Trade-offs in conservation area design: A case study from the Murchison Semliki landscape in Uganda

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Table of Contents

Acknowledgements

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Executive summary

Albertine Rift is home to nearly 1800 known vertebrate species, making it the most vertebrate rich region in Africa and the Murchison-Semliki landscape in the north eastern corner of the Albertine Rift is one of six landscapes identified as critical for conservation of biodiversity in the region. However the future of biodiversity in the landscape is in doubt. The landscape is currently being reshaped by human population growth, climate change and several competing land uses including small and large scale agriculture, carbon sequestration, forestry and exploration for petroleum and minerals, biodiversity conservation, tourism in parks and forest reserves. The cumulative impact of many pressures and recent declines in lion (*Panthera Leo*) and spotted hyaena (*Crocuta crocuta*) populations have led to questions about the future viability of these iconic species in Uganda (Omoya et al. 2013). How can we ensure biodiversity conservation in this landscape while at the same time minimizing the potential conflict with other land uses and people's livelihoods?

The field of systematic conservation planning has evolved rapidly over the past 30 years to help address the realities of a world with ever competing land uses. The discipline uses decision theory to address complex conservation resource allocation problems, and has repeatedly proven its ability to identify more efficient conservation solutions. Novel approaches to planning now allow us to carefully plan resource allocation, explore trade-offs between different interest groups (stakeholders), and promote thoughtful and informed land-use decisions.

Using a systematic conservation planning framework we examine two types of trade-offs conservation planners in the Murchison-Semliki Landscape are currently grappling with. First, we examine how the design and selection of conservation areas influences the distribution of the opportunity costs of conservation between three key stakeholders (petroleum, local agriculture and forestry) in the region. We do these by first considering the interests of each stakeholder independently to assess minimum opportunity to each stakeholder, and the impact on other stakeholders of designing conservation areas based only on the needs of a single stakeholder. We then explore options for balancing the distribution of costs between stakeholders. The process demonstrates how the Marxan decision support tool could be used to identify priority areas for conservation in the landscape. The analysis also provides insight into which areas of the landscape are non-negotiable (critical for biodiversity conservation) and which areas are potentially up for discussion and could potentially be switched with another area if it minimizes conflict between the land use options. The overlap between areas of high conservation

importance, and oil exploration, highlights the need for careful planning of extractive activities to ensure the long term conservation of species important for the tourism industry such as Rothschild giraffe (an endangered species) and the lion (vulnerable species).

Second, we look at trade-offs between the achievement of biodiversity conservation objectives and carbon conservation in the landscape. REDD+ projects are currently in development in the landscape that offer potential promises of improving local livelihoods, reducing carbon emissions and also contributing to the conservation of biodiversity. Analysis in other regions has suggested that the biodiversity benefit of payment for ecosystem service programs such as REDD+ is critically dependent on the design of the program. Here, we explore how the areas selected to maximize carbon conservation contribute to the achievement of biodiversity objectives and how conservation areas designed to achieve biodiversity objective contribute to carbon conservation. We then examine overlap in areas selected to achieve both objectives independently and potential efficiency gained from simultaneous prioritization of both objectives. We then explore identification of areas to achieve both objectives simultaneously and identify an efficiency frontier for provision of biodiversity benefits and carbon conservation at a fixed budget.

The framework presented here provides an objective and transparent way of analyzing and documenting how decisions are made. It also outlines how an inclusive decision making process can incorporate the interests of multiple stakeholders, and provide feedback on how preferences for one stakeholder group will impact the interests of others. This transparent planning process minimizes subjectivity involved in planning processes and provides an avenue for the integration of the interests of all stakeholders to be incorporated in the planning process, and how the use of a spatial optimization tool avoids inefficient outcomes. We aim for this report to provide an example of how systematic conservation planning can be used to address difficult decisions, and would encourage the Strategic Environment Assessment for Oil to seriously consider using similar methods to balance the demand for extractive resources with conservation in this landscape.

Overview

Biodiversity conservation does not occur in a vacuum, and conservation advocates have to recognize it as one of many possible land-uses, often mutually exclusive, that compete for limited space. Conservation interests have often lost the land use competition, and as a result conservation areas have often been pushed to the lands less desirable for other uses. A number of studies on the location of protected areas have shown that their placement is biased towards areas with steep slopes, and lower soil fertility, presumably because these are the lands where there is least competition (Pressey, 1994; Joppa and Pfaff, 2009). This bias in the protected area network means that many species are not represented within the existing network, and potentially increases the long term costs of conservation because of inefficient resource allocation (Tognelli et al. 2008; Watson et al. 2011).

The science of conservation planning evolved over the past twenty years to provide a more strategic framework for making conservation decisions, and overcome the bias and inefficiency that plague historic conservation decisions (Wilson et al. 2009). The information processing requirements of conservation planning can be overwhelming, but the recent advances in computing power have meant that analyses that were previously impossible can now be performed on a standard desktop computer. These advances in computing power have been accompanied by a corresponding influx of conservation software packages (commonly referred to as decision support tools) that can be applied to identify efficient solutions to complex conservation problems. Marxan is one such tool, developed and maintained by the University of Queensland, it has been used to solve a variety of complex conservation problems, and is freely available on their website: http://www.uq.edu.au/marxan/.

This report presents the results of an analysis of the Murchison-Semliki Landscape in Western Uganda (figure 1) as a case study to demonstrate how Marxan can be used to explore trade-offs in how conservation objectives are achieved.

Analytic approach

It is clear that the competing demands for sometimes incompatible land-uses pose the potential for conflict in the Murchison-Semliki Landscape. The growth of the human population in the region (augmented by an inflow of migrants looking for work in the oil fields), will place additional demands on the landscape for resources. To ensure the long-term persistence of biodiversity in the region, and continued growth in the eco-tourism sector that is reliant upon it, future development must be carefully planned with respect to the cumulative impact of all activities. Planners are being asked to balance the sometimes competing demands of development and conservation, minimize the potential for conflict, and ensure functioning ecological systems and maximize value for users.

Systematic conservation planning is the scientific discipline that applies decision theory to solve conservation resource allocation problems and formally addresses the types of complex challenges outlined above. The discipline has evolved over the last thirty years to address the ad-hoc appropriation of conservation resources and the ongoing failure to halt the decline of biodiversity. While different operational approaches have been developed within the discipline all share primary principles; 1) the use of explicit and measurable objectives, and 2) an emphasis on complementarity (Pressey & Bottrill 2009; Watson et al. 2011b).

The establishment of explicit objectives and measurable standards through which achievement of those objectives can be objectively evaluated is a critical factor in decision theory to guide resource allocation. The process of objective setting, while often contentious, ensures a common platform for comparison of alternative outcomes and enables evaluation of both the efficiency and effectiveness of proposed alternatives. The approach relies on a framework where the objectives of the analysis are clearly stated and formulated as a mathematical problem. Complementarity as a concept is closely related to efficiency. Complementarity measures how well the next set of actions compliment or what has already been done (Pressey et al. 1993). The discipline of systematic conservation planning operates on the premise that we operate in a resource limited world, where duplicated effort should be avoided if possible. If an objective could have been achieved without the additional effort or additional expense then taking that effort or incurring the expense is an inefficient use of resources (Carwardine et al. 2009).

A suite of decision support tools have been developed to enable widespread application of the analytic approach (Wilson et al. 2009). Marxan is one such tool. The Marxan decision support tool (Ball, Possingham, and Watts 2009), is a spatial optimization tool which has been used around the world to identify priority areas for conservation (Airame et al. 2003; Fernandes et al. 2005; Watson, Evans, et al. 2011). Marxan uses simulated annealing to identify multiple good options that solve the "minimum set" problem; the identification of a set of areas that achieve a set of defined objectives while minimizing the overall cost of achieving those objectives (Cocks and Baird 1989). Marxan is a spatially explicit optimization tool, that was designed to account for the heterogeneous cost of conservation action within the landscape, and identify areas where conservation objectives can be achieved most efficiently (Ball, Possingham and Watts, 2009; Game and Grantham, 2008). Cost in a Marxan does not have to be represented in strictly economic terms, it can also be the total area or a measure of landscape utility for other uses.

Many applications of decision support tools or development of plans for conservation occur without stakeholder input in the process. Recent reviews of the discipline have recognized the need for conservation planning to shift from plan generation to greater stakeholder involvement in working through the complex challenges (Reyers et al. 2010). The objective of this process was not simply the development of single plan, it was to both demonstrate how these tools can be applied and build demand for structured approaches to conservation decision making to used in the future. WCS is interested in building the capacity for such analyses to be made in Uganda and elsewhere to help minimize potential conflicts over land use and ensure the long term conservation of the rich biodiversity of this country and ensure the long term viability of its tourism industry. The process documented here was designed with stakeholder participation as a focus, and was reliant on input gather during two workshops held in Kampala in August 2012 and July 2013. This report summaries the results of this process and explores options for balancing trade-offs between different land uses while ensuring that biodiversity is conserved effectively in the landscape.

Data requirements for systematic conservation planning

Using Marxan to explore trading-offs in land-use planning requires spatially explicit information on features of conservation interest (e.g. species, ecosystems) and the suitability of the landscape for non-conservation land-uses (e.g. farming, oil extraction). Spatial information on location and abundance of conservation features in the region informs the relative value of an area for achieving conservation objectives. Information on the relative suitability for uses other than conservation enables estimation of the opportunity cost of setting aside an area for conservation. Because the Marxan optimization routine is spatially explicit, it is essential that all conservation features of interest and value for alternative land uses be defined spatially. We cannot measure the benefit of, or account for the costs of, anything that is not delineated spatially.

Ideally the planning effort would be supported by perfect information on the distribution of, and processes that support each species and ecosystem in the planning region. However, even in the best studied regions, such information is never available. This means that planning efforts typically rely on detailed information on a suite of key species, and utilize "surrogates" to represent other species. Within the parlance of conservation planning, a surrogate is a feature that acts as a placeholder or representative for a suite of species within the planning process. For example, the map of grasslands within a region could be used as a surrogate in the planning process for grassland dependent species. The use of surrogates relies on the assumption that by conserving a portion of the surrogate (eg. x% of grasslands), that grassland dependent species will also be conserved.

Marxan provides two outputs that can inform land-use planning decisions. The first is complete sets of areas that achieve the conservation objectives. The second is a measure of an area's "irreplaceability" within an efficient conservation network. Irreplaceability is an objective specific measure of conservation value that provides feedback on how likely it is that an area will be included in an efficient solution (Segan et al. 2010). Areas that are highly irreplaceable have fewer substitutes if conservation objectives are to achieved efficiently. Areas with lower irreplaceability can be more easily substituted out of conservation areas. Irreplaceability is objective specific in that different sets of objectives will yield different valuations of an areas contribution to target achievement and thus its irreplaceability to achieving those targets. Areas identified as fully irreplaceable with one set of conservation objectives may not be identified as fully irreplaceable when the objectives or criteria used to prioritize sites change. The malleable nature of irreplaceability makes it important to distinguish between a sites underlying biological value, value derived from the presence of species and ecosystems at the site, and the value of the site for a achieving a specified set of objectives. While the biological value of a site may not change in the absence of disturbance, the irreplaceability of a site can change due to; 1) change in conservation objectives, 2) change in the cost in taking conservation action or 3) conservation of other sites. While all three can change the irreplaceability of a site, none alters the biological value of the site.

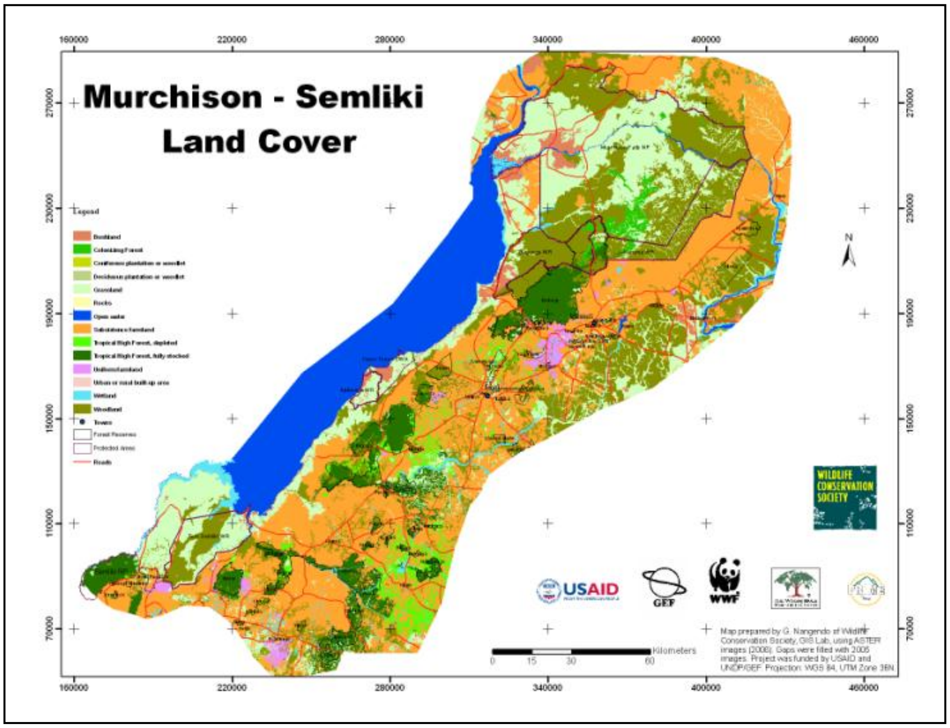

Figure 1. Map of the Murchison-Semliki Landscape showing general land cover types and location of protected areas.

Landscape profile

Biodiversity

The Murchison-Semliki Landscape is one of six key landscapes in the Albertine Rift region of Africa. The Albertine Rift is one of the most biodiverse parts of the African continent and contains more threatened and endemic vertebrates than anywhere else on the continent (Plumptre *et al.* 2007). The Murchison-Semliki landscape is home to 37 species endemic to the Albertine Rift and, 48 threatened species and 2,583 vertebrate and plant species known from the region (Table 1). Recent taxonomic changes in ungulate species indicates that several species known from the landscape will likely be classified as threatened in the near future as their populations are confined to relatively small areas (Groves and Grubb, 2012). Murchison Falls National Park is home to the world's largest population of Rothschild giraffe (*Giraffa camelopardalis*), which may be elevated to a species. The landscape is also home to a significant portion of the global population of Uganda Kob (*Kobus thomasi*) which occurs in Uganda, Virunga Park in eastern Democratic Republic of Congo (DRC) and a small area in western Kenya.

Table 1. The numbers of species, endemic species to the Albertine Rift and threatened species known from the Murchison-Semliki Landscape for five taxa.

Landscape	Mammals	Birds	Reptiles	Amphibians	Plants
Endemic species	3	0	1	2	31
Threatened species	8	4	1	0	35
Species numbers	200	684	78	41	1,580

Competing land uses in the Murchison-Semliki Landscape include:

1. Petroleum exploration and extraction, including recent discoveries in several of the protected areas in the landscape
2. Timber extraction from the forest reserves to meet some of Uganda's timber needs
3. Small scale agriculture for subsistence farming by people living in the landscape
4. Large scale agriculture such as tea, coffee and sugar plantations
5. Wildlife tourism
6. Carbon conservation through REDD+ financing
7. Biodiversity conservation

Each varies with respect to its compatibility with biodiversity conservation and relative compatibility with other land uses. Each of these land uses is also likely to expand its footprint within the landscape in the future. How can the needs of species such as lions, hyenas, chimpanzees and Rothschild giraffes which require large areas of continuous habitat in order to maintain viable populations be balanced with other activities? And will these species be able to persist in a landscape matrix that includes oil extraction, tourism, timber harvesting and agriculture?

A recent UNDP/GEF project in the Ministry of Water and Environment, and managed by WWF, developed a landscape conservation action plan for the Murchison-Semliki Landscape (MWE, 2012) with the input of a wide variety of stakeholders including the Districts, the Bunyoro Kingdom, International and National NGOs and private forest owners. The Wildlife Conservation Society (WCS) was subcontracted to undertake an analysis of the conservation needs of the landscape and fplaced viability of 'landscape species', those species that require large areas to maintain viable populations

(Didier *et al.* 2009). This analysis identified several corridors in the landscape (Fig 2) that if conserved and restored would enhance the viability of species such as chimpanzees, forest raptors, understorey migratory birds such as green-breasted pitta, and medium size carnivores such as jackals and golden cats.

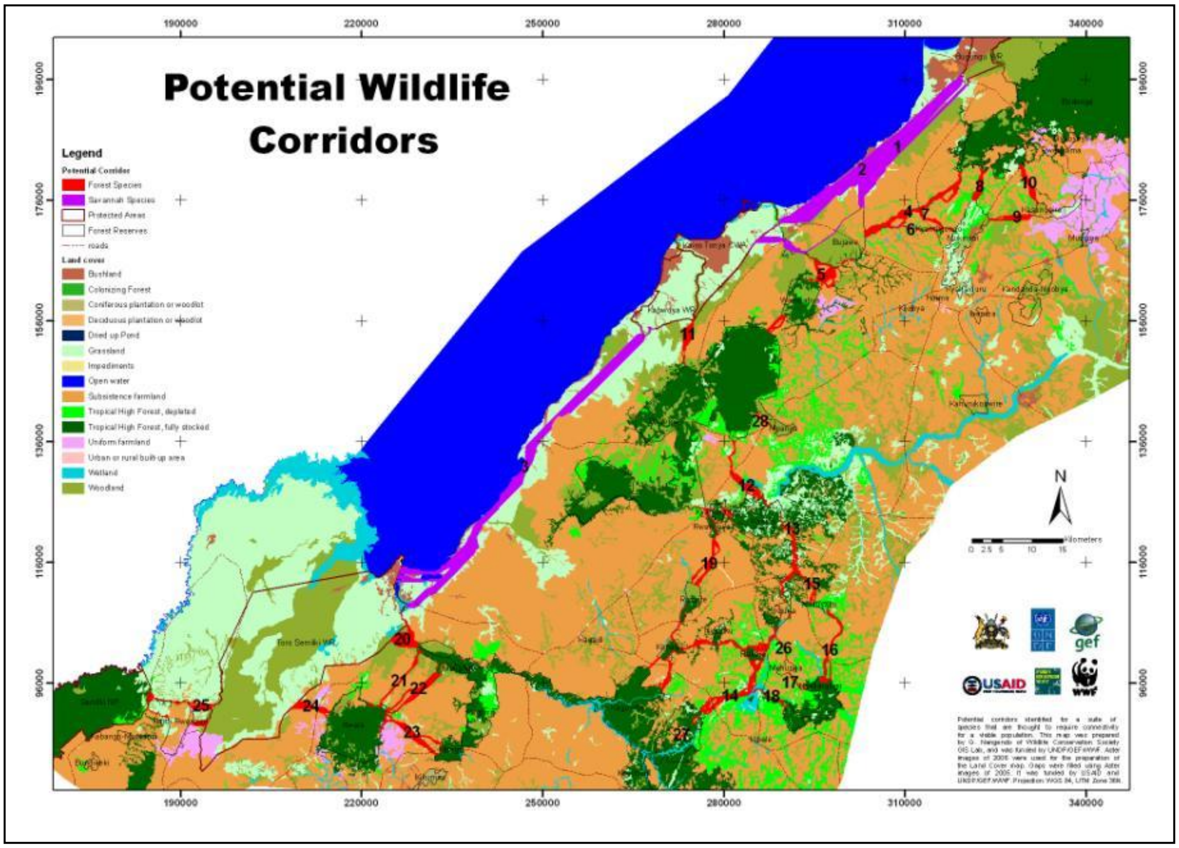

Figure 2. Areas (red and purple lines) where corridors would best be conserved or restored to maintain connectivity between forest blocks and improve the viability of landscape species.

The action plan also analyzed the feasibility of obtaining carbon financing through the REDD+ mechanism to provide an incentive to farmers in the landscape to conserve natural forest on their lands. Dr. Miguel Leal of WCS analyzed the potential income to farmers from the conservation of forest and showed that while REDD+ funding could not offset the opportunity costs of clearing forest for cash crops within the first 3-5 years of cultivation, over a twenty year period the funding could be attractive because the fertility of the soil declines over time and the amount of crops that can be grown (without inputs) is likely to decline (Leal *et al.* 2011). Carbon financing, if successful, could provide an alternative revenue stream for land owners in the region that would compliment biodiversity conservation.

Stakeholders

Local settlement/Agriculture

Between 1990 and 2005, land clearing for agricultural expansion claimed 26% of Uganda's aboveground biomass (Avitabile et al. 2012). The Murchison-Semliki Landscape is under substantial pressure and natural habitat has been converted to small scale agriculture at a rapid pace in the last ten years. Much of this transformation has taken place at the expense of natural forest on private land or within local forest reserves, but some has taken place within central forest reserves also and totals more than 8,000 hectares each year (Fig 3).

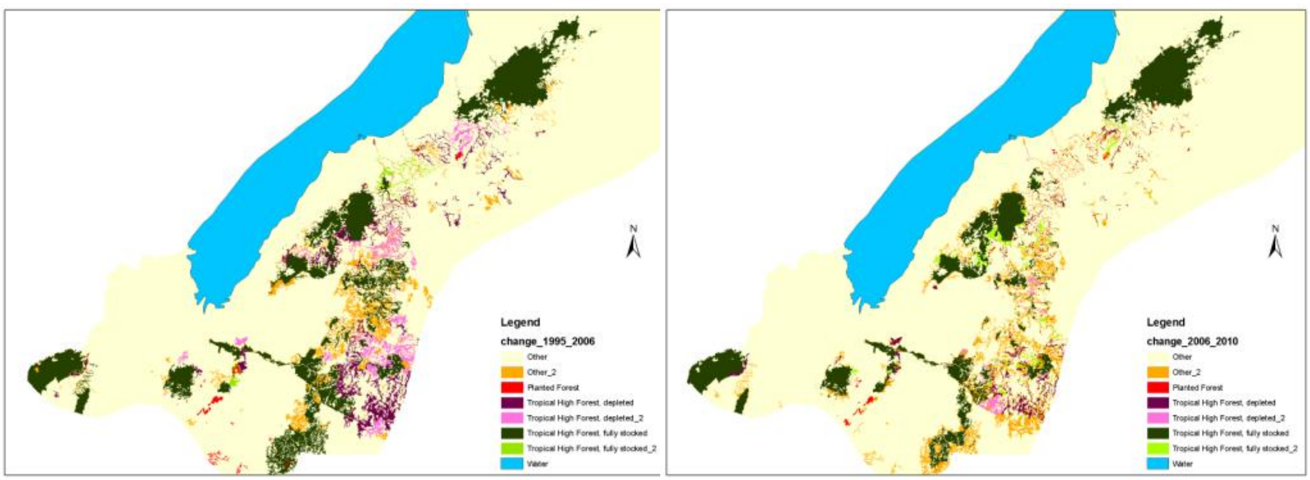

Figure 3. Forest loss in the Murchison-Semliki Landscape between 1995-2005 (left) and 2006-2010 (right). Orange = Conversion to non-forest; Pink=Conversion to degraded forest.

Agriculture is the primary driver of deforestation in the landscape. Demand is driven by a number of crops including tobacco, sugar cane, and tea, and includes both loss to both large plantations and small scale agriculture (Leal 2012). Similar changes are occurring in the remaining savanna woodlands and grasslands in the landscape where conversion to agricultural land and increased livestock grazing is leading to the degradation of these habitats.

Petroleum

The development of oil in the region will also impact ecosystems as oil pads are prepared, wells drilled, access roads created, pipelines established, people move into the area to find work and a refinery established. While oil is only projected to last 20-30 years before the wells are exhausted it is likely to have a significant impact on the landscape and there is a need to ensure that its impacts are minimized wherever it occurs and at the same time any residual environmental impacts are offset in a meaningful manner. Oil exploration inside the protected areas of the landscape is ongoing and is currently affected species in the landscape which are actively avoiding oil exploration areas (Prinsloo *et al.* 2012). This means that the contribution of protected areas to the preservation of species must be re-evaluated in areas where oil exploration is ongoing.

Forestry

Timber harvesting in the central forest reserves has modified these reserves considerably (Plumptre, 1996). There is now considerable evidence on the impact of these activities on species in landscape. Declines in species abundance have been documented for numerous of species (Owiunji and Plumptre 1998; Sekercioglu 2002) are not limited to forest dependent species. A notable exception is that some primate species have benefited and occur at higher density in some logged forests (Plumptre and Reynolds 1994). Over the past 20 years increased illegal activity, particularly illegal pitsawing, has led to greater degradation of the forests and the loss of the planned sustainability of the timber harvesting. Forest degradation and clearing has already led to the isolation of chimpanzee populations in forest reserves and will likely require the establishment of corridors of riverine forest between the various reserves to ensure viable populations in the long term.

Tourism

Tourism in the landscape is increasing and Murchison Falls National park is now the most visited park in Uganda (UWA tourism records 2011). As a result there is increased traffic in the park leading to disturbance to the animals, increased littering and pollution and increasing incidences of off-track driving leading to habitat degradation. While it is recognized that tourism brings in the funding needed to manage this park and other reserves it also has to be acknowledged that it also increases the threats to the conservation of biodiversity in the park. Species such as lions, leopards and hyaenas, are currently at very low numbers in the landscape, with an estimated 130 lions and only about 40-60 hyaenas. These species are cited by tourists as those they most want to see in Murchison Falls National Park, and 50% indicated they would be less likely to visit the park or would want the entry fees to be reduced if the species were not encountered on park visits (WCS 2012). The main area where species of tourism interest occur (eg. lions, giraffes, elephants and leopards) also coincides with the primary area of oil exploration in the Murchison Falls National Park. As such this is an area of potential conflict between the tour operators who derive a living from tourism and development of the petroleum resources in the region.

Conservation objectives

In addition to the underlying data requirements, a systematic conservation planning approach requires decision makers to articulate quantifiable conservation objectives. An example of a quantifiable objective would be the conservation of *80% of lion habitat within the region*. Conservation objectives for the analysis were established by experts from the region and/or in conservation during a first planning meeting in August 2012 in Kampala. To facilitate setting of informed targets, participants were provided range maps for and basic information on density within the landscape and IUCN Redlist status. Participants defined both an individual target and sensitivity range for each conservation objectives (Table 2).

Table 2. Base target, range of analysis established by workshop participants, and the target used in the preliminary analysis.

Ecosystems	**Target**	**Range**	**Base**
Woodland	70%	± 20%	50%
Grassland	80%	± 5%	75%
Wetland	100%	± 10%	90%
Bushland	45%	± 10%	35%
Colonizing Forest	80%	± 20%	60%
Tropical High Forest Fully Stocked	80%	± 20%	60%
Tropical High Forest Depleted	80%	± 20%	60%
Species			
Threatened species at low density (<1/km^2)	80%	± 10%	70%
Threatened species at medium density (1-20/km^2)	70%	± 20%	50%
Threatened species at high density (>20/km^2)	50%	± 10%	40%
Albertine Rift endemic species at low density (<1/km^2)	90%	± 10%	80%
Albertine Rift endemic species at medium density (1-20/km^2)	80%	± 20%	60%
Albertine Rift endemic species at high density (>20/km^2)	80%	± 20%	60%
Tourism value species (eg. chimpanzee, lion)	80%	± 15%	65%
Species where >10% of World population occurs in region	90%	± 10%	80%

The conservation objectives used in this analysis were primarily drawn from the lower range of the target identified by workshop participants (identified as "base" in Table 2). Targets were drawn from the lower range after preliminary analysis revealed that targets at the middle or upper end of the suggested ranges would require conservation areas to be established in an unrealistically large proportion of the landscape (> 80%).

Trade-off assessment

Trade-offs assessment can take many different forms. This assessment considers two types of trade-offs in the landscape; 1) Between stakeholder trade-offs in the distribution of the opportunity costs of conservation, and 2) The trade-offs between maximizing carbon and biodiversity in selected areas. The exploration of trade-offs through conservation strategy evaluation in Marxan requires defining alternative strategies and comparing outcomes of the individual strategies. A resource allocation strategy refers to the set of criteria that guide investments in conservation in the landscape.

Strategies considered in this assessment varied with respect to three components:

1) Spatial constraint - Rules on where conservation action can and cannot occur.

2) Cost - Choice of measure of efficiency against which objective achievement is measured.

3) Conservation objectives - The set of measureable objectives to be achieved.

For each strategy the Marxan optimization algorithm attempts to minimize the cost of achieving the specified conservation objectives, given the spatial constraints on where conservation action can take place. The cost against which objective achievement is measured can be as simple as the total area required, or as complex as a mix of the opportunity cost to a variety of alternative land-uses in the region.

Opportunity cost of conservation

We considered the distribution of opportunity cost of conservation under seven conservation resource allocation strategies (Table 3). The first strategy (A-Parks) uses the exiting protected area network as a base and identifies expansion priorities to complement the existing network. We then considered three strategies that attempt to minimize costs to individual stakeholders, ignoring the interests of other stakeholders. Strategy B-Oil attempts to minimize cost to oil, strategy C-Local attempts to minimize cost to local populations, and strategy D-Forestry attempts to minimize costs to forestry operations.

We considered two of these options for distributing the opportunity costs of conservation. The first method considered placing equal emphasis on the interests of all stakeholders (E-Equal), a common objective of planning processes and seen desirable outcomes of planning process (Halpern et al. 2013). The second approach attempted to apportion opportunity cost between stakeholders in accordance with expert perception of the relative importance of accommodating that group in the planning process (strategy F-AHP1).

Analytic hierarchy process (AHP) was used so to develop logically consistent weightings of the relative importance of individual activities (Saaty, 2008). AHP is commonly used in multi-criteria analysis to elicit expert opinion on the relative importance of divergent objectives, and has been previously applied to balance multiple objectives in conservation planning (Ananda and Herath 2003; Cameron, Williams, and Mitchell 2008). In AHP raters are asked to consider the importance of each objective relative to all other objectives through a series of pair wise comparisons. Expert opinion on relative importance of the individual interests was solicited at a workshop in Kampala in August of 2012 (See appendix). The AHP derived weightings for oil (0.60), timber (0.08), and local (0.32) were used to develop the weighted cost surface for strategies F and G:

$$(2) \qquad M_i = \quad W_t \times V_{it} + W_o \times V_{io} + W_l \times V_{il}$$

Where M_i is weighted cost of planning unit *i*, V_i is the normalized value of the interest in planning unit *i*, and *W* is the weight of each interest from the AHP. Opportunity cost abbreviations are: t-timber, o-oil, l-local.

A final strategy, G-AHP2, treated all planning units identified as 100% irreplaceable in strategies B-D, as non-dominated areas, or parts of the network which cannot be improved upon without adversely affecting one of the other criteria (Rothley 1999), and required their inclusion in the set of conservation areas. We did so because these planning units were identified as necessary for an efficient conservation network with respect to each individual opportunity cost (R. L. Pressey, Johnson, and Wilson 1994), and requiring their inclusion reduced the dimensions of the decision space, and focused decision maker attention on areas where real trade-offs exist.

The full extent of all national parks and wildlife reserves was locked into the set of conservation areas in the first strategy only, designed to identify where gaps in the existing protected area network could most efficiently be filled. In strategies B-G, oil exploration areas inside protected areas were treated as degazetted portions of the parks estate, because the contribution of these areas to conservation objectives is compromised by ongoing oil exploration (Prinsloo et al. 2011). This meant that they were treated in the same manner as any other portion of the landscape, and included in the set of identified conservation areas only if they efficiently contributed to target achievement.

To assess the distribution of the opportunity cost of conservation between stakeholder conservation objectives were held constant, while varying the cost surface against which the efficiency was measured and the spatial constraints, or the areas fixed as a part of the selected set of conservation areas. The use of a single set of conservation objectives facilitates comparison across scenarios, by ensuring that the achievement of conservation objectives serves as a common denominator and focuses attention on the areas identified for achieving the objectives, and the resulting impact on other potential land-uses.

Table 3. Overview of the conservation resource allocation strategies considered in the analysis. Each strategy allocates conservation resources across the landscape, in accordance with the objectives, measure of efficiency and constraints placed on where conservation action can be undertaken.

ID	Name	Measure of Efficiency	Constraints
A	Parks	Area required	National Parks and Wildlife Reserves always included
B	Oil	Petroleum area of interest	National Parks and Wildlife Reserves included if they do not overlap Petroleum interests
C	Local	Human expansion	National Parks and Wildlife Reserves included if they do not overlap Petroleum interests
D	Timber	Opportunity cost to timber	National Parks and Wildlife Reserves included if they do not overlap Petroleum interests
E	Equal	Equal weighting all interests	National Parks and Wildlife Reserves included if they do not overlap Petroleum interests
F	AHP1	Stakeholder MCA weighting	National Parks and Wildlife Reserves included if they do not overlap Petroleum interests
G	AHP2	Stakeholder MCA weighting	National Parks and Wildlife Reserves included if they do not overlap Petroleum interests. Areas identified by all individual strategies included.

Biodiversity and carbon conservation

To assess the trade-off between representation of biodiversity and maximization of carbon contained in the selected conservation areas, the total cost of the areas selected was held constant. Fixing the cost meant that the selected areas did not always achieve the specified conservation objectives, unlike the assessment of trade-offs in the opportunity cost of conservation. Each solution along the trade-off frontier varied with respect to the extent to which biodiversity objectives and carbon were maximized for the fixed cost. The fixed cost at which the trade-off curve was developed was set at the lowest cost of achieving all conservation objectives in the baseline. For the baseline biodiversity assessment total area was used as the cost and no planning units were locked into the solution set.

We then calculated representation of carbon within the Marxan solution and used this as the first point of the trade-off curve (point A) or the point at which biodiversity representation was maximized at the expense of carbon which was not considered when identifying the areas. To establish the maximum amount of carbon that could be represented in the same area, we calculated the carbon return on investment (ROI) for each planning unit as (carbon content / area) and iteratively added planning units to the set until the cost threshold was reached (Fig 4). This process provided us with the final point (point C) on the trade-off curve or the point at which carbon conservation is maximized at the expense of achievement of biodiversity conservation objectives. We then calculated the representation of all biodiversity features in the solution that maximized carbon conservation (point C). Representation of the each biodiversity feature in the carbon conservation configuration served as the minimum value for each conservation feature.

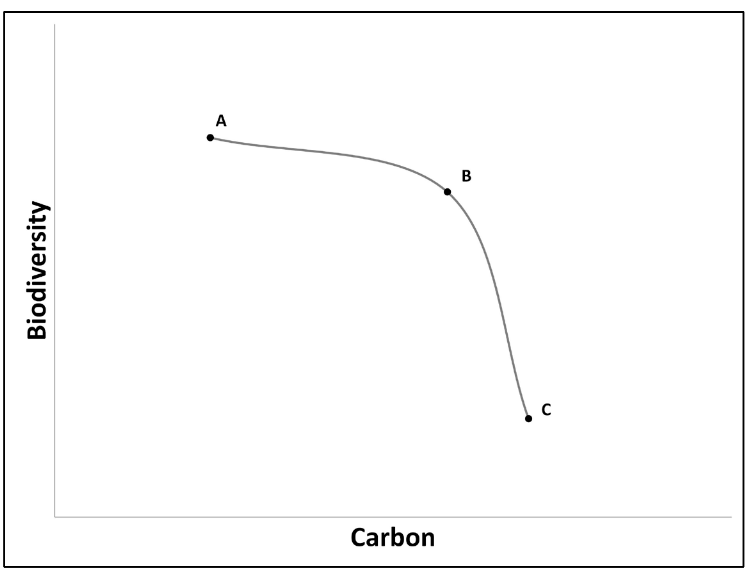

Figure 4. Schematic representation of the biodiversity carbon efficiency frontier. Point "A" is the point at which biodiversity is maximized at the expense of carbon, Point "C" is the point at which carbon is maximized at the expense of biodiversity and point "B" is a point along the frontier that balances representation of each.

Marxan was used to identify configurations along the efficiency frontier between points A & C. For biodiversity features targets were set through linear interpolation between the conservation target for the feature (maximum amount) and the amount represented in the carbon conservation configuration (minimum amount). Target levels for each feature were set in accordance to equation 2:

$$2)\ T_{js} = T_j - \left(T_j - \min R_j\right) \times D_s$$

Where *Tjs* is the target for feature *j* in strategy *s*, *Tj* is the baseline target for feature j, R_j is the proportion of feature *j* represented in any strategy, and D_S ranges from 0-1 and is the weighting factor applied to all biodiversity features in strategy *s*. As D_S increases the target for the feature approaches the minimum for that feature. If the target for the biodiversity feature was met in carbon conservation configuration (*Tj* <= min R_j) then the target for that feature was kept constant at *Tj* for all strategies.

Independent weighting factors (D_S) were used for biodiversity and carbon features for each strategy. This meant that targets for all conservation and carbon features were varied in unison. An iterative search method was used to select target combination (eg. 74% of biodiversity, 42% of Carbon) that had the same cost as the baseline. Configurations that resulted in costs higher or lower were discarded.

This process allowed us to establish the efficiency frontier for landscape configuration with respect to biodiversity and carbon conservation. For each point along the frontier there is no other alternative set of conservation areas with the same area that could improve outcomes for biodiversity or carbon conservation with making the other objective worse off. The frontier we identify through this process represents the pareto efficient outcomes.

We also considered the potential efficiency gain from considering biodiversity and carbon conservation simultaneously when identifying conservation areas. To do this, we overlaid the most spatially efficient set of areas to achieve the each target independently to identify the area that would need to be considered if each objective was achieved while ignoring the other objective. We then prioritized achievement of both biodiversity and carbon objectives simultaneously. The difference between the two sets was treated as the efficiency gain from simultaneous planning.

Data Summary

The ABCG project team began to collect and process the information required to examine trade-offs in the Murchison–Semliki landscape in early 2012. Data layers and processing are discussed for each data layer below.

Planning region

We divided the planning region into 24673 1km^2 hexagonal planning units that formed the discrete units available for inclusion in conservation areas. The extent of each conservation and socio-economic feature was calculated by overlaying the planning unit layer with each feature. All planning units that contained only areas already appropriated for human use (n = 3845) were excluded from inclusion in the set of conservation areas. For planning units that were partially modified (n= 9831), both the conservation benefit and cost of acting in the planning unit were restricted to only those areas that remained intact.

Protected areas

There are eighty-one conservation areas in the landscape classified into six management categories. To avoid overestimating current levels of protection (Rodrigues et al. 2004), we followed the methods of prior assessments (Watson, Evans, et al. 2011) and treated areas as protected only if they were effectively managed for conservation. In the Murchison Semliki landscape this included National parks and Wildlife reserves, excluding categories which are managed primarily for non-biodiversity outcomes or are currently highly degraded (MWE 2012). The spatial extent of each protected area was then overlaid onto the planning units for the region to determine the proportion of each planning unit was protected.

Conservation features

Ecosystems

A land cover map for the region was developed using 30m Aster imagery captured in 2005 and 2006. Supervised classification was used delineate 11 cover types. Land cover types were further classified into a binary map of modified and intact vegetation classes. Areas classified as plantation/woodlot, farmland, urban or rural built were classified as 'modified' cover types, and all other types were classified as intact vegetation types. Conservation targets were set for intact vegetation types identified as priorities in the strategic plan (MWE 2012).

Species

Species distribution model maps were developed for large mammal, bird, flora listed as threatened, considered endemic to the Albertine rift, or identified as critical to maintain tourism the landscape (n=23). Preliminary models were developed using Maxent version 3.3.3e (Phillips, Anderson, and Schapire 2006; Phillips and Dudík 2008) and observations sourced from the Global Biodiversity Information Facility data (GBIF 2012), and unpublished observations from the Wildlife Conservation Society. The distribution of each species was modeled at the extent of the whole of the Albertine rift and then clipped to the planning region extent. The predicted range of each species was clipped to the unmodified lands layer to avoid overestimation of suitable habitat for each species (Jetz, Sekercioglu, and Watson 2008). All range maps were then subjected to expert validation during two workshops and recommended modifications were incorporated.

Four species who met the above criteria, but whose range was only marginally inside planning region, were excluded from the analysis based on expert advice, these include blacked winged pranticole (*Glareola nordmann*), blue duiker (*Philantomba monticola*), blue monkey (*Cercopithecus mitis*) and oribi (*Ourebia ourebi*).

Ecosystem services

Ecosystem services refer to the benefits human societies derive from natural systems. Two ecosystem services were considered in our assessment, carbon storage and tourism.

Carbon conservation

Spatial representations of the distribution of above carbon within the landscape were derived from three sources. The first was an assessment of biomass in tropical forest globally that used ground measurement and lidar data on forest height to estimate biomass from remotely sensed imagery at 1km^2 resolution (Saatchi et al. 2011). The second biomass estimate was drawn from a continental scale assessment of above ground biomass in Africa that used 1km^2 resolution MOIDS imagery and GLAS lidar imagery (Baccini et al. 2008). The third estimate was drawn from a national assessment of Uganda's above ground woody biomass using 30m^2 landsat TM imagery (Avitabile et al. 2012). In general there was strong spatial similarity between the three estimates of biomass in the landscape (Table 4). Where a single estimate of carbon captured in the landscape is reported we have selected the middle of the three estimates.

Table 4. High level of agreement between three estimates of biomass in the Murchison Semliki Landscape. Spearmean's rank correlation coefficient (rho) between each of the three different estimates used. Each estimate is listed by the first author of the study.

	Avitabile	Saatchi	Baccini
Avitabile	1.000	0.744	0.890
Saatchi	0.744	1.000	0.789
Baccini	0.890	0.789	1.000

To identify where conservation efforts are most likely to realize immediate benefits in the form of averted loss of forest biomass we used an estimate of forest transition developed as a part of a REDD+ baseline for the project area (Leal 2012). Estimated conservation risk by 2030 was developed using IDRISI land change modeller and changes in land cover from 1995-2006 and 2006-2010 as training periods (Leal 2012) (Fig. 5). The model showed that the smaller forests fragments, particularly those outside protected areas were most at risk of being lost.

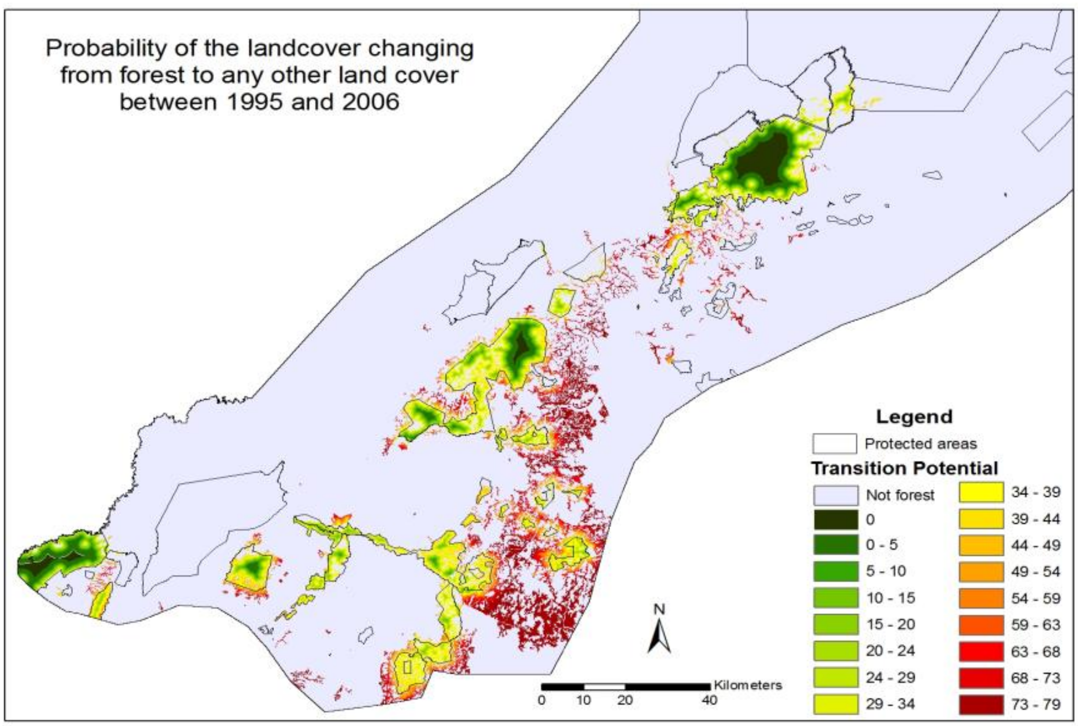

Figure 5. The probability of forest conversion by 2030. Forest loss model was calibrated based on observed changes between 1995-2005 and 2005-2010.

We multiplied site transition potential by 2030 by site biomass to derive an estimate of averted carbon loss. This provides an estimate of estimated carbon loss from deforestation in the next 15 years (hereafter referred to as "high risk carbon").

Tourism

The potential contribution of each portion of the landscape for tourism was quantified as the combined abundance of charismatic species in the area. The suite of species of high value for tourism value were identified based on results of a survey of park tourists and included those species cited by tourists as those they most want to see in Murchison Falls National Park, and indicated that they would be less likely to visit the park if the species were not encountered on park visits (WCS 2012).Species included in the tourism value layer included; african elephant (*Loxodonta africana*), chimpanzee (*Pan troglodytes*), giraffe (*Giraffa camelopardalis*), hippopotamus (*Hippopotamus amphibius*), leopard (*Panthera pardus*), Lion (*Panthera leo*) and shoebill (*Balaeniceps rex*).

Socio-economic features

Examining trade-offs between the opportunity cost of conservation under different spatial configurations of conservation areas, requires spatially explicit information on the opportunity cost to an individual stakeholder of engaging in the desired activity in each portion of the landscape. This information provides the context in which conservation decisions are to be made. This analysis uses preliminary information on three prospective land uses within the region (Figure 6). We used these layers for illustration purposes only, and their inclusion should not be interpreted as an endorsement that these are the only land uses that should be considered in the planning process. We did not attempt to place an economic value on any activity. Like the opportunity costs, values are expressed as a percentage of the total in the landscape.

Local Livelihoods

The Murchison-Semliki landscape is densely populated and currently supports 32 million people in region slightly smaller than 25000 km^2, leaving virtually no land remaining unclaimed (Leal et al. 2011). Many residents engage in small scale agriculture and utilize the forests and bushland for collection of wood for fuel and other forest products (Leal et al. 2011; MWE 2012). The expansion of protected areas may restrict opportunities to engage in these activities. The opportunity cost to local populations of lost access to portions of the landscape was represented as a combination of population density and access (distance to roads). Areas with higher population density or in closer proximity to roads were assigned a higher opportunity cost, to reflect likely increased utilization. The proportional value of areas included inside conservation areas is hereafter referred to as the local cost.

Petroleum

To delineate the area of interest for the petroleum industry, bounding polygons were created to encompass all known discoveries and active exploration areas (PEPD 2013). The total area measured 2514 km^2, and included areas inside Murchison Falls national park, and three wildlife reserves treated as protected in this analysis. The proportion of this area included inside conservation areas was treated proxy for opportunity cost to the petroleum industry (hereafter referred to as oil).

Forestry

Maxent was used to develop distribution models for seven high value timber species (Albizia coriaria,Entandrophragma angolense, Entandrophragma cylindricum, Entandrophragma utile, Khaya anthothec, Lovoa swynnertonii, Milicia excelsa, Olea welwitschii) in the landscape. The seven layers were summed to create a single layer that captured the richness of high value timber species in each planning unit. We treated the summed richness as a proxy for opportunity cost to the timber industry, and the proportional inclusion of the total value of this layer is hereafter referred to as the cost to timber.

To aggregate across opportunity cost measures with different units we followed the methods of Klein et al. (2008) and calculated the proportional contribution of the each planning unit to the total value of the feature within the landscape:

$$(1) \qquad V_{ij} = \frac{a_{ij}}{\sum_i^n a_{ij}}$$

Where V_{ij} is the normalized value of activity *j* in planning unit *i*, and a_{ij} is the value of planning unit *i* for activity *j*. This normalized the un-weighted contribution of any individual opportunity cost to the overall cost of conservation in the landscape to one. Thus unweighted optimization against the aggregated cost surface placed equal emphasis on minimization of impact to all three opportunity costs.

Results

Conservation landscape of today

Modified vegetation types currently cover 9,237 km^2 (38%) of the Murchison-Semliki landscape with the remaining intact areas dominated by woodland (25%), grasslands (21%) and forested cover types (12%). The existing protected area network includes eight areas and covers 5,999 km^2 (25%) of the landscape. The existing protected areas meet or exceed representation targets for only eight of the 31 conservation features (Table 5). None of the target bird species and only two mammals, Giraffe and Hippopotamus, were represented at target levels inside the existing parks.

Table 5. Representation of conservation features in the a) Existing protected areas, b) representation in protected areas if areas of interest oil are treated as degazetted areas, and c) Conservation target - Target levels of representation for each feature

Feature	Current Protection	Current Protection excluding oil interest areas	Conservation Target
Ecosystems			
Woodland	41%	34%	50%
Grassland	45%	31%	30%
Wetland	11%	1%	90%
Bushland	39%	5%	30%
Colonizing Forest	86%	86%	50%
Tropical High Forest Fully Stocked	11%	11%	50%
Tropical High Forest Depleted	1%	1%	40%
Bird Species			
African white-backed vulture (Gyps africanus)	63%	24%	85%
Grey crowned crane (Balearica regulorum)	21%	9%	54%
Nahan's Partridge (Francolinus nahani)	4%	5%	53%
Shoebill (Balaeniceps rex)	54%	45%	59%
Mammal Species			
African elephant (Loxodonta africana)	60%	40%	39%
Chimpanzee (Pan troglodytes)	11%	10%	25%
Giraffe (Giraffa camelopardalis)	91%	66%	58%
Hippopotamus (Hippopotamus amphibius)	59%	41%	50%
Hyena (Crocuta crocuta & Hyaena hyaena)	72%	41%	80%
Leopard (Panthera pardus)	55%	29%	57%
Lion (Panthera leo)	61%	30%	83%
Uganda mangabey (Lophocebus ugandae)	19%	17%	29%
Plant Species			
Balsamocitrus dawei	17%	14%	12%
Beilschmiedia ugandensis	33%	24%	73%
Coccinia mildbraedii	28%	17%	61%
Entandrophragma utile	3%	2%	19%

Entandrophragma angolense	7%	7%	77%
Entandrophragma cylindricum	4%	4%	47%
Guarea cedrata	5%	4%	46%
Hallea stipulosa	16%	12%	13%
Khaya anthotheca	12%	11%	20%
Lovoa swynnertonii	6%	6%	47%
Lovoa trichilioides	1%	0%	35%
Prunus africana	3%	2%	66%
Carbon			
Avitable	18%	16%	0%
NASA	35%	29%	0%
WHRC	31%	25%	0%
Avitable (High risk)	4%	4%	0%
NASA (High risk)	6%	6%	0%
WHRC (High risk)	5%	5%	0%

Examining the opportunity cost of the current parks network we find that opportunity costs of the current network are not distributed evenly between the three stakeholders. Costs borne by the oil industry appear to be far higher than other stakeholders (Fig6). This result may be partially attributable to the fact that the current parks were designed prior to the discovery of oil in the region. However we caution against over interpretation of the distribution of opportunity costs within the current network for two reasons. First the existing parks network has not precluded oil exploration activities from advancing, and thus the opportunity cost to oil is substantially less than the full area of overlap with the existing parks. Second, the opportunity cost to local stakeholders is a function of roads and population density, both of the which are lower inside the parks estate. The lower population density and fewer roads are likely to be partially a function of the presence of the parks, and thus would underestimate the value of opening the parks to local stakeholders.

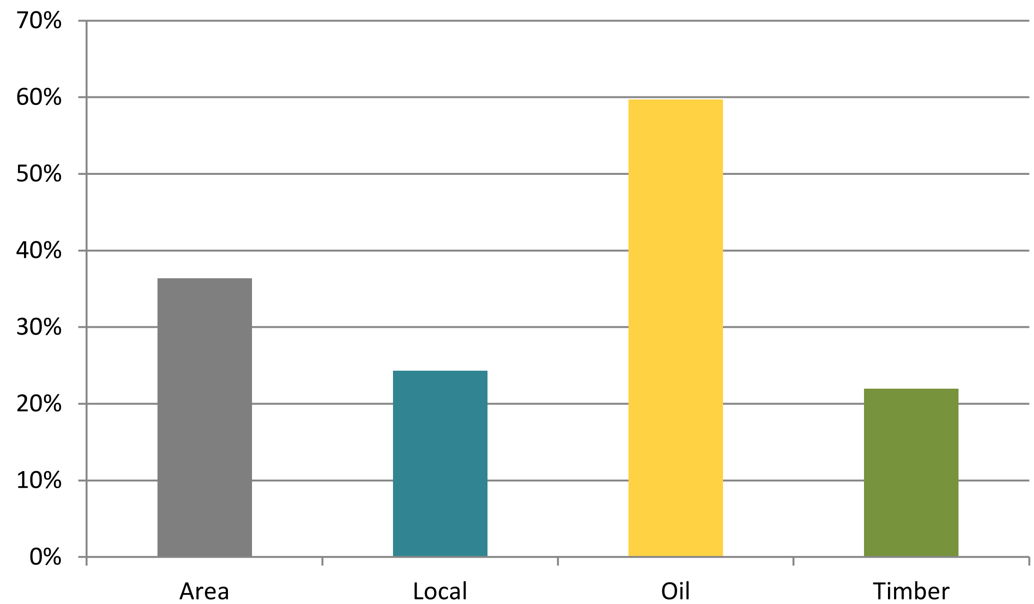

Figure 6. Distribution of opportunity cost in each the current parks network

Overlaying the 2,514 km^2 of oil exploration areas onto the existing protected area network shows that 1,501 km^2 (60%) of the area is located inside existing protected areas. The area of overlap accounts for 16% of the size of the total protected area estate in the landscape. Significant portions of the distribution of many conservation features were found inside the oil explorations areas (Table 6). Notably this included more than a 1/4 of the range for several iconic species, including African white-backed vulture (*Gyps africanus*), Grey crowned crane (*Balearica regulorum*), African elephant (*Loxodonta africana*), Giraffe, and Lion. Oil exploration areas also included 28% of the area identified as having high value for tourism.

Table 6. Proportion of conservation features found inside oil exploration areas.

Feature	**Inside oil exploration areas**	**Feature**	**Inside oil exploration areas**
Ecosystems		**Plant Species**	
Woodland	9%	Balsamocitrus dawei	5%
Grassland	25%	Beilschmiedia ugandensis	11%
Wetland	31%	Coccinia mildbraedii	31%
Bushland	59%	Entandrophragma utile	1%
Colonizing Forest	<1%	Entandrophragma angolense	1%
Tropical High Forest Fully Stocked	<1%	Entandrophragma cylindricum	3%
Tropical High Forest Depleted	<1%	Guarea cedrata	1%

Bird Species		Hallea stipulosa	4%
African white-backed vulture (Gyps africanus)	43%	Khaya anthotheca	5%
Grey crowned crane (Balearica regulorum)	44%	Lovoa swynnertonii	4%
Nahan's Partridge (Francolinus nahani)	1%	Lovoa trichilioides	2%
Shoebill (Balaeniceps rex)	15%	Prunus africana	2%
Mammal Species		**Carbon**	
African elephant (Loxodonta africana)	29%	Avitable	4%
Chimpanzee (Pan troglodytes)	3%	NASA	10%
Giraffe (Giraffa camelopardalis)	29%	WHRC	9%
Hippopotamus (Hippopotamus amphibius)	0%	Avitable (High risk)	0%
Hyena (Crocuta crocuta & Hyaena hyaena)	32%	NASA (High risk)	0%
Leopard (Panthera pardus)	43%	WHRC (High risk)	0%
Lion (Panthera leo)	45%		
Uganda mangabey (Lophocebus ugandae)	4%		

Treating oil exploration areas as degazetted portions of the park network reduced the areal extent of the parks network from 5999km^2 to 4498km^2. The resulting decrease in coverage caused the number of conservation features meeting their representation targets to fall to five, meaning only 16% of the conservation features met their targets (Table 4). The median proportion of a feature's target that was included inside the existing protected areas dropped from 59% in the current network to 33% when oil exploration areas were excluded (eg. representation gap of the median conservation feature increased from 31% of the target to 67% of the target). However, degazetting oil exploration areas did not have a uniform impact on all species and ecosystems. The impact was primarily observed in the reduced protection afforded to the savanna specialist species, including a 40% reduction in proportion of landscape range in protected areas of the threatened African white-backed vulture (*Gyps africanus),* and loss of 32%, 31%, 27%, for lion (*Panthera leo*), leopard (*Panthera pardus*) and giraffe (*Giraffa camelopardalis)* respectively.

Trade-offs in the opportunity costs of conservation

Independent consideration of different strategies and their impacts on other objectives

If the current protected area network is maintained, we show that targeted expansion amounting to 12% of the landscape area could overcome all species and ecosystem representation gaps. However, this expansion results in high opportunity costs, and requires 73% of oil exploration areas (which are the highest opportunity cost to any stakeholder in any strategy) and therefore extremely unlikely to be implemented. When we attempted to minimize inclusion of oil exploration areas, we found the same conservation objectives could be achieved in just 42% of the area of interest for oil exploration. However, the configuration required the largest area and highest opportunity costs to both local and timber of any strategy considered (Fig 7). The opportunity cost to both local populations and forestry was minimized in strategies C-Local and D-Timber that focused solely on minimizing cost to each, in which opportunity costs were reduced to 36% and 52% respectively.

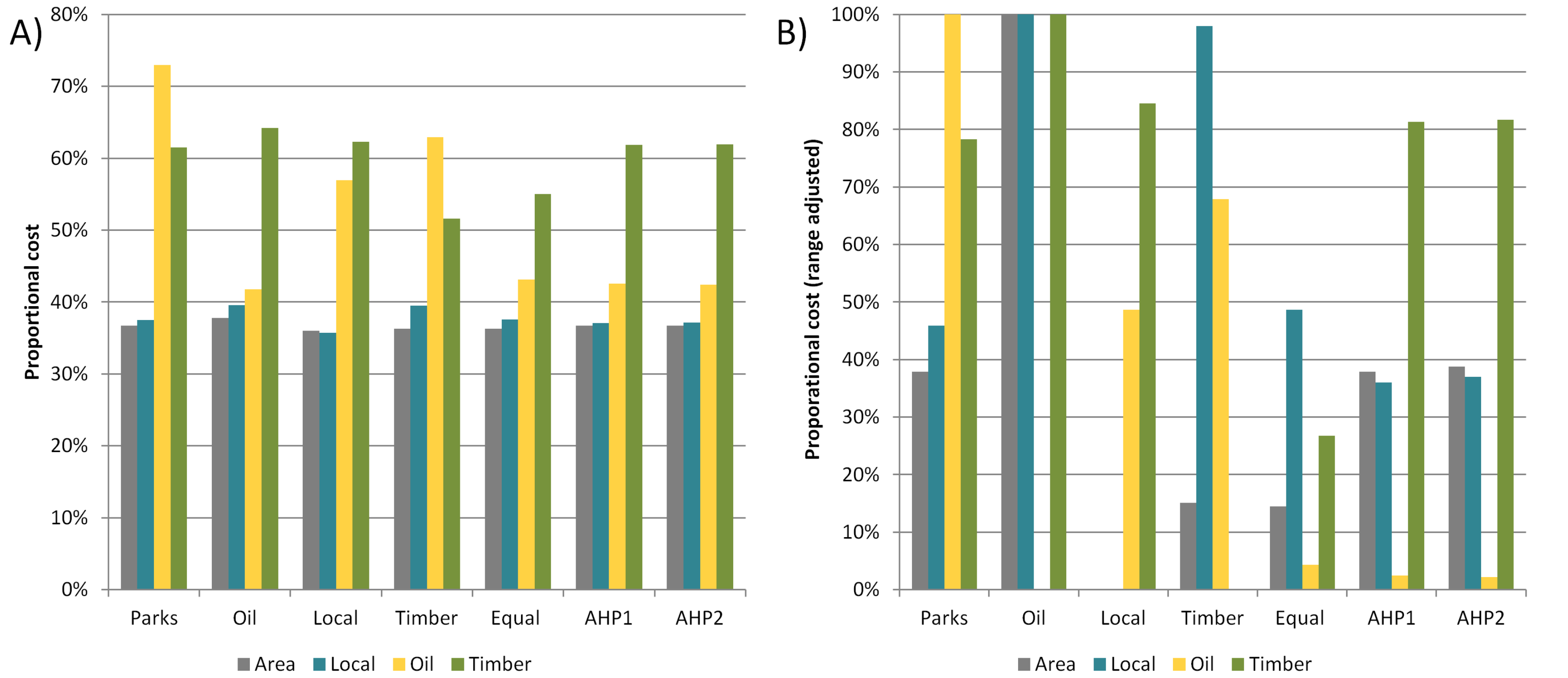

Figure 7. Distribution of opportunity cost in each conservation strategy. The opportunity cost of conservation is not distributed evenly between stakeholders, and the selection of conservation strategy has broad implications for that distribution. A-Proportion of the total opportunity cost that is included in areas identified for conservation. Higher values indicate greater opportunity cost to that stakeholder. B-Range weighted stakeholder opportunity cost. Opportunity cost above minimum possible cost to the stakeholder in any strategy expressed as a proportion of the difference in range in opportunity costs in all strategies in which conservation targets are met (equation 3). A value of 100% indicates the highest possible opportunity cost for that stakeholder, and a value of zero indicates the lowest opportunity cost in any strategy.

Strategy B (Oil), was the most spatially dissimilar to the expansion priorities identified with the existing parks (Table 7) indicating the extent to which the presence of oil alters the conservation priorities of the landscape. Among strategies that seek to accommodate the presence of oil inside protected areas, we find that strategies B-Oil and D-Timber result in the most spatially dissimilar sets of conservation priorities (Table 7). Strategy B-Oil resulted in costs to timber 24.4% higher than the minimum required to achieve the conservation objectives. Pursuing a strategy focused only on minimizing impact on timber resulted in costs to oil 50.7% higher than the minimum required to achieve conservation objectives (Fig 7). The higher costs to each user are the results of failing to consider the interests of the user when identifying conservation areas.

Table 7. Similarity of conservation areas identified in each conservation strategy. Pearson's correlation coefficient of the similarity for areas identified with each of the seven conservation resource allocation strategies.

	A-Parks	B-Oil	C-Local	D-Timber	E-Equal	F-AHP1	G-AHP2
A-Parks	1.000	0.784	0.915	0.837	0.813	0.836	0.835
B-Oil	0.784	1.000	0.845	0.768	0.886	0.945	0.946
C-Local	0.915	0.845	1.000	0.831	0.874	0.906	0.905
D-Timber	0.837	0.768	0.831	1.000	0.874	0.806	0.805
E-Equal	0.813	0.886	0.874	0.874	1.000	0.945	0.944
F-AHP1	0.836	0.945	0.906	0.806	0.945	1.000	0.998
G-AHP2	0.835	0.946	0.905	0.805	0.944	0.998	1.000

Additional focus on the trade-off between oil and timber appears warranted by inspection of the range in potential outcomes for each stakeholder. Opportunity cost to oil was the most variable, ranging from a minimum of 42% to a maximum of 73%, and opportunity cost to timber had the second widest range (52%-64%) in the seven strategies. In contrast to the range of potential impacts on oil and timber, the areal extent of conservation areas varied less than 2%, and local opportunity cost varied just 4%. The larger the between strategy range in potential opportunity costs the greater the flexibility there is for altering the spatial configuration of conservation areas to reduce costs to that stakeholder. Narrower range reflects the extent to which opportunity cost may be more dependent on the conservation objectives, rather than the choice of strategy to achieve those targets.

Balancing opportunity cost

Distribution of opportunity cost in the three strategies that considered multiple stakeholders simultaneously (E-Equal, F-AHP1, G-AHP2) was narrower than in single interest strategies (B-Oil, C-Local, D-Timber), but opportunity costs were never equally distributed (Fig 7). Placing equal emphasis on each stakeholder, we found total opportunity costs of 38%, 43% and 55% for local, oil and timber respectively (Fig 7). These reflect relative increases above the minimum required to meet conservation targets of 3.2%, 5.2%, and 6.5% for oil, local and timber respectively. Relative distribution of the opportunity cost in strategy E-Equal appears roughly equal when we calculated based on proportional loss (Fig 7A), but appears highly skewed in favor of oil when compared to range of expected outcomes (Fig 7B).

Applying stakeholder preferences in strategy F-AHP1 reduced costs above the minimum required to meet conservation targets for oil and local to just 1.9% and 3.9% respectively, but resulted in an increase to 19.9% for timber. Local populations benefit most when shifting from equal weighting to stakeholder preferences, despite the fact that the weighting of local interests as a proportion of the total cost surface increases only marginally (from 0.32 to .33 of total cost weighting) between strategy E-Equal and strategy F-AHP1. The difference in outcomes between the two strategies can be attributed to the change in weighting for oil (from .33 to .65) and timber (from .33 to 0.08). The reduction in local opportunity costs in moving between the two strategies is a result of the greater alignment with oil than with timber, which is also evident in the spatial similarity of strategies B-Oil and C-Local and dissimilarity of each to strategy D-Forestry (Table 6). Conservation areas identified through use of the weighted cost surface most resembled the interests of the oil industry reflecting the emphasis that stakeholders placed on minimizing impact on oil.

Moving from the distributional equity strategy (E-Equal) to the stakeholder weighted strategy (F-AHP) resulted in an absolute decrease in opportunity cost of 0.49% and 0.58% for local and oil respectively, but an increase of 6.89% for timber. The distribution of opportunity cost relative to the between strategy range varied substantially, with higher local costs in strategy E-Equal and higher cost to timber in strategy F-AHP1 (Fig 8). The trade-off is even more striking when we consider that strategy E-Equal affords oil 96% of the value of the best possible outcome, while local and timber retain 51% and 73% of the value of their best possible outcomes. Caution should be used to prevent over-interpretation of the range weighted outcomes (Fig 8b), because the smaller range in expected opportunity costs to local expansion and agriculture serves to magnify the apparent shift from between E and F, which in absolute terms changes only from 40% to 38%, while the larger range of outcomes for oil serves to minimize range weighted changes in cost to oil.

Strategy 7-AHP2 considered forced inclusion of areas identified as required for efficient achievement of conservation objectives in each of the individual stakeholder strategies; B-Oil, C-Local and D-Forestry, this included 6,213 km^2 (Fig. 9). We found no significant change in selection frequency for any planning unit between strategies 6-AHP1 and 7-AHP2, which differed only in that all non-dominated areas from the individual stakeholder scenarios were locked into AHP2, but were not locked into AHP1. The similarity of the two suggests little benefit from locking the areas in when the same cost surface was utilized.

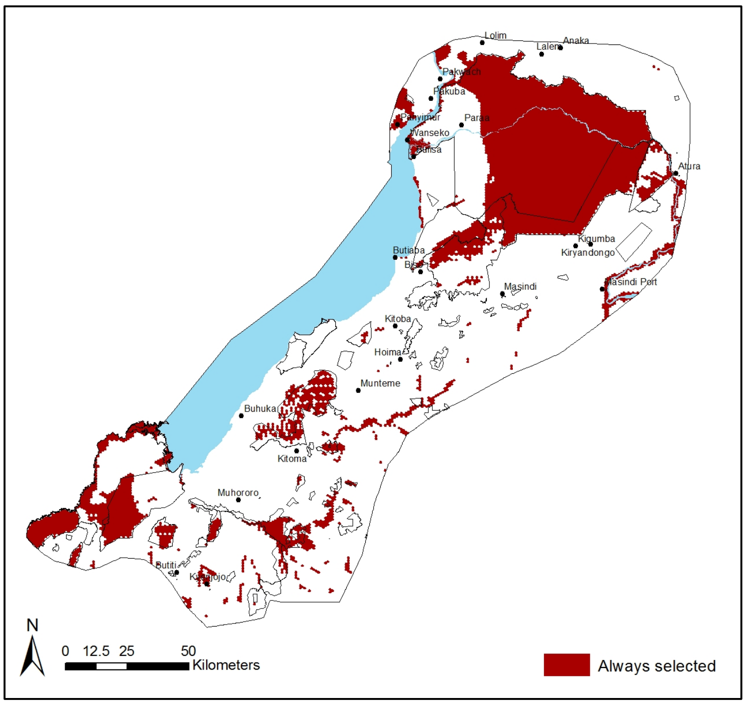

Fig 9. Areas that are irreplaceable for the efficient achievement of conservation objectives in the landscape. Areas in red have 100% selection frequency in strategy's B-Oil, C-Local and D-Forestry that attempt to minimize opportunity cost to each stakeholder individually. The areas in red are not sufficient to achieve conservation objectives on their own, but are the cornerstones for the building a representative and efficient network of protected areas in the Murchison-Semliki landscape.

Impact of stakeholder trade-offs on conservation features

A constant set of conservation objectives were achieved in all strategies, but the area identified to achieve those objectives differed between strategies, significantly impacting where conservation efforts would be targeted for some species, while areas identified for other species remained relatively unchanged (Table 8).

Resolution of these trade-offs will impact where conservation action occurs but the changes are likely to impact some species more than others. Areas targeted for African white-backed vulture (Gyps africanus) or Shoebill (Balaeniceps rex) conservation varied only modestly (4.4% and 7.4% of area targeted respectively), while areas targeted for chimpanzee (Pan troglodytes) and Uganda mangabey (Lophocebus ugandae) conservation varied more substantially, 27% and 25% respectively.

Moving away from the expansion priorities identified based on the existing parks networks, the areas targeted to conserve bushlands (Table 8) and *Balsamocitrus dawei* shifted most dramatically: median between strategy change was 68.4% and 66.1% of total targeted area. African elephant (Loxodonta africana) and leopard (Panthera pardus) were the mammal species most impacted by the move away from park expansion priorities, with shifts of 28.3% and 24.3% in targeted area respectively. When all possible strategies were considered, bushland conservation areas were most likely to change when shifting from one strategy to any other strategy, with a median shift of 54.4% of targeted area. We find that *Hallea stipulosa* and *Balsamocitrus dawei*, had the largest shift of any flora species with median shifts of 49.9% and 45.7%, while the most impacted mammal species were chimpanzee (Pan troglodytes) 27.1% and Uganda mangabey (Lophocebus ugandae) 24.8%.

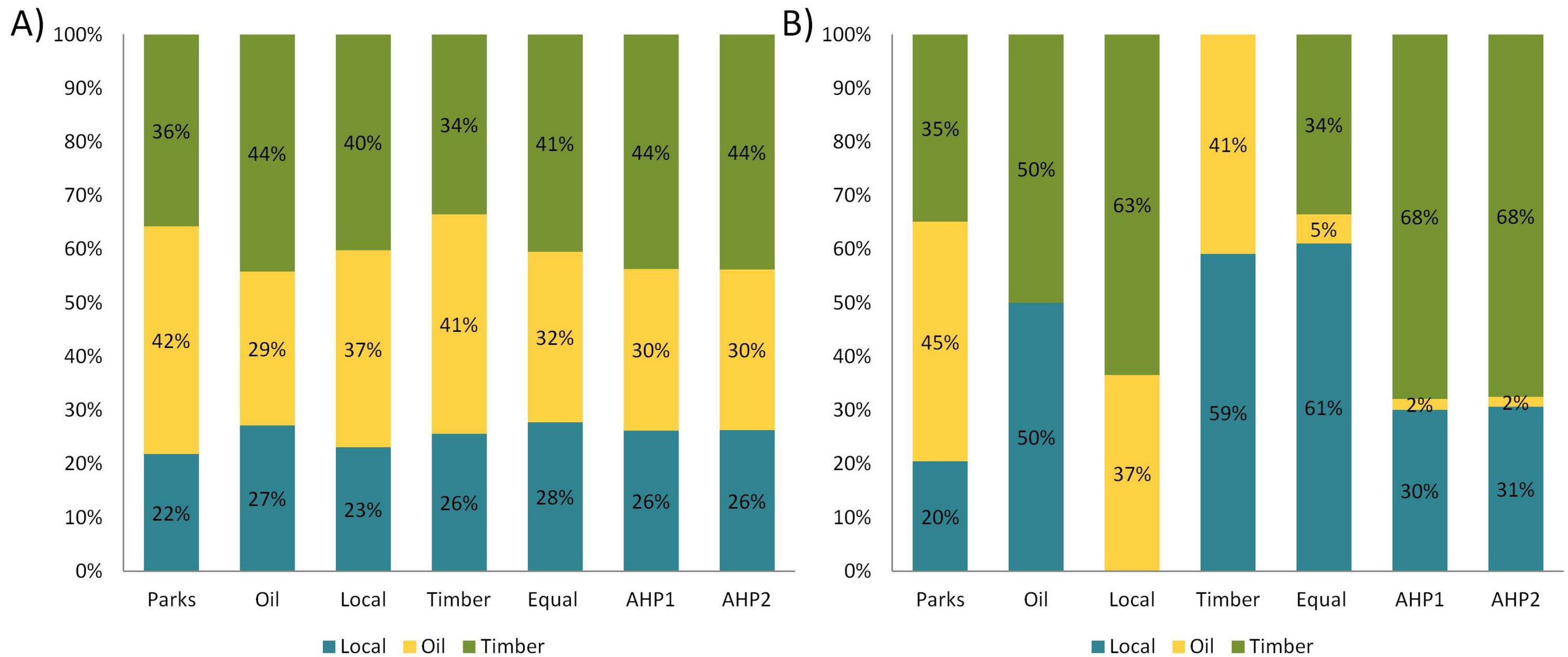

Figure 8. Relative distribution of opportunity cost in each conservation strategy. A) Stakeholder proportion of the total strategy opportunity cost, calculated by dividing the stakeholder opportunity cost by the summed opportunity cost to all stakeholders in the strategy. B) Stakeholder proportion of the range weighted total opportunity cost of the strategy. Range weighted proportion dividing the range weighted value for each stakeholder (as calculated in equation 3) by the summed range weights for all stakeholder in the strategy. Lower values indicate a lower proportion of the relative opportunity costs in the strategy. Weighted opportunity cost goes to zero for stakeholders in the strategy that minimizes opportunity cost to that stakeholder.

Table 8. Conservation features that experience the largest spatial shift in the areas targeted for protection when shifting between individual resource allocation strategies. The top five features are listed with the proportion of the target achieved in a different location.

	Parks	Oil	Local	Timber	Equal	AHP1
Oil	Bushland (85%) Balsamocitrus dawei (57 %) Hallea stipulosa (51%) Elephant (33.4 %) Grassland (31.9 %)					
Local	Bushland (44 %) Hallea stipulosa (33%) Balsamocitrus dawei (26 %) Uganda mangabey (23%) Grassland (17 %)	Bushland (73.3 %) Balsamocitrus dawei (67 %) Hallea stipulosa (61 %) Chimpanzee (34%) Grassland (31 %)				
Timber	Balsamocitrus dawei (115.%) E. utile (108 %) Hallea stipulosa (93.7 %) Khaya anthotheca (64.5 %) Guarea cedrata(58.2 %)	Balsamocitrus dawei (161%) Hallea stipulosa (123 %) E. utile (117 %) Khaya anthotheca (75.9 %) Chimpanzee (63.1 %)	Balsamocitrus dawei (134.%) E. utile (118 %) Hallea stipulosa (114 %) Khaya anthotheca (69 %) E. cylindricum (63 %)			
Equal	Balsamocitrus dawei (106.9 %) Bushland (86.5 %) Hallea stipulosa (82.7 %) Entandrophragma utile (82 %) Khaya anthotheca (47.8 %)	Balsamocitrus dawei (113.4 %) Entandrophragma utile (88 %) Hallea stipulosa (81 %) Khaya anthotheca (55.1 %) Chimpanzee (50 %)	Balsamocitrus dawei (103.6 %) Entandrophragma utile (86.8 %) Hallea stipulosa (83.2 %) Bushland (54.6 %) Entandrophragma cylindricum (48.6 %)	Bushland (104 %) Hallea stipulosa (43%) Crowned crane (38 %) Balsamocitrus dawei (35 %) leopard leopard (30.3 %)		
AHP1	Bushland (87 %) Balsamocitrus dawei (45.1 %) Hallea stipulosa (40.4 %) Elephant (32.6 %) Grassland (31.4 %)	Balsamocitrus dawei (40.6 %) Hallea stipulosa (36.4 %) Chimpanzee (24.8 %) E. utile (19.9 %) Tropical High Forest Depleted (17.5 %)	Bushland (54.9 %) Balsamocitrus dawei (37.2 %) Hallea stipulosa (32.9 %) Elephant (21.5 %) Grassland (19.8 %)	Bushland (102 %) Hallea stipulosa (89.9 %) Balsamocitrus dawei (63.7 %) Chimpanzee (42.3 %) Uganda mangabey (42.2 %)	Hallea stipulosa (48%) Balsamocitrus dawei (31.8 %) Chimpanzee (27.1 %) E. utile (26 %) Uganda mangabey (24.2 %)	
AHP2	Bushland (87.3 %) Balsamocitrus dawei (45.7 %) Hallea stipulosa (42.1 %) Elephant (33.1 %) Grassland (31.3 %)	Balsamocitrus dawei (39 %) Hallea stipulosa (37.6 %) Chimpanzee (25.4 %) E.utile (20.4 %) Tropical High Forest Depleted (17%)	Bushland (54.4 %) Balsamocitrus dawei (37.3 %) Hallea stipulosa (33.5 %) Elephant (21.8 %) Grassland (19.9 %)	Bushland (101.2 %) Hallea stipulosa (92.1 %) Balsamocitrus dawei (64.5 %) Chimpanzee (42.8 %) Uganda mangabey (42.6 %)	Hallea stipulosa (49.9 %) Balsamocitrus dawei (31.2 %) Chimpanzee (27.5 %) E. utile (25.6 %) Uganda mangabey (24.8 %)	None

Tradeoffs between conservation of biodiversity and carbon

The baseline biodiversity strategy required 48% of landscape area and conserved 49% -53% of total landscape carbon and 51% -55% of high risk carbon (variance in carbon conserved is related to choice of data source used to estimate carbon content). Maximizing carbon conserved in the same areal footprint, we found that 67% -75% of total landscape carbon, including 82%-88% of high risk carbon could be conserved in 48% of area. The baseline biodiversity strategy conserved carbon equal to that which could be conserved in 34% of the landscape with the carbon maximization strategy. Overlap in the areas selected in the two strategies was relatively high, amounting to 50% conservation areas identified (24% of the landscape) through each approach (Fig 9). Overlap between the two strategies would be expected to increase with the use of a more heterogeneous cost surface (eg. minimizing cost to an individual stakeholder). When both objectives were considered simultaneously we found that the area required to achieve both targets was 32% smaller than when both objectives were pursued independently (Figs 10 & 11).

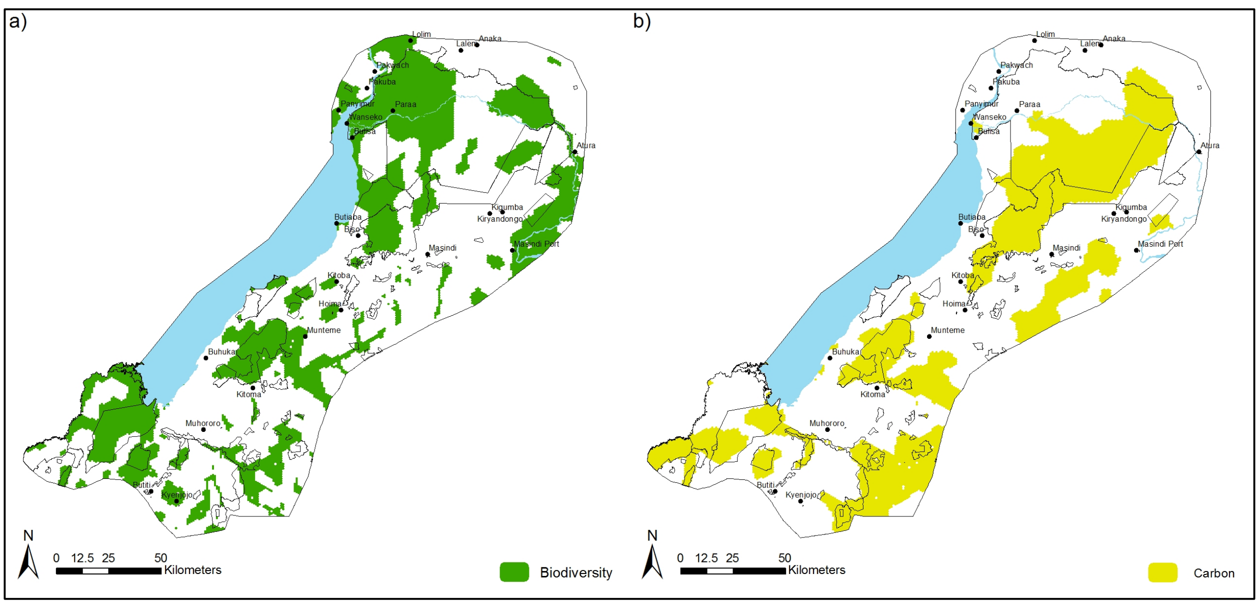

Figure 9. Comparison of the spatial configuration of conservation areas to achieve only biodiversity objectives with those that maximize carbon conservation. A) Configuration of conservation areas to most efficiently achieve biodiversity objectives, B) Configuration of conservation areas to maximize carbon conserved.

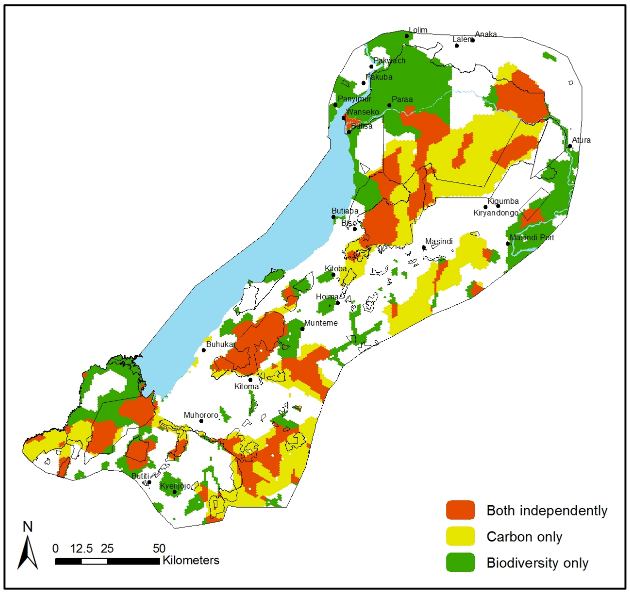

Fig 10. Area of overlap between the baseline biodiversity strategy and the carbon maximization strategy are highlighted in orange.

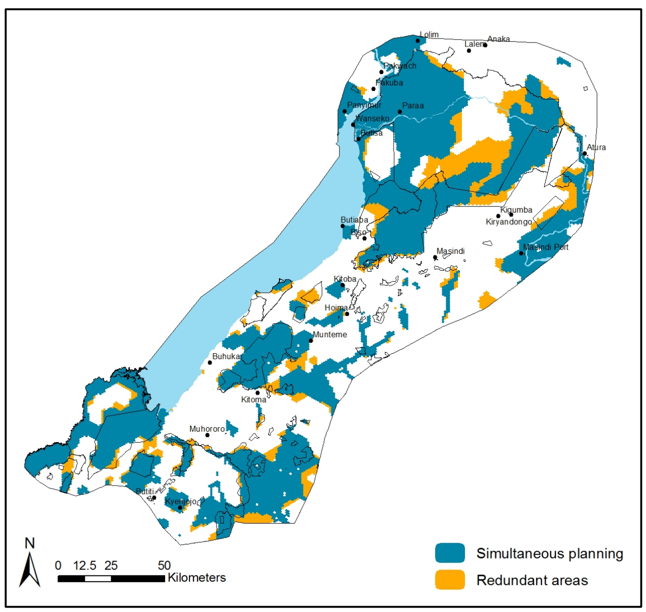

Fig 11. Consideration of biodiversity and carbon when identifying conservation areas reduces the areal footprint of conservation areas in the landscape by 32%. The areas identified in blue achieve both carbon and biodiversity objectives and render the areas identified in orange redundant. The areas identified in orange are the result of optimizing to achieve each target independently and spatially overlaying the two solutions.

The carbon maximization strategy also shifted the location of conservation areas in the landscape towards ecosystem types with higher carbon content (forested types) and away from ecosystem types with lower carbon content (savannah and bushland). Level of representation of wetland ecosystem types showed the greatest between strategy variability. Over 96% of mapped wetlands were included in the conservation areas of baseline biodiversity strategy, while the carbon maximization strategy captured just 26% of wetlands (Fig 12).

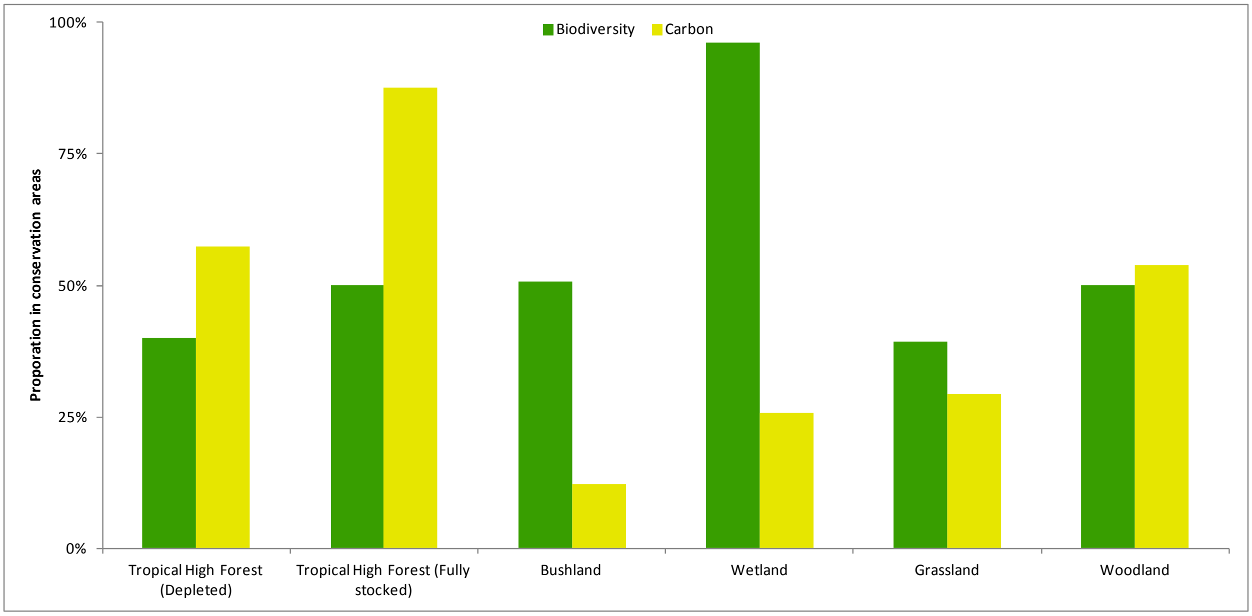

Figure 12. Representation of major ecosystem types in the baseline biodiversity strategy (green) and carbon maximization strategy (yellow). Representation of ecosystem types with lower estimate carbon content was far lower in the carbon maximization strategy.

Conservation outcomes for several key species in the landscapes were radically different in the baseline biodiversity strategy relative to the carbon maximization strategy. Representation of obligate forest species dependent species, chimpanzee (*Pan troglodytes)* and Uganda mangabey (Lophocebus ugandae) was far higher than in the baseline biodiversity strategy (Fig. 13). While representation of savanna species including white back vulture (Gyps africanus) and hyena species were well below established conservation targets. Unsurprisingly the tourism value in the landscape was also impacted by the shift to carbon conservation. The areas identified to maximize carbon conservation contained 35% of the total tourism value in the landscape, 45% less than that contained in the biodiversity conservation solution.

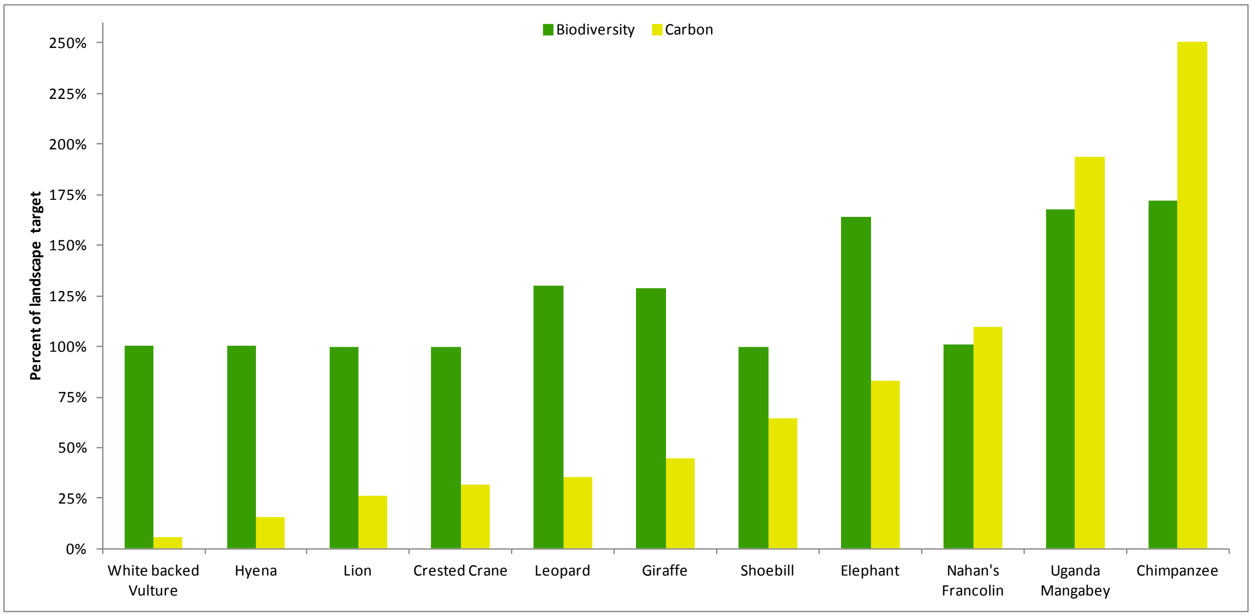

Figure 13. Proportion of landscape conservation target achieved in the baseline biodiversity configuration and in the carbon maximization strategy.

The baseline biodiversity strategy and carbon maximization strategy resulted in dramatic differences in the distribution of the opportunity cost of conservation (Fig 14). A carbon maximization strategy resulted higher opportunity cost to timber interests in the region, and lower opportunity cost to the oil interests relative to the baseline biodiversity strategy (Fig 14).

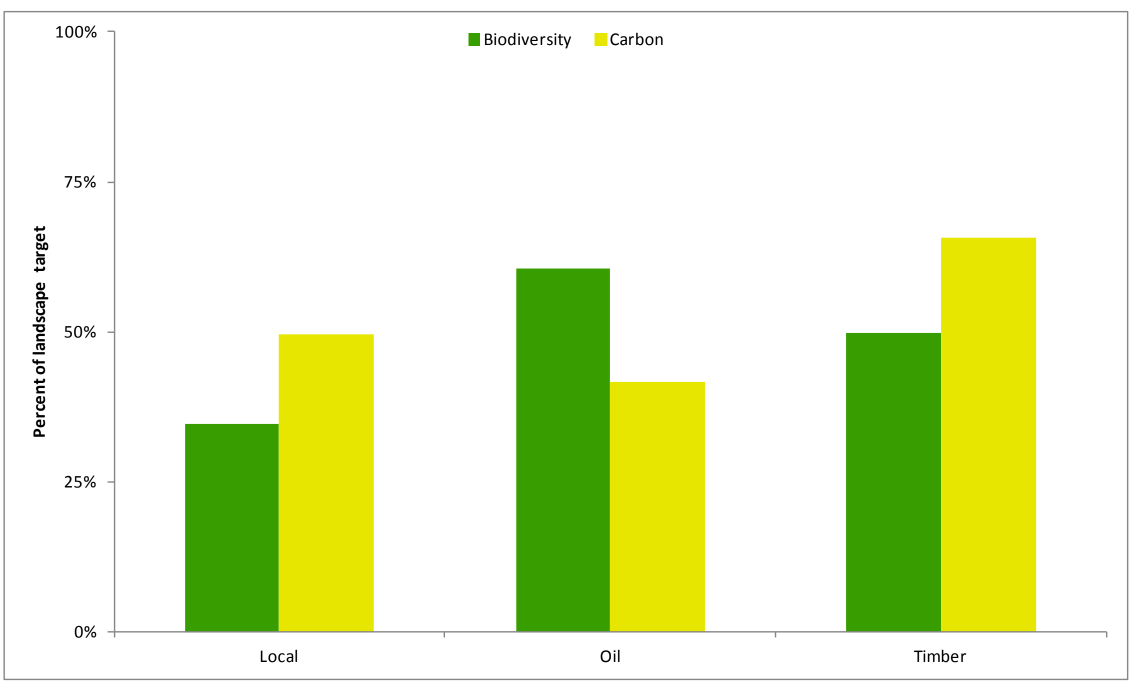

Fig 14. Difference in the distribution of the opportunity cost between three stakeholder groups in the baseline biodiversity strategy and carbon maximization strategy. Total area included is held constant at 48% of the landscape in each strategy and thus not included here.

Exploring the trade-off between solutions that preference achievement of biodiversity objectives with those that maximize carbon conservation we found that for a small decrease in emphasis on either single objective would result in substantial improvements in the outcome measure for the other objective. For a 1% reduction in biodiversity conservation could increase total carbon conserved by 14% and high risk carbon by 16%. A 3% reduction in biodiversity conservation could increase carbon conservation by 28% and conservation of high risk carbon by 41%. The high marginal returns for increasing emphasis on carbon conservation when moving away from the a biodiversity conservation only approach were also found when moving away from a carbon only solution by placing small emphasis on achievement of conservation targets. For a 3% decrease in carbon conserved the shortfall gap in achievement of biodiversity conservation targets was reduced by 10% (Fig 15).

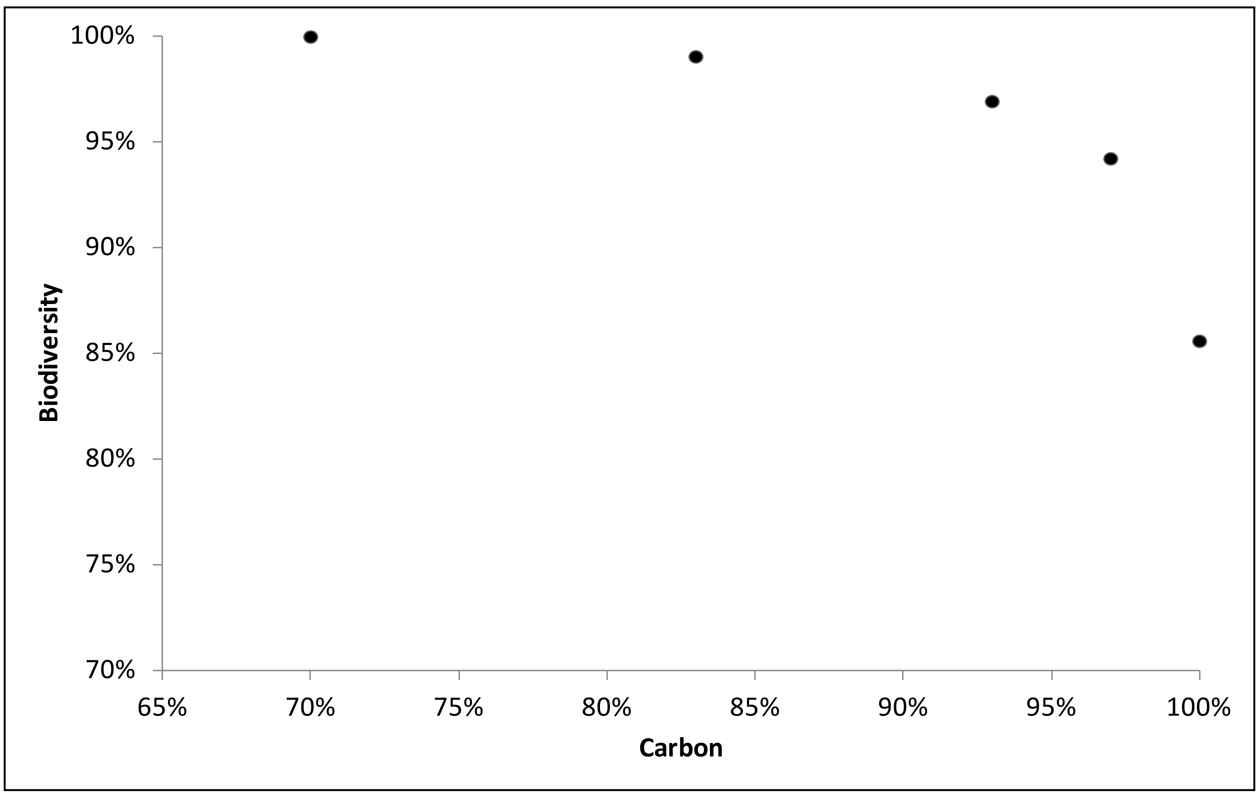

Fig 15. Efficiency frontier for the provision of carbon and representation of biodiversity in 48% of the Murchison-Semliki landscape. 48% was used to develop the efficiency because it was the minimum area in which the baseline conservation objectives could be achieved.

Discussion

The analysis revealed that there is significant spatial flexibility in where the preliminary conservation targets can be achieved in the Murchison-Semliki landscape. The impact of this spatial flexibility is readily apparent in the potential distribution of both the opportunity costs between stakeholders in the landscape and in amount of each conservation feature included in the regions conservation areas. Despite this flexibility, it was not possible to achieve the conservation objectives at zero opportunity cost to any resource user, even when that opportunity cost was the primary consideration. Minimizing cost to an individual stakeholder increased costs to other stakeholders by up to 51%. This suggests that careful consideration should be given to where conservation actions are targeted to avoid unnecessary impacts on individual stakeholders.

The inclusion of at least some portion of the area identified as higher value to each stakeholder suggests that the conservation values in these areas of the landscape is irreplaceable and robust to any underlying uncertainty in which cost should be used to prioritize conservation in the landscape (Carwardine et al. 2010). This result is a function of the spatial overlap of biodiversity and other uses of the landscape, and suggests that cooperation and trade-offs will be required to secure the conservation future of the landscape. We have presented a framework to elucidate those trade-offs for the stakeholders impacted by them, and a suggested a process that will help them explore the impacts of individual decisions and help them work through the resolution required to ensure the conservation future of the landscape.

The suggested process involves exploring the impact Conservation strategies that focus primarily on the interests of an individual stakeholder (eg. strategies 2-4), establish baselines for overlap between the conservation objectives and the interests of that stakeholder group. These baselines inform the interpretation of other landscape configurations that consider a complex mix of stakeholder interests, by providing insight into the expected impact in the absence of competing landscape interests. For example, in strategy 5 which attempts to minimize inclusion of high value timber areas, the opportunity cost to timber is just under 50% of the total landscape value. In all other scenarios, the opportunity cost incurred by timber is higher than 50% (Figure 8). The higher opportunity cost reflects how accommodating the interests of multiple stakeholders can place an additional burden on an individual stakeholder group.

Other planning exercises have recognized that economic efficiency is often not the sole measure by which proposed plans are measured, and many stakeholders often look at the equitability of outcomes (Klein et al. 2008). We also looked at the distribution of lost opportunity to potential users. We found that by adjusting the relative importance of avoiding areas of high importance to individual users there was a wide variety in how the costs of planning were distributed between users. Relative load placed on areas of prospective interest to the petroleum industry ranged from 19-45%, and the relative load on timber ranged from 32-58% (Figure 11). These differences are not inconsequential. We found that avoiding extreme impacts requires thoughtful planning that simultaneously considers the interests of individual stakeholders.

It is clear that for the biodiversity of the Murchison-Semliki Landscape be conserved in the long term, careful planning will be required to minimize the impact of other activities. This particularly applies to timber extraction, the oil industry and small/large scale agriculture, which are seen as the primary threats to species persistence in the landscape (MWE 2012). One such effort is being undertaken by the Strategic Environmental Assessment (SEA) for oil in the Albertine rift in Uganda which is aiming to plan for the long term impacts of the oil industry in this region. However, the current SEA process is focused primarily on oil and biodiversity. As this analysis has demonstrated, planning processes that focus on only a single stakeholder are likely to result in significant additional costs to stakeholder groups that are not considered. Failure to consider the cumulative impacts of the many activities that impact the species and ecosystems can also result in short-sighted solutions that fail to account for the cumulative impact of all activities and potentially jeopardize the conservation future of the landscape. Planning for the future of the landscape should take a holistic view of the landscape that incorporates land uses such as carbon, timber harvesting, agriculture and tourism, to ensure that all objectives are achieved.

Analysis in other regions suggests the potential for biodiversity co-benefits from payment for ecosystem service schemes are realized when those schemes specifically account for biodiversity values in their design (Larsen, Londoño-Murcia, and Turner 2011). Our analysis revealed that there are also clear trade-offs to be made in the design of conservation areas to achieve biodiversity and carbon conservation objectives. The analysis also revealed that moving away from a strategy that considered only maximizing carbon conservation or biodiversity conservation and placing a small emphasis on the other objective, resulted in large improvements in outcomes for the previously unconsidered objective at minimal cost to the primary objectives. From a carbon only strategy, a 3% decrease in carbon conserved reduced the biodiversity conservation shortfall gap by 10%, while from a biodiversity only strategy a 1% decrease in biodiversity conserved could result in nearly a 20% increase in carbon conserved.

Caveats

While we treat existing protected areas and wildlife reserves in the region as part of the network, a previous assessment of the effectiveness of protected areas in Uganda noted that management does not effectively address the full suite of threaten processes (Mugisha and Jacobson 2004). Recent surveys of the bush meat trade in west Africa also found that threatened species were more likely to be found in markets in close proximities to protected areas (Fa et al. 2014). Our analysis does not treat conservation areas currently managed by local communities (eg. community forestry areas) as protected, because current levels of conservation investment is insufficient to secure these areas from the stressors that threaten them (MWE 2012). The conservation benefits of appropriately managed local conservation areas have been demonstrated in other regions (Mugisha and Jacobson 2004; Nolte et al. 2013), and with increased enforcement these areas could play a critical role in securing the conservation future of the landscape.

The data and targets utilized in this analysis are preliminary, and the analysis of overlap and impact should be treated as preliminary as well. The process involved only a subset of the data and stakeholders who need to be included in the larger decision making process. The trade-offs identified within the assessment are a function of the conservation objectives, and modification of those objectives will likely change the nature of the trade-offs identified (Halpern et al. 2013). This primary aim of the report is to demonstrate how a spatial optimization tool, Marxan, could be used to identify efficient conservation areas while balancing the opportunity costs to multiple stakeholders. It also provides a methodology to identify a) areas critical for achievement of conservation objectives and b) areas where trade-offs maybe required where greater efforts need to be made to ensure that two or more land uses are compatible.

Project evaluation

In the landscapes where the Wildlife Conservation Society (WCS) works it is rarely plays the role of specifying which activities are allowable and which are not or where individual land uses will be allocated in the landscape. Decision making power resides in the local and national government authorities with regional jurisdiction and the within the communities and business of the region which WCS seeks to support. With this in mind the philosophy that drove design of the planning process was primarily 'performance' not 'conformance' based (Laurian et al. 2010). 'Performance' based plan evaluation focuses on the extent to which the planning process influences the decision making process, while conformance based evaluation criteria focus on the extent to which areas identified within the planning process are selected for conservation action (Laurian et al. 2010). Thus the effectiveness of this work should be measured not just as the extent to which the priority areas identified in this process are conserved, but the extent to which future planning processes in the landscape utilize a structured decision methodology and emphasize the cumulative impact of planning decisions on biodiversity.

Leading local practitioners through a step-wise conservation planning analysis that clearly elucidated the trade-offs between individual objectives before trying to balance those interests was critical for building confidence in the systematic planning approach and demystifying the "black box" of decision support tool (Marxan). The novelty of this approach is that we were not just interested in the design of a single set of areas (Green et al. 2009), the objective was also to build local demand for approaching conservation decisions more systematically. Lessons learnt from other planning processes and the recent changes in the Murchison Semliki landscape highlight that plans will not be perfect and will require revisiting and modification as new information becomes available or as conditions and resource use change (Day 2002; Pressey et al. 2013). Thus it was important to emphasis process, and not just outcomes, as the process will likely require repeating and updating. Because of time constraints we did not seek to train stakeholders in formally running the tools themselves, rather we focused on efforts on understanding objective based decision making and the building capacity to formulate questions in this manner. To achieve this, we set aside time during the workshops to allow practitioners that were not previously experienced using a decision support tool, to deconstruct the complex planning problem and iteratively add elements to the problem as the output aligned with expectations and confidence was built. This was accomplished in an interactive session that used the Zonae Cogito to modify parameters and display results from Marxan in real time (Segan et al. 2011). The sessions began with a single conservation objective (conservation of single forest type) and first worked through the how changes in the cost surface affected areas selected for conservation and then how additional conservation targets influenced the area selected. This process built confidence in the decision support tool and allowed practitioners to embrace the output of the tool as their own, rather than feeling it was something imposed upon them.

Conclusion

The discovery of oil in the Albertine graben fundamentally altered the opportunity cost of conservation and trajectory of the Murchison-Semliki landscape. However this will not be the last change and we are already witnessing how climate change is and will continue to impact the landscape (Watson, Cross, et al. 2011). The conservation challenges facing the Murchison Semliki landscape are not unique, indeed the mineral and petroleum boom in Africa is now widespread (Edwards et al. 2014). Addressing this and the growing challenges of climate change and population growth requires systematic and data driven approaches to landscape conservation that can incorporate the interests of all stakeholders. The analytic framework utilized here provides a model for how similar challenges in other landscapes could be addressed through the use of a transparent, objective-based planning framework.

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Appendix

Expert elicitation of relative importance of stakeholder interests

Analytic hierarchy process (AHP) was used so to develop logically consistent weightings of the relative importance of individual activities (Saaty, 2008). AHP is commonly used approach in multi-criteria analysis to elicit expert opinion on the relative priority of divergent options. Each socio-economic land use option (agriculture, REDD+, oil development, timber harvesting and biodiversity-oriented tourism) was compared with each other in terms of their relative importance. A rating scale of 1-9 was used to achieve this (e.g. if group members thought one activity was much more important than another, they would give a score of 9. Conversely, if group members thought the activity was much less important than the other, they were to give a score of 1/9. A score of one indicated that the two were of equal importance). As groups conducted the pair-wise comparison, a consistency score was provided to them to ensure that their rating where logically consistent.

The meeting was divided into two groups, each having representation from the different stakeholder groups at the meeting. The first group was asked how they felt the Government of Uganda currently assessed the importance of each land use in the landscape in terms of what is currently happening on the ground. The second group was asked, if they were government, how much importance would be placed on each land use activity in the landscape.

The two groups came up with similar scores but there were also clear differences (Table 1). Both groups identified agriculture as by far the most important land use in the landscape. There was some disagreement with the next most important activity with the first group identifying oil as a very important land use to the Government of Uganda whereas the second group identified tourism as the next most important activity because of its longer term potential for income generation. REDD+ activities were seen to be much more important by the second group than the first group. Timber harvesting in the landscape was not scored highly by either group.

Table S3. A pair-wise analysis of the importance of socio-economic activities in the Murchison-Semliki landscape. The importance of each activity in the first column was compared against each of the other activities, with the highest rating being a 9 and the lowest rating being 1/9. The overall weight (relative importance) is provided in the last column.

Group 1. Group 1 assessed from the perspective of what they thought the Government of Uganda was currently placing priority on.

	Agriculture	REDD+	Oil	Timber	Tourism	Overall Weight
Agriculture	1.00	9.00	3.00	5.00	7.00	0.4989
REDD+	0.11	1.00	0.11	0.33	0.20	0.0327
Oil	0.33	9.00	1.00	5.00	3.00	0.2688
Timber	0.20	3.00	0.20	1.00	0.33	0.0729
Tourism	0.14	5.00	0.33	3.00	1.00	0.1266

Group 2. Group assessed as if they were government, and could place importance on whichever activity they felt was most important.

	Agriculture	REDD+	Oil	Timber	Tourism	Overall Weight
Agriculture	1.00	7.00	5.00	7.00	5.00	0.5450
REDD+	0.14	1.00	0.33	3.00	0.33	0.0826
Oil	0.20	3.00	1.00	3.00	0.33	0.1311
Timber	0.14	0.33	0.33	1.00	0.33	0.0498
Tourism	0.20	3.00	3.00	3.00	1.00	0.1915