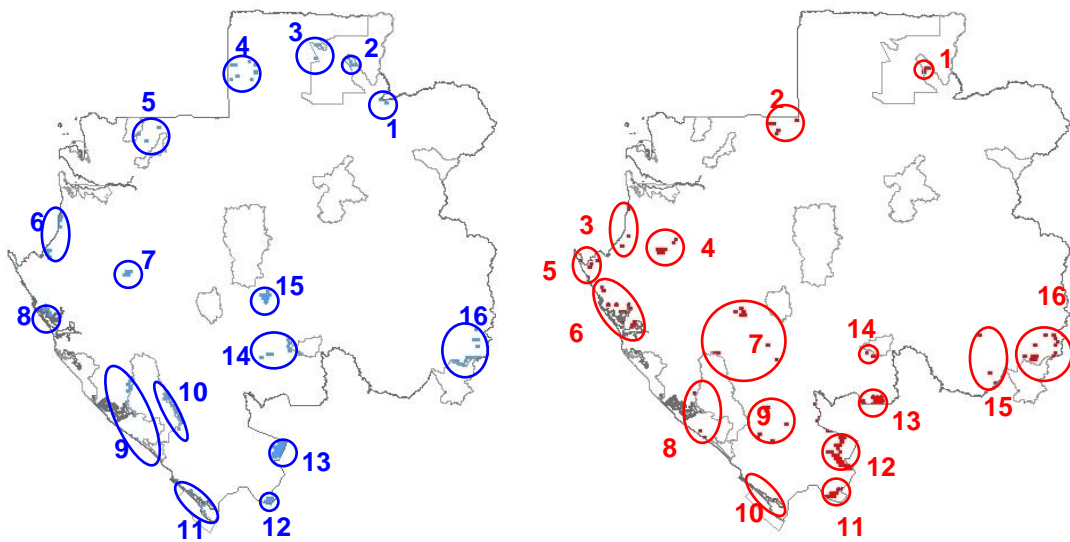


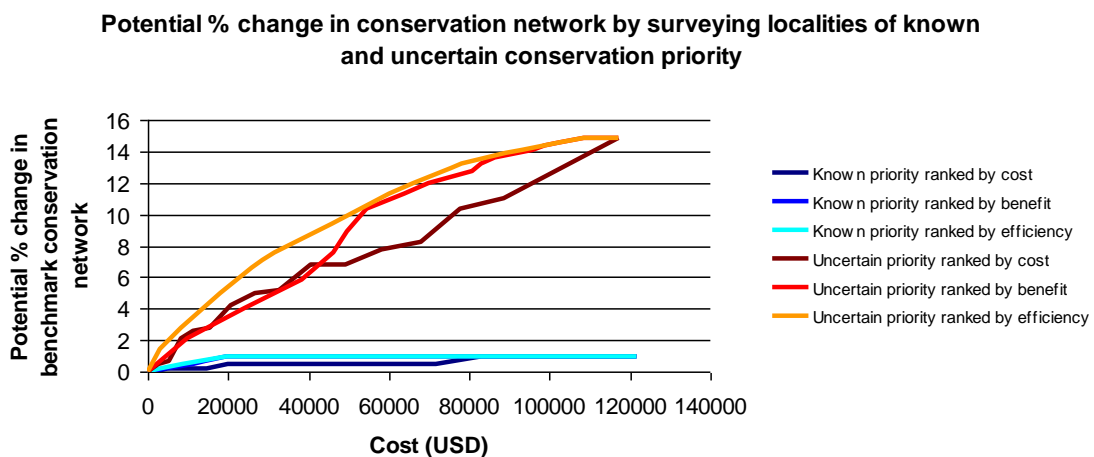
Table 2. Survey localities for both survey sets (in Fig. 5), species requiring survey per locality, survey cost (USD), decision benefit and cost-efficiency (*10,000).

Locality	Species to survey	Cost	Benefit	Efficiency
Localities of known conservation priority (blue)				
1 - Belinga	14	4,360	0	0
2 - Minkébé	7, 14	9,772	0	0
3 - Ntem	6, 14	7,693	0	0
4 - Oyem	3, 14	6,648	0	0
5 - Monts de Cristal	7, 20	5,409	0	0
6 - Wonga Wongé	4, 10	3,053	0.24	0.77
7 - Evaro	13	1,824	0	0
8 - Omboué	1, 4, 10, 13	5,398	0.24	0.44
9 - Gamba	1, 2, 4, 5, 10, 13, 16	8,664	0	0
10 - Monts Doudou	8, 12	8,181	0	0
11 - Mayumba	1, 4, 5, 10, 13	5,256	0	0
12 - Koko	8, 12	5,553	0	0
13 - Mabanda	8, 12	11,419	0	0
14 - Mbigou	12, 14, 20	12,595	0	0
15 - Iboundji	7, 14, 19, 20	14,488	0	0
16 - Batéké	9, 11, 14	11,226	0.47	0.42
Localities of uncertain conservation priority (red)				
1 - Minkébé	7, 14	8,425	0.71	0.84
2 - Sam	3, 14	5,986	0.71	1.18
3 - Wonga Wongé	4, 10	2,488	0.47	1.89
4 - Lac Gomé	13, 16, 17	5,053	1.41	2.79
5 - Port Gentil	1, 4, 10	3,055	1.41	4.62
6 - Omboué	1, 2, 13, 16, 17	9,884	2.12	2.14
7 - Fougamou	7, 12	10,943	0.71	0.65
8 - Gamba	4, 5, 10, 13	2,671	0.24	0.88
9 - Tchibanga	8, 12	8,001	1.65	2.06
10 - Mayumba	1, 4, 5, 10, 13	3,233	0.47	1.46
11 - Koko	8, 12	6,039	0.24	0.39
12 - Mabanda	8, 12	14,356	1.88	1.31
13 - Malinga	12, 14, 20	9,193	0.94	1.02
14 - Birougou	12, 14, 20	9,559	0.47	0.49
15 - Boumango	11, 14, 20	4,075	0.24	0.58
16 - Batéké	9, 11, 14	14,112	1.88	1.33

Whereas cost was similar for both sets, the benefit of surveying the set with uncertain priority was 15 times greater (Fig. 6, Table 2). If all localities were surveyed,

information gained by this set could potentially change the network by 14.82%, versus the known priority set by less than one percent (0.94%). All localities in the uncertain priority set were beneficial to survey, potentially changing the benchmark network by up to 2.12% per locality. In contrast, only three localities in the known priority set offered even modest decision benefit to survey (potentially changing the benchmark network by up to 0.47% per locality); the rest delivered no benefit because they were already included in the benchmark network. Surveying places where conservation priority was uncertain was 16 times more cost-effective per survey dollar than surveying where priority was already known.

Figure 6. Potential change in the conservation network from the two survey sets, per dollar. The uncertain priority set could potentially change the network up to 14.82%, versus the known priority set, by up to only 0.94%. We ranked sites within each set by cost, benefit, and cost-efficiency and found that the order in which localities are surveyed matters if funds are insufficient to survey the complete set.



5.4.7 PRIORITIZING SURVEY SETS AND LOCALITIES

Further, prioritizing each of the localities by cost, benefit, or cost-effectiveness mattered for both sets (Fig 6, Table 2). For the set with known conservation priority, full benefit (0.94% change in network) was achievable by surveying only three localities, and could be met four times cheaper when ranked by benefit or cost-effectiveness than by cost (\$19,677 vs. \$83,037). This is important because without incorporating information on benefit, a project manager might implement the whole set in order of cost, potentially spending five times the amount needed for the same result (\$19,677 vs. \$101,862). In contrast to this set, full benefit for the set with uncertain priority was 15 times greater (14.82% change in network), with every locality contributing benefit. Prioritization within this set not only gave greater decision benefit, it also saved time and effort: for example, at about half the budget, we could achieve ~1/3 more benefit by surveying localities ranked by efficiency versus cost, reducing the number of surveys from 11 to seven.

5.5 DISCUSSION

Designing protected areas to conserve rare or threatened species is often complicated by uncertainty in the distribution of species (Possingham et al. 2007). Surveys represent a financial investment to reduce that uncertainty. Maximizing the efficiency of survey effort requires an understanding of how that uncertainty affects the decision.

We designed two novel survey strategies that capitalized first on existing information to identify priority areas for protected area expansion as an *a priori* decision. To improve on this decision, one strategy targeted areas identified as high-priority for expansion; the other targeted areas of promising but uncertain priority to protect. Surveying the high-priority areas would verify their importance for conservation. Surveying the promising areas would provide alternative places to protect these species. Both strategies gain biodiversity information to plan land use better, but the latter generates new solutions for conservation, giving more decision benefit per survey dollar.

We argue that survey effort – or indeed any effort to reduce uncertainty for land use decisions – should be invested in gaining information that allows decisions to be made which would be impossible to make without it. Our key message to decision-makers, field managers and accountants is that uncertainty is only important to the extent it would change a decision. Invest smartly in reducing it, by targeting the information that would most change or challenge what you would do in the absence of that information, even if much of the overall uncertainty still remains.

Targeting uncertainty is important for conservation planning based on species' distribution models, which typically require spatial completeness to avoid biasing the placement of protected areas. Optimal surveying for these models asks, 'Where should we survey to efficiently improve a statistical distribution model, so that we can design a better reserve system?' In contrast, our study, acknowledges that land use decisions are not *only* driven by the distribution of species we seek to protect. We ask: 1) Given

what we know about the distribution of species and land uses, where would we expand our reserve system? 2) Given a limited survey budget, where would surveying most improve the placement of that network? This directed our surveys to places where we could meet our objectives efficiently, rather than to places with high uncertainty in species' distributions alone, especially where it was inconsequential to the decision at hand.

In developing this method, we had to simplify our case study in several important ways. First, the study included only 20 expert-mapped species' distributions, and only six representations of conservation opportunity by land use type. A more realistic scenario might include more species or other models, better representation of conservation or opportunity cost, or other features to protect or survey such as habitat types. We also simplified assumptions about spatial and ecological relationships by combining species' probabilities per unit as non mutually-exclusive independent events. Second, survey costs were simplified, calculated as individual round-trips to each locality, versus a more natural or efficient travel circuit among localities. Third, benefit was also simplified in two important ways. First, we assumed perfect detection – that surveying would clarify presence or absence, which is often not the case. Second, because surveys were directed towards places of more likely presence, we assumed that if surveyed, they would potentially be added to the network because they held the species. A better way of calculating benefit might include dynamic updating of target achievement as surveys progressed. Given complex field realities, such simplifications always have to be made when planning surveys, and no plan will be possible to implement off-the-shelf. However, having a framework for designing surveys and

evaluating options by their tradeoffs provides an important layer of decision support in fieldwork.

The importance of cost-effective sampling is well-recognized (Balmford and Gaston 1999, Funk et al. 2005, Gardner et al. 2008), and other studies have assessed the tradeoff between investing in sampling and management actions (Grantham et al. 2008, Grantham et al. 2009), but the question of how to allocate a dedicated survey budget to inform protected area expansion is different. The approach we develop is one way forward for making the best use of limited funds for the collection of field data, and is applicable to other survey questions, regions, or even the collection of other types of information to address other uncertain land use variables.

Our experience as practitioners is that there is a need for better approaches for how to allocate limited survey effort to solve land use problems. We have seen field evaluations to identify new protected areas target places which are already favored to protect, to give scientific justification to a decision that has essentially already been made, or collect data primarily to improve knowledge about the distribution of species which are already well-protected elsewhere. Although we acknowledge that sometimes there are political or tactical reasons why these types of surveys may be important, in this study we refocus the question on surveys designed to efficiently inform conservation and land use decisions. Our results suggest first using the information at hand to make an *a priori* decision, then identifying where to go to gain information that specifically improves that decision.

Other ecological applications have also recognized the usefulness of *a priori* decision analyses and the need to evaluate the value of collecting new information for management and monitoring (Grantham et al. 2008, Grantham et al. 2009, McDonald-Madden et al. 2010, Wintle et al. 2010, Runge et al. 2011, Possingham et al. 2012). The value of information depends on several factors, including how uncertain a decision-maker is, the cost of making a wrong decision, the cost of acquiring new information, and the ability to take action to change an outcome once this information is acquired (Macaulay 2005). Information has the most value when uncertainty is high, much is at stake, and actions can be taken to change the outcome. Applied to our case study, this implies that if survey information is truly used to decide where to protect, it will have a high value, especially at sites where conservation priority is uncertain, because land protection may be our best defense against losing these rare and threatened species. We encourage the development and application of ecological decision analyses, especially to support decision-makers operating in data-poor contexts, who need to be discriminating about the value of information, and choose to invest in that which makes the most impact to better land use decisions.

Chapter 6

GENERAL DISCUSSION

6.1 KEY FINDINGS

This study investigated how a systematic approach to spatial planning could support real-world conservation decisions, through a case study in Gabon. It characterized species, habitat and land use features, creating a new information base to support decision-making in a data-poor context; assessed the conservation status of terrestrial vertebrates and the ecological representation of existing protected areas; and identified priority species, habitats, locations and actions required to meet conservation targets efficiently, across land managed by different sectors. The study also developed a novel method to help managers decide where to invest in field surveys to gather information about which sites to protect, thus contributing to the field conceptually and methodologically. The work advances the research, development and practice of conservation prioritization and spatial planning, particularly in data-poor contexts.

Key contributions and findings:

- 1) This study filled a major knowledge gap by revealing the conservation status of Gabon's terrestrial vertebrate species. We found that 9% of these species,

which included amphibians, reptiles, birds and mammals, met at least one criterion for conservation attention (Chapter 3). One-quarter of these species are currently unprotected, suggesting possible gaps in protection (Chapter 3).

- 2) Mapping the distribution of species, habitats and land uses across the country, largely for the first time, we discovered that these features exhibit strong spatial structure. Most priority species are narrowly distributed – 1/3 cover <1% of Gabon, and another 1/3 cover 1-5% (Chapter 3). Habitat distribution is similar, with 37% of land units covering <1% of Gabon, and 43% covering 1-5% (Chapter 2). The distribution of land uses is also skewed – oil, mining and agriculture permits together cover <5% of land, national parks cover 11%, and logging permits extend over half the territory (54%; Chapter 2).
- 3) Setting representation targets to clarify conservation goals, we found that national parks met only 12% of species targets (Chapter 3) and one-quarter of habitat targets (Chapter 2). However, using optimization, we found that many spatial solutions exist which could meet all targets, with minimal impact on land used for local livelihoods (Chapter 3). We distilled these options down to a handful of sites that the country needs to protect to achieve targets efficiently (Chapter 3).
- 4) The spatial structure of biodiversity and land uses dictates that for Gabon to achieve its conservation targets, biodiversity management on production lands must be stepped up (Chapter 2-4). For example, critical biodiversity sites overlapped with nearly one-quarter (23%) of onshore oil extraction permits, and nearly one-tenth (9%) the area of mineral extraction permits (Chapter 4). We

provide management recommendations for permit-holders whose land contributes importantly to these national conservation goals (Chapter 4).

- 5) Finally, we developed a novel method to support decisions about where to survey to inform protection decisions in a data-poor context. Rather than surveying areas already thought to be important to conserve (a common decision bias), our method directs effort towards areas where distributions were uncertain, but there was the potential to reveal new and perhaps unexpected places where conservation targets might be achieved (Chapter 5). Competition for land is rapidly increasing across Central Africa – this strategy will give decision-makers more options for where to protect, which may increase the chance of conservation success.

6.2 THE FINDINGS IN CONTEXT – WHY DO THEY MATTER?

Gabon is credited with an extremely low rate of deforestation (Sannier et al. 2013), some of Africa’s greatest remaining populations of forest megafauna (Blake et al. 2008), a long natural coastline fringing vast marine waters, and a relatively new network of national parks (Anonymous 2002). By many standards, the country is considered a conservation success. However, the performance of its protected areas in representing biodiversity has never been critically or systematically examined for its gaps and potential to improve. *How well are national parks actually protecting the country’s biodiversity resources? How could that protection be efficiently extended to achieve any unmet conservation targets?* This overdue evaluation is important for

national accountability, but more importantly, for putting new mechanisms in place to ensure that the country's biodiversity is effectively conserved.

Putting conservation mechanisms in place requires engaging people in choices they make about land and natural resource management (Knight et al. 2008). During the course of this work, a great deal of time and effort was invested in this engagement, which I do not discuss in this thesis. However, due in part to this engagement, I outline three examples of how the process of conducting this study and its findings may be helping to alter the course of conservation or land management in Gabon. In each case, I begin by discussing the existing situation in Gabon, described as the “Status quo,” then explain ongoing work to improve the status quo in the future, as the “Outlook”.

6.2.1 IMPROVING SPECIES PROTECTION LAWS

Status quo: Wildlife managers in Gabon have always been severely hampered by lack of information about population trends and distributions of the species in their charge. Today, only two studies documenting population trends for two species exist, both of them revealing precipitous declines – between 1983 and 2000, Gabon lost over half of its gorilla population to Ebola and commercial hunting (Walsh et al. 2003), and approximately 60% of its elephants to hunting-related pressures in the last decade (Maisels et al. 2013). Loss of these large forest architects from Central African landscapes is alarming, as it is thought to indicate faunal erosion and changes in ecosystem function at other levels (Abernethy et al. 2013). However, outside of hunting

control and national park management, little is known or done to target species-level protection in Gabon for the majority of wildlife species.

Outlook: By drawing attention to a wider (but manageable) set of species that merit conservation attention, this study convinced the National Parks Agency and Wildlife Department to adopt a transparent, criteria-based procedure to assess species status based on biology, distribution and threat, and to use a decision tree to help determine which species meet criteria for national protection. Currently, species protection lists are being revised, and new legal text drafted; this new text may include habitat protection for species outside protected areas, which have so far only been protected by law from hunting. In other words, had this study not been done, I speculate that: 1) a number of species would still be missing from protection consideration in Gabon today; 2) habitat protection for species would likely not be under consideration in this revision; and 3) justification for species protection would be unclear and unavailable to law-makers or others who might challenge, need to defend, or otherwise seek rationale for the decision.

6.2.2 CLARIFYING PRIORITIES FOR PROTECTION BEYOND PARKS

Status quo: Conservation in Gabon is heavily focused on apes, elephants and national parks. Priorities for “conserving biodiversity” otherwise remain somewhat vague, partly due to lack of an articulated set of goals that define the big picture, allowing managers to put a site or feature’s contribution to overall targets in perspective (Pressey et al. 2003). This lack of clarity hinders both conservation and ‘green’ business (Meijaard

and Sheil 2012), as the conservation sector tends to struggle to define or defend its biodiversity priorities (or High Conservation Values (Jennings et al. 2003)) on the ground, and 'green' operators struggle to understand what they need to do to respect these priorities or values in Gabon.

Outlook: By defining a set of conservation features and delineating priority areas for their protection, this study delivers much-needed guidance to protection decisions that go beyond apes, elephants and parks. I outline two ways that this information is being used. First, priority areas identified in this study are being considered as one layer of information in the National Land Use Plan, so that future land use decisions may be evaluated with these areas in mind. Second, since this study was designed to be compatible with the High Conservation Value concept, many features and priority areas are directly applicable to guide 'green' operations to areas with less environmental risk. Thus, had this study not been done, I suspect that: 1) biodiversity priority areas, and the features that define them, would remain unspecified; 2) these areas would not be under consideration in land use planning; and 3) would potentially be facing more encroachment than they are today, even from 'green' operations, for lack of being guided elsewhere.

6.2.3 A SYSTEMATIC APPROACH TO NATIONAL SPATIAL PLANNING

Status quo: Like many countries, land use in Gabon has evolved in an ad hoc and opportunistic manner to meet various needs at different times, versus having been planned, designed or explicitly coordinated across different interests to achieve

particular goals (Albrechts 2004). During the course of this thesis, many separate land-use problems emerged for the government to solve in different parts of the country – for example, where to site new agricultural projects or military training grounds, how to zone the Exclusive Economic Zone for multiple uses, and how to handle cases where mineral hotspots overlap with national parks. Finding political solutions to some of these problems proved difficult, in part due to lack of a sound technical and conceptual base for planning. Over time, the need for a systematic, coordinated approach to planning became increasingly evident.

Outlook: Eventually, the government formally established a National Land Use Plan to coordinate and manage land and water use among ten sectors across terrestrial, freshwater and marine realms. Partly through the experience of solving problems like those listed above, which were addressed in a rational manner, and partly through the example and proof of concept provided in this study, a systematic method to planning was validated in the Terms of Reference as the approach for national land use planning. Thus, although a coordinated approach to planning may have emerged out of need, without having demonstrated and communicated the approach applied in this thesis along the way, it is possible that a less systematic, structured or information-based approach to national level planning would be employed today.

6.3 CONTRIBUTION TO APPLIED CONSERVATION SCIENCE AND SPATIAL

PRIORITIZATION

In the Introduction to this thesis (Chapter 1), I identified three themes relevant to many real-world conservation problems that remain somewhat rarely addressed in the peer-reviewed literature – exploring them in this work contributes to their development in the field of applied conservation science and spatial prioritization. I summarize how this work contributes to each theme.

6.3.1. PLANNING IN DATA-POOR CONTEXTS

Some of the most instructive examples of applied conservation plans in the literature come from areas which admittedly benefitted from “relatively good data” (for the Great Barrier Reef, (Fernandes et al. 2005) p.1734), “a long history of biological exploration” (for the Cape Floristic Region (Cowling and Pressey 2003) p.1), and occurrence in “one of the more “data-rich” parts of the world” (in Australia (Pressey et al. 2000) p.55). In contrast, planners working in tropical forests often operate in “data vacuums” (Gardner et al. 2007), and are thus obliged to use innovative proxies to represent the biological patterns and processes that are important to plan for, but which lack information. For example, working in an Amazonian region with “near-complete lack of biological and physical data” (p.485), Thieme et al. (2007) relied heavily on remotely-sensed datasets and first principles of conservation biology and geography to produce a freshwater conservation plan. Also in Amazonia, Tole (2006) lacked species-level data for amphibians and reptiles, so modeled habitat suitability at the family level, using probabilities of suitability to define priority areas. In Cambodia, where data were

“staggeringly incomplete or non-existent” (p. 227), Strange et al. (2007) combined tree data collected for another purpose with stakeholder mapping for planning.

Like these studies, the work presented in this thesis used a mosaic of remotely-sensed datasets (Chapters 2, 3), first principles of ecology and geography (Chapters 2, 3), probabilities of habitat suitability (Chapter 5), data collected for other purposes (Chapter 2-5) and expert knowledge (Chapters 2-5). Drawing on examples elsewhere (Bailey 1987, Leathwick et al. 2003, Beier and Brost 2010), it leveraged global datasets (IUCN 2010, Rondinini et al. 2011) with local knowledge in attempt to make the most of multiple sources of information in a complementary way. The resulting collection of biodiversity maps, although modest, sets a new precedent for Africa’s forested tropics, and the compilation of land use layers is possibly the most comprehensive in the region – being able to analyze these features together gives new understanding of, and ability to generate new solutions for, conservation and land use problems. This study is an uncommon example, at least in Central Africa, of harnessing existing information and applying it to real-world environmental decisions (Possingham 2012), thereby contributing to the field of applied conservation research and prioritization.

6.3.2 FOCUSING ON WHAT MATTERS IN A DECISION

Land use decisions are fraught with uncertainty, particularly in data-poor contexts. But different kinds of uncertainty exist (Regan et al. 2002), and not all uncertainty matters (Runge et al. 2011) – a key idea developed in this thesis is that uncertainty will never be completely removed in a decision, but is only important to the extent it might change the decision. Decision-makers should focus on the elements of the decision that matter

in the end. In particular, given the opportunity to gain information before making a decision, a decision-maker should focus on that which has the most potential to change or influence the outcome, and will do so efficiently.

This idea is consistent with thinking developed in the “Value of Information” literature (Raiffa 1974), derived from the field of economics, and applied only relatively recently to the natural resources, particularly for monitoring (McDonald-Madden et al. 2010) and adaptive management (Runge et al. 2011, Williams et al. 2011). These studies recognize that while gaining information through monitoring can inform and improve management, the benefits do not always outweigh the costs of acquiring it; monitoring programs need to be rationally evaluated to ensure that investing in new information actually improves management cost-effectively (McDonald-Madden et al. 2010).

This thesis asserts the same principle, applied to information gained to improve planning – we suggest that, especially in little-studied regions, collecting new data will always improve the state of knowledge, but data collection needs to be rationally designed to ensure that the information gained actually improves our ability to make protected area decisions efficiently. Where this concept has been investigated before, some studies have found that investing in new information was an effective way to improve planning (Runting et al. 2013), while others found diminishing returns from information gained in field surveys to change planning outcomes (Grantham et al. 2008). This study recognized that uncertainty is only important to the extent it will change a decision, so surveys done to inform protected area expansion should be designed to reveal new, perhaps unexpected places where conservation could be

achieved. This thesis makes a unique contribution to the field of applied prioritization by developing a method that managers can use to evaluate the benefits of gaining information in different survey designs for improving protected area decisions, allowing the concept to become more widely tested and used.

6.3.3 DESIGNING PRIORITIZATIONS THAT CAN RESPOND TO VARIOUS NEEDS

Finally, an important theme of this work is its contribution to the body of knowledge that aims to close the research-implementation gap (Knight et al. 2006b, Knight et al. 2008). Like other authors (Prendergast et al. 1999, Theobald et al. 2000, Pierce et al. 2005, Knight et al. 2006b, Gibbons et al. 2008, Smith et al. 2009, Lindenmayer et al. 2013), I found that bridging this gap depends heavily on social engagement, good working relationships, trust and communication. However, two other elements fundamental to the systematic process itself seemed to help its acceptance in Gabon. First, the logical science-based approach lends credibility, a certain amount of objectivity, and transparency, which may help cut through political agendas and refocus protection decisions on biodiversity, versus on historic, anecdotal or even personal preferences. Second, a simple but explicit design allows it to be flexible to different applications. For example, because of the way this study was conceived – in terms of spatial extent and resolution (Briggs 2001), choice of surrogates (Margules et al. 2002, Pressey 2004), data (Williams et al. 2002) and planning scenarios – both its input and output results have proven useful for other, unintended applications, such as identifying biophysically suitable areas for agriculture, with minimal environmental impacts. The systematic approach and flexible design have essentially helped to create a planning platform relevant to different uses, a model which may be more widely

applicable to other countries, particularly in parts of the world like Central Africa which tend to lack, yet urgently need, more rational, accountable models and practices in environmental management.

6.4 LIMITS OF THE STUDY AND FUTURE WORK

This study is one example of how applied conservation planning might be approached in a data-poor context, but as a single case study, it was inevitably limited in many ways. I discuss just two principal shortcomings, and how they are being or may be addressed in future work.

6.4.1 LIMITED SCOPE

Limitations: A major limitation of the study was its near-exclusive focus on conservation goals and data. Maintaining this focus allowed a first characterization of conservation aspects of planning, which was appropriate to meet the goals of the study. However, including social, economic, or other goals and data beyond conservation would have ultimately strengthened the work, broadened its application, and made the conservation scenarios themselves more realistic (Knight et al. 2008). For example, in Chapter 2, I evaluate land allocated to six sectors, but do not examine those land uses or their social or economic aspects in detail, focusing instead on binary habitat conservation (in a protected area or not). In Chapter 3, rather than addressing a wider set of planning objectives, I only consider conservation targets, which limits the scope and realism of the planning scenarios greatly (Klein et al. 2009, Halpern et al.

2013). Also in this chapter I use a simple proxy for 'cost' in Marxan, instead of representing the economic costs of conservation accurately (Naidoo et al. 2006, Richardson et al. 2006), since cost data were not available. These limits in overall scope significantly hinder this study's applicability, and beg the inclusion of other goals and data in future iterations.

Further, even within the narrow scope of conservation, this study focused primarily on static patterns of terrestrial systems and species, ignoring most aquatic systems and biota, all non-vertebrates, ecological processes, and the dynamic nature of biological patterns and processes in space and time. In terms of habitat representation, although some surface water and flooded systems were mapped in Chapter 2, and the planning units used in Chapter 3 were river catchments, explicit inclusion of freshwater, brackish and marine systems was not undertaken, despite their importance in planning (Abell et al. 2007, Spalding et al. 2007). In terms of species, for practical reasons, the study was limited to primarily-terrestrial species, even though these taxa represent a fraction of the biological diversity that needs to be planned for, particularly in the tropics (Dirzo and Raven 2003). In addition, no ecological or dynamic processes were incorporated, despite their well-known role in generating and maintaining biodiversity pattern (Rouget et al. 2006), and the need to plan for processes (as well as patterns) to ensure their persistence (Pressey et al. 2007). Hence, even within the narrow scope of conservation, all these exclusions are major shortcomings that were simply beyond the scope of a single thesis, but certainly need to be addressed in the future.

Future work: While the work presented in this thesis was limited in scope, one of its purposes was to trial systematic planning in Gabon to explore the potential for more comprehensive work in the future; in this vein, the study served its purpose. Indeed, in terms of the wider planning scope, a series of social and economic studies are currently being pursued by the government as part of the National Land Use Plan to address planning in different economic sectors (oil, mining, logging, agriculture) as well as rural and informal-sector land use. Instead of planning just for conservation, it would be useful for the next iteration to address multiple objectives, better reflecting different sectorial needs, and evaluate more realistic costs, benefits and tradeoffs of different zones and configurations across the land and seascape (Polasky et al. 2008, Watts et al. 2009, Moilanen et al. 2011, Halpern et al. 2013). In addition, the scope of planning for conservation is also becoming more comprehensive in the country. During the course of this work, several non-governmental organizations developed interest in conservation planning in Gabon (for example, Tear et al. 2014). Thanks to their interest, work is now underway to incorporate a wider suite of features, knowledge and considerations in conservation planning, including expertise from fields such as botany, ichthyology, and marine sciences. Instead of just planning for protected areas, future conservation planning that is able to take into consideration the conservation costs and benefits of different land use zones may be especially useful to feed into the national planning process.

6.4.2 METHODOLOGICAL SHORTCOMINGS

Limitations: Decision analysis would be best informed by empirical evidence.

However, even in data-rich contexts, expert opinion is often the only information available, and therefore a crucial resource to capitalize upon, despite inevitable limits to any expert's knowledge, objectivity or accuracy (Kuhnert et al. 2010). This study relied on expert knowledge mostly in the conservation assessment (Chapter 3), and mapping (Chapters 2, 3). Both processes were conducted by some of the best taxonomic and natural history experts for Gabon, yet the group was small, the work was rapid, and unavoidably incurred an unquantified degree of error. In terms of the mapping component in particular, habitat and species maps drew upon thousands of hours of expert field observation, but were not explicitly ground-truthed or quantitatively validated themselves, placing a serious limitation on the objectivity and repeatability of the work (Boitani et al. 2011). Like other similar studies (Thieme et al. 2007), we caution against using these maps alone, without ground validation, to make a decision – they may be better considered a starting point, versus an ending point, for site evaluation. Best practice in applied planning calls for using the best expert knowledge available, treated with rigorous prioritization techniques (Knight et al. 2009), as practiced in this study. Nonetheless, weak validation is a cause for caution in this work.

Future work: There are a number of ways in which these shortcomings could be improved in future work. First, in terms of the conservation assessment (Chapter 3) – a process which always depends on expert knowledge (IUCN 2012a) – it could be improved by including a wider range of taxonomic and geographic expertise, and a

more thorough process of elicitation, evaluation and documentation of information gathered from the experts. Ideally, Gabon would be able to engage in an assessment process at the standard of a recognized national Red List review (IUCN 2012a). Second, in terms of species and habitat mapping (Chapters 2, 3), this process could be improved with more field data that would allow statistical validation of the models (Elith and Leathwick 2009). To this end, the government is engaged in compiling tree inventory data from logging permits throughout Gabon (similar to the sample presented in Maniatis et al. 2011), that might allow habitat mapping based on empirical data. The outlook is more difficult for other taxonomic groups, which are less well-documented – although technology such as camera traps and GPS loggers is increasingly being used, datasets are still poorly developed. As these datasets gain greater spatial coverage, they could perhaps be analyzed with more rigorous techniques for incorporating expert knowledge (Martin et al. 2005, Kuhnert et al. 2010) and explicit treatment of uncertainty (Burgman et al. 2005), to improve model development.

6.5 CONCLUSION

Spatial prioritization and systematic planning methods have been developed for the purpose of aiding decision-makers in the complex task of making more rational land use choices, yet remain underutilized in many situations which might benefit from them greatly. Applying these methods to a tropical forested country in a data-poor part of the world, this study contributes to the research, development and practice of spatial planning, and to investigating how it could support real-world conservation decisions. As land use pressures and opportunities evolve rapidly around the world, decision-

makers will face increasingly difficult political choices about how to use limited land and water resources to achieve different, often competing goals related to the land. Spatial prioritization will play an important role in determining how those choices go. By demonstrating, developing and enabling the uptake and use of a systematic approach to planning, this study makes a fundamental contribution to the principles and practice of making informed land use decisions.

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8 ANNEX: RELATED PUBLICATIONS GENERATED DURING THE THESIS

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Patch-occupancy models indicate human activity as major determinant of forest elephant *Loxodonta cyclotis* seasonal distribution in an industrial corridor in Gabon

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ABSTRACT

The importance of human activity and ecological features in influencing African forest elephant ranging behaviour was investigated in the Rabi-Ndoko corridor of the Gamba Complex of Protected Areas in southwest Gabon. Locations in a wide geographical area with a range of environmental variables were selected for patch-occupancy surveys using elephant dung to assess seasonal presence and absence of elephants. Patch-occupancy procedures allowed for covariate modelling evaluating hypotheses for both occupancy in relation to human activity and ecological features, and detection probability in relation to vegetation density. The best fitting models for old and fresh dung data sets indicate that (1) detection probability for elephant dung is negatively related to the relative density of the vegetation, and (2) human activity, such as presence and infrastructure, are more closely associated with elephant distribution patterns than are ecological features, such as the presence of wetlands and preferred fresh fruit. Our findings emphasize the sensitivity of elephants to human disturbance, in this case infrastructure development associated with gas and oil production. Patch-occupancy methodology offers a viable alternative to current transect protocols for monitoring programs with multiple covariates.

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The Influence of Hunting on Antipredator Behavior in Central African Monkeys and Duikers

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ABSTRACT

Many animals can adjust their behavioral strategies to reduce predation risk. We investigated whether rain forest monkeys and duikers alter their antipredatory behavior in response to hunting by humans in southwestern Gabon. We compared monkey and duiker responses to human observers in an area where hunting is prohibited, to those in a nearby area where hunting pressure is moderate but spatially variable. The results of our study indicate that monkeys become more secretive when hunted, commencing alarm calls only when at a certain distance (typically > 50 m) from humans. We found no difference in monkey group size between hunted and no-hunting areas. In no-hunting areas, duikers often freeze in response to approaching observers, but in hunted areas they abandon this strategy and rapidly flee from humans. Duikers also whistle more often in areas where they are hunted frequently. Our findings have at least two important implications. First, behavioral observations of monkeys and duikers may be useful in gauging local hunting intensity in African rain forests. Second, duiker densities are likely to be overestimated in hunted areas, where they more readily flee and whistle, and underestimated in no-hunting areas, where they rely on freezing behavior to avoid detection. Because behavioral adaptations to hunting vary both among species and localities, these differences should be considered when attempting to derive population-density estimates for forest wildlife.

Does rainforest logging threaten marine turtles?

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Abstract

Industrial logging is expanding rapidly in Central African rainforests. We suggest that logging operations in this region pose an indirect threat to nesting marine turtles, especially the Critically Endangered leatherback turtle *Dermochelys coriacea*. This occurs because some logs are being lost or abandoned during downriver transport to coastal timber yards; the lost logs float out to sea and then often wash ashore, where they accumulate on beaches used by nesting turtles. We used a light aircraft to survey logs along the entire coastline of Gabon, and also studied the impacts of logs at Pongara Beach, one of the world's most important turtle nesting areas, during the 2002-2003 and 2003-2004 breeding seasons. Nearly 11,000 lost logs were counted along Gabon's beaches, with an estimated commercial value of USD 11.1 million. Logs were unevenly distributed along the coast, reaching a peak density of 247 logs km⁻¹. At Pongara, logs blocked 30.5% of the beach. These logs had a number of negative effects on marine turtles, causing 8-14% of all nesting attempts (n = 2,163) to be aborted or disrupted. Initiatives to remove lost logs and driftwood from critical nesting beaches may be the most effective means to reduce their deleterious impacts on threatened marine turtles.

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Notes and records

Movements of four forest elephants in an oil concession in Gabon, Central Africa

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Introduction

Infrastructure developments, particularly roads and settlements, can restrict the movements of African forest elephants (*Loxodonta africana cyclotis*; Barnes *et al.*, 1991; Blake *et al.*, 2007; Buij *et al.*, 2007; Blake *et al.*, 2008). Although activities and land-use types generally associated with roads provide forage that may attract elephants to a

increasingly large portions of remaining elephant habitat (CBFP, 2006; Laporte *et al.*, 2007). If hunting is controlled, extractive concessions may add considerable area to conservation landscapes (Elkan *et al.*, 2006; Laurance *et al.*, 2006; Clack *et al.*, 2009). As resource extraction reaches the most remote parts of the forest elephant's range outside protected areas (Blake *et al.*, 2007), data that document elephant responses to a variety of forest uses and management strategies are needed. A central question is to what extent elephants can survive along gradients of increasing human influence.

Research within our forested study area in southwestern Gabon (1°50'–3°10'S; 9°15'–10°50'E), where limited persecution exists with relatively intense resource extraction, has shed some light on elephant movements in human use areas: (i) forest elephants from several genetically defined sub-populations congregate in the oilfields; some are year-round residents while others are seasonal migrants from adjacent parks (Eggert *et al.*, unpublished data), (ii) movements are influenced more by human presence (roads, settlements) than by ecological factors (water, fruit), even in un hunted areas (Buij *et al.*, 2007), (iii) roads depress elephant abundance, particularly where hunting is present (Laurance *et al.*, 2006) and (iv) stress levels are not elevated in un hunted human use areas, indicating that nonthreatened elephants may acclimate to humans (Munshi-South *et al.*, 2008).

The present study adds to this body of knowledge by detailing movement patterns of four forest elephants fitted

Biodiversity and conservation genetics research in Central Africa: new approaches and avenues for international collaboration

Nicola M. Anthony · Patrick Mickala · Katharine A. Abernethy · Christiane Atteke · Pulchérie Bissiengou · Michael W. Bruford · Francisco Dallmeier · Thibaud Decaëns · Akaibe Dudu · Adam Freedman · Mary Katherine Gonder · Olivier Hardy · John Hart · Kathryn Jeffery · Mireille Johnson · Flore Koumba Pambo · Alexandra Ley · Lisa Korte · Sally A. Lahm · Michelle Lee · Jake Lowenstein · Jean-François Mboumba · Dyana Ndiade Bourobou · Alfred Ngomanda · Stephan Ntie · David Sebag · John Sullivan · Hadrien Vanthomme · Virginie Vergnes · Erik Verheyen · Breda Zimkus

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Abstract A five-day international workshop was recently convened at the Université des Sciences et Techniques de Masuku in Gabon to enhance international collaboration among Central African, US and European scientists, conservation professionals and policy makers. The overall aims of the workshop were to: (1) discuss emerging priorities in biodiversity and conservation genetics research across Central Africa, and (2) create new networking

opportunities among workshop participants. Here we provide a brief overview of the meeting, outline the major recommendations that emerged from it, and provide information on new networking opportunities through the meeting web site.

Keywords Africa · Conservation genetics · Biodiversity

Notes on the distribution and status of small carnivores in Gabon

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Abstract

The distribution and status of small carnivore species in Gabon have never been comprehensively assessed. We collated data from general wildlife surveys, camera-trap and transect studies and analyses of bushmeat consumption and trade, to map their country-wide occurrence and assess current exploitation levels. Records of Common Slender Mongoose *Herpestes sanguineus* and Cameroon Cusimanse *Crossarchus platycephalus* represent the first confirmation of their occurrence in Gabon. Cameroon Cusimanse was believed to extend into north-east Gabon, but the Slender Mongoose records extend its known range well outside that previously suspected. We furthermore extended the known range for Egyptian Mongoose *Herpestes ichneumon*. Crested Genet *Genetta cristata* has also been proposed to occur in Gabon but our records were not suited to evaluating this possibility given the difficulties of separation from Servaline Genet *G. servalina*. Most species appear to be distributed widely across the country. While several are commonly recorded in hunter catch and bushmeat markets, they form only a small proportion (3.4% and 3.1%, respectively) of all bushmeat records. However, in proximity to settlements, small carnivore exploitation, for bushmeat and use of body parts in traditional ceremonies, appears to have adverse effects on species richness and abundance.

Keywords: bushmeat, camera-trap, *Crossarchus platycephalus*, distribution, *Herpestes ichneumon*, *Herpestes sanguineus*

Review



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One contribution of 18 to a Theme Issue 'Change in African rainforests: past, present and future'.

Subject Areas:
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Keywords:

Extent and ecological consequences of hunting in Central African rainforests in the twenty-first century

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Humans have hunted wildlife in Central Africa for millennia. Today, however, many species are being rapidly extirpated and sanctuaries for wildlife are dwindling. Almost all Central Africa's forests are now accessible to hunters. Drastic declines of large mammals have been caused in the past 20 years by the commercial trade for meat or ivory. We review a growing body of empirical data which shows that trophic webs are significantly disrupted in the region, with knock-on effects for other ecological functions, including seed dispersal and forest regeneration. Plausible scenarios for land-use change indicate that increasing extraction pressure on Central African forests is likely to usher in new worker populations and to intensify the hunting impacts and trophic cascade disruption already in progress, unless serious efforts are made for hunting regulation. The profound ecological changes initiated by hunting will not mitigate and may even exacerbate the predicted effects of climate change for the region. We hypothesize that, in the near future, the trophic changes brought about by hunting will have a larger and more rapid impact on Central African rainforest structure and function than the direct impacts of climate change on the vegetation. Immediate hunting regulation is vital for the survival of the Central African rainforest ecosystem.



Contributed Paper

Using Genetic Profiles of African Forest Elephants to Infer Population Structure, Movements, and Habitat Use in a Conservation and Development Landscape in Gabon

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Abstract: Conservation of wide-ranging species, such as the African forest elephant (*Loxodonta cyclotis*), depends on fully protected areas and multiple-use areas (MUA) that provide habitat connectivity. In the Gamba Complex of Protected Areas in Gabon, which includes 2 national parks separated by a MUA containing energy and forestry concessions, we studied forest elephants to evaluate the importance of the MUA to wide-ranging species. We extracted DNA from elephant dung samples and used genetic information to identify over 500 individuals in the MUA and the parks. We then examined patterns of nuclear microsatellites and mitochondrial control-region sequences to infer population structure, movement patterns, and habitat use by age and sex. Population structure was weak but significant, and differentiation was more pronounced during the wet season. Within the MUA, males were more strongly associated with open habitats, such as wetlands and savannas, than females during the dry season. Many of the movements detected within and between seasons involved the wetlands and bordering lagoons. Our results suggest that the MUA provides year-round habitat for some elephants and additional habitat for others whose primary range is in the parks. With the continuing loss of roadless wilderness areas in Central Africa, well-managed MUAs will likely be important to the conservation of wide-ranging species.

Keywords: connectivity, conservation outside parks, *Loxodonta cyclotis*, multiple-use areas, noninvasive sampling