

LETTER • OPEN ACCESS

## Optimizing investments in national-scale forest landscape restoration in Uganda to maximize multiple benefits

To cite this article: Jesse D Gourevitch *et al* 2016 *Environ. Res. Lett.* **11** 114027

View the [article online](#) for updates and enhancements.

### Related content

- [Restoring degraded tropical forests for carbon and biodiversity](#)  
Sugeng Budiharta, Erik Meijaard, Peter D Erskine et al.
- [Spatially explicit estimates of forest carbon emissions, mitigation costs and REDD+ opportunities in Indonesia](#)  
Victoria Graham, Susan G Laurance, Alana Grech et al.
- [Landscape configuration is the primary driver of impacts on water quality associated with agricultural expansion](#)  
Rebecca Chaplin-Kramer, Perrine Hamel, Richard Sharp et al.

## Environmental Research Letters



## LETTER

## Optimizing investments in national-scale forest landscape restoration in Uganda to maximize multiple benefits

## OPEN ACCESS

## RECEIVED

14 September 2016

## REVISED

19 October 2016

## ACCEPTED FOR PUBLICATION

26 October 2016

## PUBLISHED

17 November 2016

Original content from this work may be used under the terms of the [Creative Commons Attribution 3.0 licence](#).

Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.



Jesse D Gourevitch<sup>1</sup>, Peter L Hawthorne<sup>2</sup>, Bonnie L Keeler<sup>2</sup>, Craig R Beatty<sup>3</sup>, Michelle Greve<sup>4</sup> and Michael A Verdone<sup>5</sup>

<sup>1</sup> Gund Institute for Ecological Economics, University of Vermont, Burlington, VT, USA

<sup>2</sup> Institute on the Environment, University of Minnesota, St. Paul, MN, USA

<sup>3</sup> Global Forest and Climate Change Programme, International Union for Conservation of Nature, Washington DC, USA

<sup>4</sup> Department of Plant Science, University of Pretoria, Hatfield, South Africa

<sup>5</sup> Department of Agricultural and Resource Economics, Colorado State University, Fort Collins, CO, USA

E-mail: [Jesse.Gourevitch@uvm.edu](mailto:Jesse.Gourevitch@uvm.edu)

**Keywords:** Bonn Challenge, carbon, decision-making, ecosystem services, forest landscape restoration, opportunity costs, spatial optimization

Supplementary material for this article is available [online](#)

**Abstract**

Forest loss and degradation globally has resulted in declines in multiple ecosystem services and reduced habitat for biodiversity. Forest landscape restoration offers an opportunity to mitigate these losses, conserve biodiversity, and improve human well-being. As part of the Bonn Challenge, a global effort to restore 350 million hectares of deforested and degraded land by 2030, over 30 countries have recently made commitments to national forest landscape restoration. In order to achieve these goals, decision-makers require information on the potential benefits and costs of forest landscape restoration to efficiently target investments. In response to this need, we developed an approach using a suite of ecosystem service mapping tools and a multi-objective spatial optimization technique that enables decision-makers to estimate the potential benefits and opportunity costs of restoration, visualize tradeoffs associated with meeting multiple objectives, and prioritize where restoration could deliver the greatest benefits. We demonstrate the potential of this approach in Uganda, one of the nations committed to the Bonn Challenge. Using maps of the potential benefits and costs of restoration and efficiency frontiers for optimal restoration scenarios, we were able to communicate how ecosystem services benefits vary spatially across the country and how different weights on ecosystem services objectives can affect the allocation of restoration across Uganda. This work provides a generalizable approach to improve investments in forest landscape restoration and illuminates the tradeoffs associated with alternative restoration strategies.

**1. Introduction**

Increasing global demand for food, fuel, fiber, and shelter has resulted in expansion of croplands, pastures, and urban areas (Foley *et al* 2005). Such changes in land use are driving the loss and degradation of natural ecosystems (Gibbs *et al* 2010) and altering global carbon, hydrologic, and nutrient cycles (MEA 2005). Over the past 300 years, there has been a net loss of ~700–1100 million hectares of forests globally (Ramankutty and Foley 1999). The loss of natural forest ecosystems has reduced the capacity of

these lands to provide valuable ecosystem services and threatens human well-being (Foley *et al* 2005, Balthazar *et al* 2015). Confronting the effects of forest loss and degradation will require assessing the tradeoffs between competing land uses and the ecosystem goods and services those lands provide.

In particular, forest landscape restoration (FLR) is gaining prominence as a strategy to mitigate climate change, improve water quality, and increase biodiversity (Lamb *et al* 2005). This is a strategy that can help countries to meet international targets such as the UNFCCC REDD+ program, Convention of

Biological Diversity Aichi Targets, Rio +20 goals, and the newly adopted Sustainable Development Goals. In recognition of these opportunities, the Bonn Challenge was launched in 2011 with the goal of restoring 350 million hectares of degraded lands by 2030. Over 30 countries have already committed over 100 million hectares to FLR under the Bonn Challenge, with more commitments forthcoming (Bonn Challenge 2016).

Achieving the restoration goals set by the Bonn Challenge will require national and sub-national governments and stakeholders to define their objectives for restoration and prioritize where to restore given limited resources. In order to assist national and regional governments and planning authorities in this task, international organizations have developed generalizable methodologies to help decision-makers engage diverse assemblages of stakeholders to identify FLR opportunities, develop local capacity, and identify potential financing mechanisms to support broad-scale restoration (IUCN and WRI 2014). These approaches are currently being applied in over 30 countries at the national and sub-national levels and are generating demand for information on the potential benefits and costs of FLR to more efficiently target investments.

In many countries, ecosystem services information is critical to communicating the potential benefits of restoration commitments and making a business case for restoring degraded lands. Local and regional authorities undertaking restoration planning increasingly require tools that allow them to simultaneously consider a suite of objectives associated with restoration investments, such as carbon sequestration, biodiversity conservation, food security, and water quality. Other countries planning for FLR have used benefits transfer approaches for ecosystem services assessments, such as those broadly applied by The Economics of Ecosystems and Biodiversity (TEEB, TEEB Foundations 2010). These approaches can yield large monetary estimates for the values of restoration, but these methods are aspatial and do not allow users to visualize tradeoffs among competing objectives. Because the potential benefits and costs of restoration are spatially heterogeneous and depend on ecological, socioeconomic, and climatic factors (Chazdon 2008), accurately quantifying and mapping the potential benefits and costs of restoration requires spatially-explicit modeling. Moreover, potential benefits of restoration are often measured using different (i.e. non-monetary) metrics, which can make it challenging for decision-makers to evaluate tradeoffs among competing objectives.

We aimed to add value to the restoration assessment process by combining ecosystem services mapping tools and a multi-objective spatial optimization approach that improves upon benefits transfer approaches. We applied our approach in Uganda in support of their national-level restoration commitments under the Bonn Challenge. Driven by increased

demand for forest products and agricultural expansion (Obua *et al* 2010), Uganda has recently experienced widespread forest loss and degradation. Between 2000 and 2012, forest cover decreased by approximately 300 000 hectares, equal to 1.8% of the country's total land area, excluding water (Hansen *et al* 2013). In support of transition to a 'Green Economy', a pillar of Uganda's Vision 2040 (Uganda National Planning Authority (NPA) 2007), the Ugandan national government committed to the Bonn Challenge in 2014. The Ugandan government is still in early stages of planning its national restoration strategy and requires information that will help them target investments in restoration.

To identify the objectives for restoration, a stakeholder-engagement process was started in June 2014 by the Ugandan Ministry of Water and Environment. Stakeholder workshops, following the restoration opportunities assessment methodology (IUCN and WRI 2014), were held in seven regions of Uganda. In each region, officials and stakeholders from local government, civil society, and the private sector were invited to workshops to build a common understanding of the restoration planning process, discuss their environmental and social challenges due to land degradation, and to determine what changes communities hope to achieve through restoration. Many of the stakeholders' stated goals were erosion control, climate change mitigation, and increased resilience of ecosystems to disturbances, such as disease and pest outbreaks.

Building on the stakeholder engagement process, we aimed to develop generalizable screening tools that would allow decision-makers to visualize the full range of optimal restoration scenarios and understand tradeoffs among different ecosystem services given resource constraints. Our approach was not intended to prescribe a single 'optimal' solution for restoration prioritization, but instead to deliver spatially-explicit information on multiple ecosystem services provided by restoration, identify districts most likely to deliver the greatest benefits for the lowest costs, and visualize tradeoffs between objectives. Our work contributes to growing demand for and development of multi-objective optimization tools for ecosystem service assessments (Seppelt *et al* 2013). These approaches are increasingly being applied to conservation planning worldwide (e.g. Nelson *et al* 2008, Polasky *et al* 2008, Babbar-Sebens *et al* 2013, Gaddis *et al* 2014, Cibin and Chaubey 2015), but have yet to be applied to national-scale FLR. Our work contributes to this growing literature on how to effectively map and prioritize investments in conservation or restoration designed to maximize the delivery of ecosystem services at large spatial scales, with limited data availability and a computationally efficient optimization algorithm. As more countries plan FLR strategies, these approaches are now being scaled worldwide to help decision-makers and stakeholders efficiently identify, target, and

**Table 1.** Mapping and modeling tools, parameters, and data sources used to evaluate each objective.

Objective	Indicator	Modeling tool	Parameters	Data sources
Climate change mitigation	Change in carbon storage	Quantile regression	Current carbon storage Climatic factors	Saatchi <i>et al</i> (2011) Hijmans <i>et al</i> (2005)
Improve water quality	Change in soil loss to stream network	InVEST SDR model	Land cover Digital elevation model Rainfall erosivity Soil erodibility Cover-management factor Support practice factor	Chen <i>et al</i> (2015) Lehner <i>et al</i> (2006) Vrieling <i>et al</i> (2014) FAO <i>et al</i> (2012) Yang <i>et al</i> (2003) Yang <i>et al</i> (2003)
Improve habitat for biodiversity	Species richness	GIS overlay analysis	Species distribution maps	IUCN (2014)
Minimize opportunity costs	Value of agricultural production	GIS raster algebra	Crop areas Crop yields, prices, and enterprise budgets	Monfreda <i>et al</i> (2008) Kraybill and Kidoido (2009)

allocate national and local resources for restoration. Here we present our methods for ecosystem services assessment and spatial optimization, describe their application in Uganda, and discuss challenges and opportunities associated with broader adoption and use of these methods in other contexts.

## 2. Methods

### 2.1. Mapping potential values of restoration

Based on stakeholder-identified ecosystem services of interest, we quantified and mapped the potential impact of FLR on carbon storage, soil loss to the stream network, species richness, and the value of crop production (table 1). Here, FLR is defined as the process of restoring the ecological functionality of a landscape to its state prior to degradation and reforestation (IUCN and WRI 2014). We assumed that restoration entails permanent, conservation-oriented forest cover where a restored parcel is entirely covered by trees.

We estimated potential above-ground carbon storage following the methods in Greve *et al* (2013). Using quantile regression, we predicted how a range of climatic factors influence the upper limit of biomass carbon storage for the Central and East African region (extent: 20 to 40°E and 9°N to 9°S) under conditions of no disturbance. We modeled the relationship between the upper bound (90% quantile) amount of actual forest carbon storage (Saatchi *et al* 2011) and mean annual temperature, temperature seasonality, annual precipitation, and precipitation seasonality (Hijmans *et al* 2005) using the *quantreg* package (Koenker 2009) in R version 3.1.1. We ran all possible 90% quantile regression models with three or four of the above predictor variables and their quadratics (48 models) and determined the AIC weight of each. The model with all four predictor variables and their quadratics had the highest AIC weight (AIC weight >0.999 99) and was used to predict potential carbon storage. We calculated the difference between

potential carbon storage and actual carbon storage (Saatchi *et al* 2011) to produce a map of the potential for restoration to increase carbon storage. We set any negative values for potential carbon storage to zero. Although soil quality and the underlying geology of soils in Uganda will likely affect tree growth and carbon storage potential (Oren *et al* 2001), particularly in severely degraded areas (Bolwig 2002), we did not consider these factors due to lack of available data for soil characteristics and geology in Uganda.

We estimated soil loss to the stream network using the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) Sediment Delivery Ratio (SDR) model version 3.2. InVEST is free and open-source, has relatively low data requirements, and is well suited for large spatial-scales (Sharp *et al* 2015). The SDR model calculates soil loss to the stream network on each pixel as the product of the revised universal soil loss equation and the proportion of soil lost that reaches the stream network. We estimated the potential benefit for restoration to improve water quality by calculating the difference in sediment loss to the stream network under a ‘current’ scenario, represented by a 2010 land cover map (Chen *et al* 2015), and a ‘restored’ scenario, represented by an entirely forested land cover map. We assumed climate and landscape factors, such as slope and hydrologic connectivity, were unchanged between scenarios.

We mapped species richness using species range maps that represent the known ranges of mammal, reptile, amphibian, and bird species’ populations (IUCN 2014). We assumed that restoration that occurs in locations with potentially high species richness also has a high potential to positively impact the presence and persistence of those species. To map species richness, we overlaid all of the range maps and counted the number of overlapping polygons that were at least partially within a given pixel.

Decision-makers in Uganda also requested information on the opportunity costs of restoration. For this model, we assumed that restoration and agricultural land uses are exclusive of each other and

estimated the opportunity costs according to the value of the annual average agricultural production of 21 crops. We defined the value of agricultural production on pixel  $i$  as,  $V_i = \sum_{j=1}^{21} A_{ij}(R_j - C_j)$ , where  $A_{ij}$  is the harvested area of crop  $j$  on pixel  $i$ ,  $R_j$  is the annual revenue of crop  $j$ , and  $C_j$  is the annual production costs of crop  $j$ . We assumed that annual revenue and production costs are spatially homogeneous which is why the subscript denoting pixels,  $i$ , is absent from these terms in the equation. The annual revenue of crop  $j$  is the product of crop yield and crop price. The annual costs of producing crop  $j$  were calculated using an enterprise budget approach which estimates the costs of crop production as a function of variable costs including household labor, hired labor, cost of material inputs (e.g. seeds and fertilizer), and the cost of employing mechanized equipment to assist with site preparation and harvesting. We applied this method using gridded crop-specific harvested area data at a  $\sim 10$  km resolution to represent  $A_{ij}$  (Monfreda *et al* 2008) and crop-specific national averages for crop yields, prices, and enterprise budgets (Kraybill and Kidoido 2009).

## 2.2. Identifying opportunities for FLR

We identified potential opportunities for FLR based on where forest cover was lost between 2000 and 2013 using the Hansen *et al* (2013) Global Forest Change dataset. While this dataset likely underestimates all the potential areas available for restoration, there currently is no published dataset that adequately maps FLR opportunities within Uganda or globally that accounts for forest lost prior to 2000 (Veldman *et al* 2015). Despite the underestimation of this dataset, we assumed for this exercise that Uganda only has sufficient resources to restore 50% of all land identified as restoration opportunities.

## 2.3. Optimizing restoration for multiple objectives

We used a multi-objective spatial optimization approach to construct efficiency frontiers that illustrate the tradeoffs between different objectives and identify the districts that have the potential to deliver the greatest benefits from restoration. The efficiency frontiers represent a set of spatially-explicit optimal restoration scenarios where returns to one objective cannot be increased without diminishing returns to another objective. We defined the objective function to maximize the value of benefits from carbon storage, water quality, and biodiversity, and minimize opportunity costs by allocating the optimal amount of land for restoration within each district. In the absence of *a priori* weights for each objective, we generated efficiency frontiers between two objectives by continuously varying weights on each objective from 100% on one objective to 100% on the other objective over 10 000 optimization iterations, thus allowing decision-makers to visualize the tradeoffs associated with a full range of preferences. For a given weight  $w_o$  on each

objective  $o$ , the value of restoration on each pixel  $p$  on a raster grid is  $v_{wp} = \sum_o w_o v_{op}$ . We only considered the value of restoration on pixels that were identified as opportunity areas for restoration. To allocate area for restoration within each district, we sorted the  $v_{wp}$  values in descending order to fit a benefit-area curve to the cumulative value with a quadratic function. The fit curves for each district,  $f_{wd}(x_d)$ , give the weighted value of benefits expected from district  $d$  under weights  $w$  when  $x_d$  area is restored. We used a convex optimization algorithm in the CVXOPT package in Python 2.7 to allocate restoration area among decision-units (Andersen *et al* 2015). The objective function to maximize the total potential benefits across all districts was

$$\max_x \sum_d f_{wd}(x_d).$$

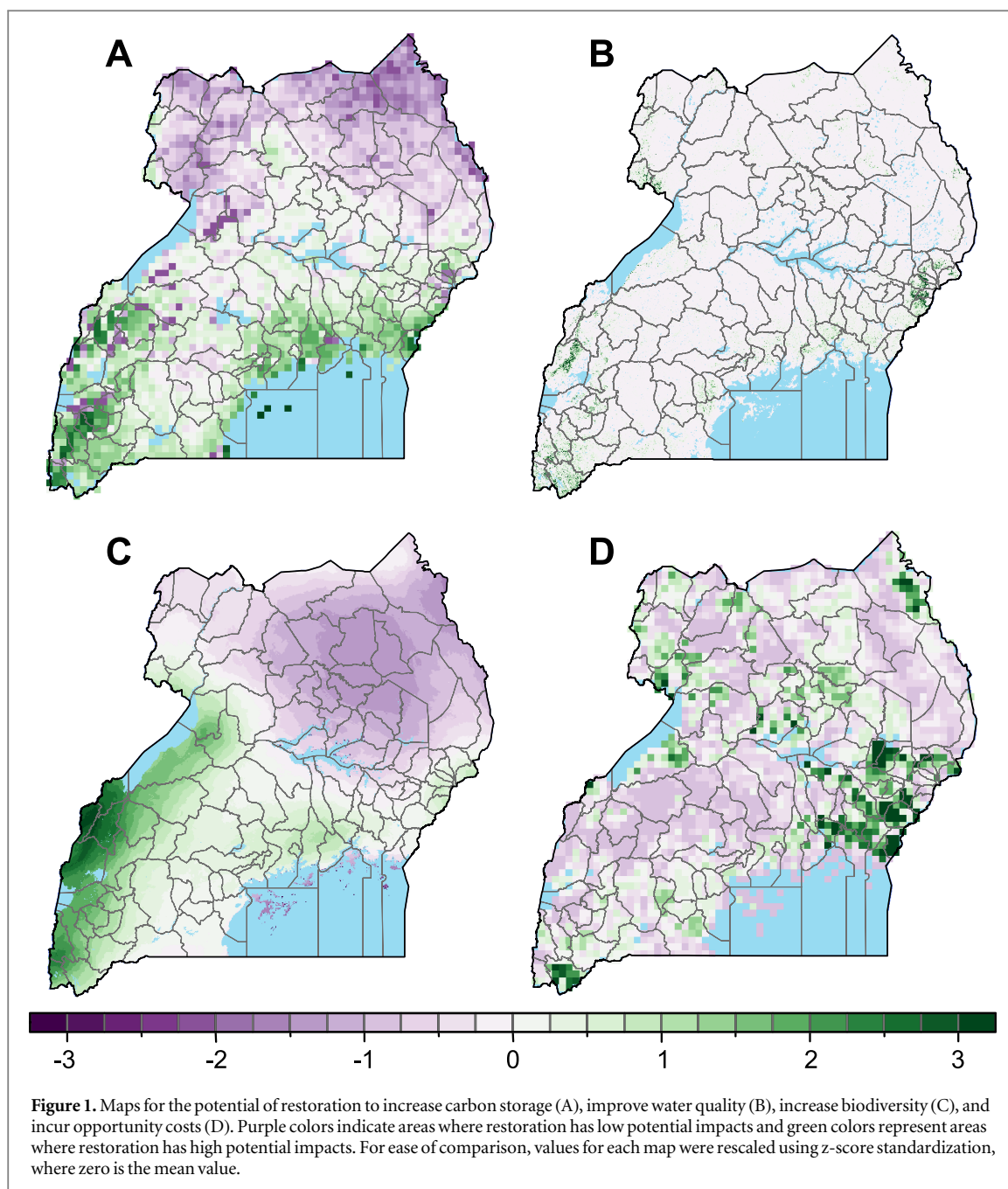
Assuming resource constraints limit the total amount of area available for restoration, we set  $x_d$  equal to 50% of restoration opportunities. We generated frontiers with each possible pair of objectives. While it is possible to optimize for more than two objectives using this approach, it is difficult to visualize tradeoffs using efficiency frontiers with more than two dimensions without *a priori* weights for each objective (Lautenbach *et al* 2013). A more detailed explanation of these methods is included in the Supplemental Materials.

## 2.4. Comparing optimal and non-targeted scenarios

We compared the outputs of the multi-objective optimization scenarios with a non-targeted scenario for restoration planning. The non-targeted scenario represents an approach where an equal proportion of available restoration opportunities within each district are randomly restored, without considering the pixels or districts with the highest potential benefits. We estimated the benefits of restoration within each district under the non-targeted scenarios as the product of the proportion of restored restoration opportunities (50%), the total area of restoration opportunities within each district, and the mean benefit from restoration for restoration opportunities within each district.

## 3. Results

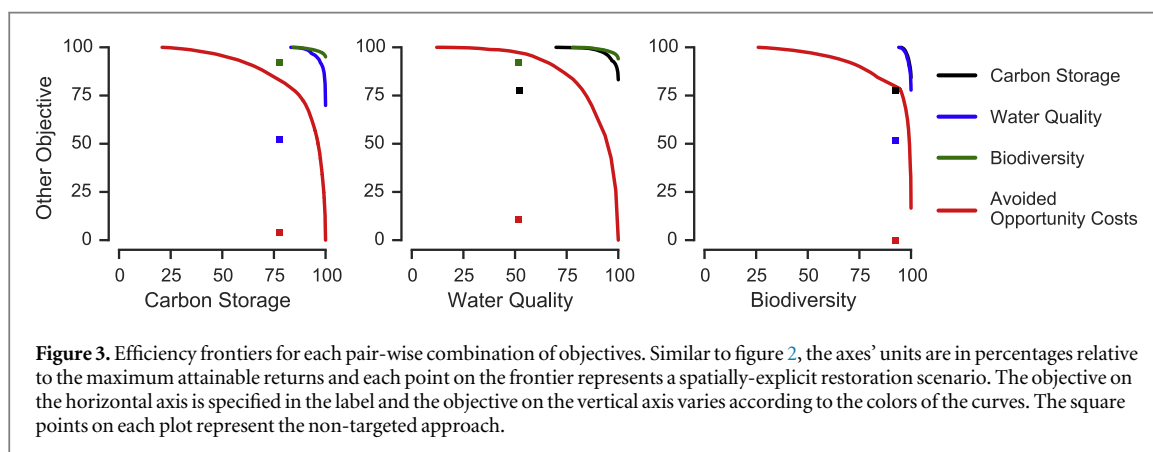
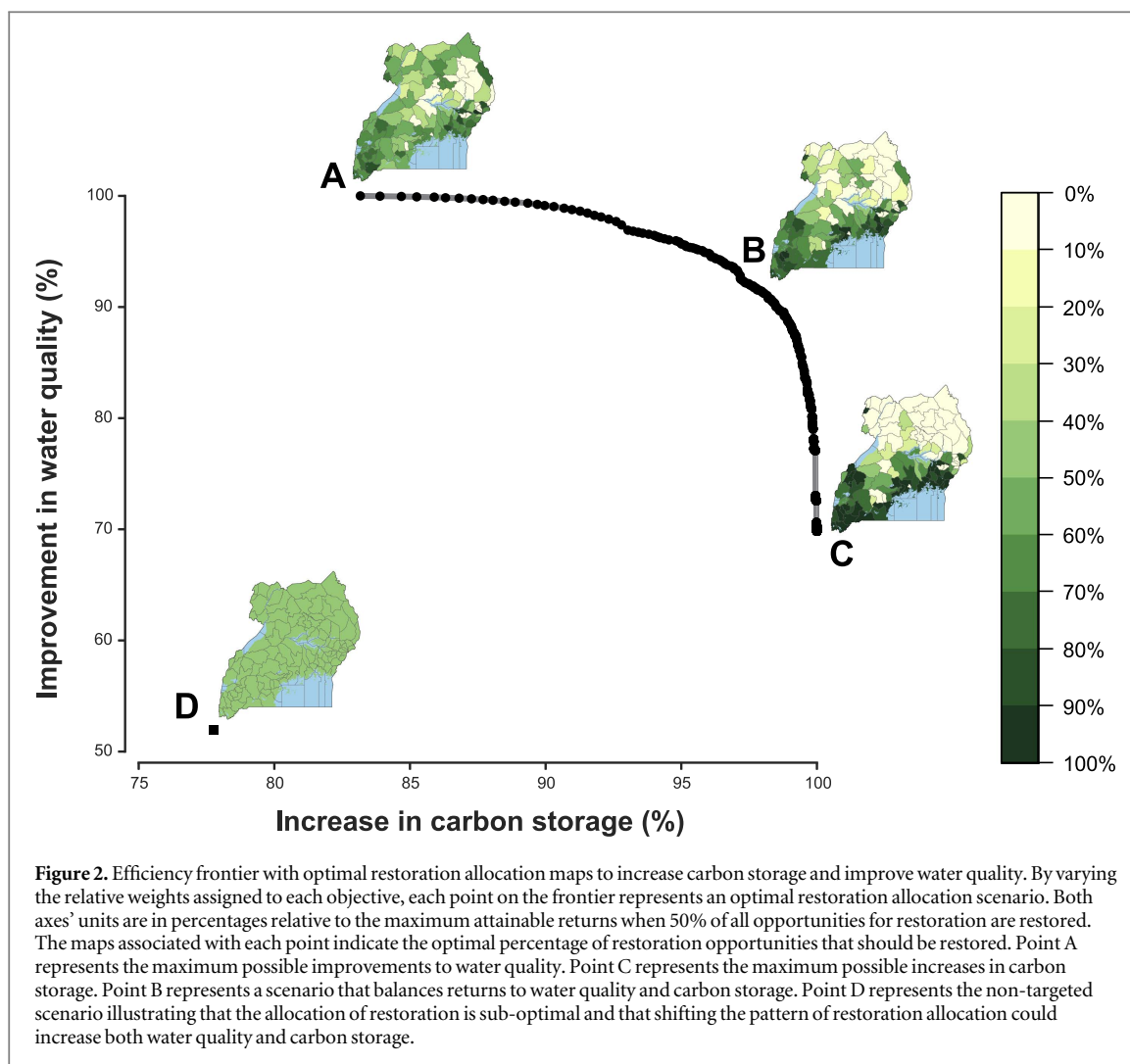
The potential values of restoration, defined by each of the four objectives, varied across the study area (figure 1). Regions of Uganda with more severe degradation, relatively higher mean temperatures and annual precipitation, and less seasonality have greater potential to increase carbon storage if restored to forest. The highest value parcels for improving water quality are those that are close to the stream network, have steep slopes, and have large upslope contributing areas. The combination of these factors results in a relatively small proportion of parcels with high relative



value for improving water quality. Restoration is more likely to benefit biodiversity in the western and south-east regions, where there is a high concentration of overlapping species distributions. The opportunity costs of restoration are greatest in the eastern and southern regions, where agricultural production is high. These trends demonstrate that restoration in a particular region of the country may not provide the same relative benefits to each objective.

We identified the range of optimal restoration scenarios using efficiency frontiers (figure 2). Points on the frontier represent optimal restoration allocation scenarios, whereas points under the frontier indicate the sub-optimal non-targeted scenario, where values for both objectives can be increased with no additional cost. Depending on how the objectives are weighted

relative to each other, the optimal amount of land allocated for restoration within each district shifts to different regions of the country. For example, if the goal of restoration is to maximize increases in carbon storage, decision-makers should allocate resources for restoration to the southeastern and southwestern districts (figure 2). However, if water quality were weighed more heavily than carbon storage, the priority districts for restoration would be more evenly distributed. Increasing carbon storage does not come at the cost of diminished water quality. Rather, depending on where restoration occurs, the total potential increases in carbon storage and water quality vary relative to each other. Highly degraded parcels with relatively higher mean temperatures and annual precipitation are most valuable to increasing carbon



storage, whereas parcels close to the stream network with steep slopes will be most valuable to improving water quality (Greve *et al* 2013, Hamel *et al* 2015).

Regardless of where restoration occurs, we found that restoration will enhance carbon storage, water quality, and biodiversity. However, different districts provide greater relative benefits to one objective than other objectives, so the exact ratio of benefits relative to each other depends on the location of restoration

(figure 3). For example, due to the large number of parcels with relatively high value for both carbon storage and biodiversity, it is possible to simultaneously achieve 83% of the maximum increase in carbon storage and 96% of the maximum increase in biodiversity. The tradeoffs between carbon storage, water quality, and biodiversity are relatively minimal compared with their tradeoffs with the opportunity costs. Under our assumption that restoration and

agricultural production are mutually exclusive, the optimal scenario for minimizing opportunity costs will entail forgoing FLR, resulting in very low returns to the other benefits of restoration. Moreover, the shape of the efficiency frontiers (figure 3) depends on the spatial patterns and distribution of restoration values (figure 1). Because carbon storage and biodiversity have a large proportion of high value pixels compared to water quality, the returns to these objectives remain relatively constant as weights are shifted towards another objective. We also show that the optimization approach provides a substantial value over the non-targeted scenario (figure 3).

#### 4. Discussion

Our work added value to the restoration planning processes in Uganda by communicating how the potential benefits and tradeoffs of restoration vary spatially. Our use of efficiency frontiers enabled decision-makers to visualize tradeoffs that may affect where investments in restoration should be targeted. These efficiency frontiers do not prescribe a particular restoration strategy, but rather illustrate the full range of optimal restoration scenarios depending on the relative weights placed on each objective.

Our results were presented to the Ugandan government and other stakeholders as part of their national FLR assessment and planning process. The communication of our analysis, consideration of several ecological and sociopolitical factors (e.g. severity of forest degradation, district-level governance), and the resulting policy discussions have led to a preliminary identification of priority districts for restoration. The final restoration assessment by the Ugandan government is forthcoming, but preliminary results from the government planning process identify districts that overlap with those identified here and those selected by stakeholders. By communicating the potential benefits and tradeoffs of restoration scenarios using accessible visual aides, our analysis underscores the value of salient, credible, and legitimate ecosystem service information in decision-making (Posner *et al* 2016).

While ecosystem service modeling and spatial optimization provide important information for restoration planning, it is critical that these approaches are embedded within local co-development and participatory processes. The set of objectives that we optimized for were easily quantifiable, however there are other considerations for restoration that are more complex and less easily modeled using the tools we presented. Our analysis is therefore simply one of many inputs that are required for developing an efficient and equitable national-scale FLR assessment. There are also several areas of new research that could enhance our approach. These include: (1) collection of more recent, higher resolution, and locally-specific

datasets for forest loss and degradation, forest composition, and other model parameters, (2) development and application of models that account for beneficiaries of restoration, temporal variation and spatial dependencies in the potential value of restoration, local biodiversity dynamics, management factors that affect carbon storage, and multifunctional agricultural landscapes, such as agroforestry or silvopasture, and (3) consideration of indirect impacts of restoration, such as displacement of forest loss to other unprotected regions.

As dozens of other countries engage in FLR planning, decision-makers require actionable information to guide investments. Our approach provides a generalizable framework for FLR planning that can be applied to other countries that have committed to the Bonn Challenge and complements existing restoration planning methodologies (IUCN and WRI 2014). For many countries, availability of recent high-resolution data is often sparse and modeling capacity is limited. Although similar approaches have been used in other conservation planning decision-contexts, this framework has relatively low data requirements, is computationally efficient, and is agnostic to the objectives for restoration.

Improving human well-being, mitigating climate change, and protecting biodiversity are all central challenges to both conservation and development. The Bonn Challenge provides a global mechanism to address these challenges. However, there is still the opportunity to better incorporate ecosystem service information into policy and management decisions. Here, we demonstrated a method for integrating ecosystem service information into a national-level FLR assessment. The knowledge gained from implementing these methods is practical and can improve the potential benefits of restoration. In addition to informing FLR planning, this information can also be used to attract private investments in financing restoration, encourage other countries to commit to the Bonn Challenge, and design payments for ecosystem services (PES) schemes (Guerry *et al* 2015).

#### Acknowledgments

This work was funded by UKAid from the UK government through the International Union for Conservation of Nature's KnowFor program. Additional financial and institutional support was provided by the Natural Capital Project, a partnership between the University of Minnesota, Stanford University, the World Wildlife Fund, and the Nature Conservancy. MG was supported by the National Research Foundation of South Africa (Grant Number 98889). The authors declare no conflicts of interest.



## References

- Andersen M, Dahl J and Vandenberghe L 2015 CVXOPT: Python software for convex optimization, version 1.1.7 (<https://pypi.python.org/pypi/cvxopt/>) (Accessed: 28 April 2015)
- Babbar-Sebens M, Barr R C, Tedesco L P and Anderson M 2013 Spatial identification and optimization of upland wetlands in agricultural watersheds *Ecol. Eng.* **52** 130–42
- Balthazar V, Vanacker V, Molina A and Lambin E F 2015 Impacts of forest cover change on ecosystem services in high Andean mountains *Ecol. Indicator* **48** 63–75
- Bolwig S 2002 *Land Use Change and Soil Degradation in the Southwestern Highlands of Uganda* (Washington DC: The International Food Policy Research Institute)
- Bonn Challenge 2016 <http://bonnchallenge.org/> (Accessed: 24 August 2016)
- Chazdon R L 2008 Beyond deforestation: restoring forests and ecosystem services on degraded lands *Science* **320** 1458–60
- Chen J, Chen J, Liao A, Cao X, Chen L, Chen X, He C, Han G, Peng S and Lu M 2015 Global land cover mapping at 30 m resolution: a POK-based operational approach *ISPRS J. Photogramm. Remote Sens.* **103** 7–27
- Cibin R and Chaubey I 2015 A computationally efficient approach for watershed scale spatial optimization *Environ. Modelling Softw.* **66** 1–11
- FAO, IIASA, ISRIC, ISSCAS, and JRC 2012 *Harmonized World Soil Database (version 1.2)* (Italy: FAO)
- Foley J A, DeFries R, Asner G P, Barford C, Bonan G, Carpenter S R, Chapin F S, Coe M T, Daily G C and Gibbs H K 2005 Global consequences of land use *Science* **309** 570–4
- Gaddis E J B, Voinov A, Seppelt R and Rizzo D M 2014 Spatial optimization of best management practices to attain water quality targets *Water Resour. Manage.* **28** 1485–99
- Gibbs H K, Ruesch A, Achard F, Clayton M, Holmgren P, Ramankutty N and Foley J 2010 Tropical forests were the primary sources of new agricultural land in the 1980s and 1990s *Proc. Natl Acad. Sci.* **107** 16732–7
- Greve M, Reyers B, Lykke A M and Svenning J 2013 Spatial optimization of carbon-stocking projects across Africa integrating stocking potential with co-benefits and feasibility *Nat. Commun.* **4** 1–9
- Guerry A D, Polasky S, Lubchenco J, Chaplin-Kramer R, Daily G C, Griffin R, Ruckelshaus M, Bateman I J, Duraipappah A and Elmqvist T 2015 Natural capital and ecosystem services informing decisions: from promise to practice *Proc. Natl Acad. Sci.* **112** 7348–55
- Hamel P, Chaplin-Kramer R, Sim S and Mueller C 2015 A new approach to modeling the sediment retention service (InVEST 3.0): case study of the Cape Fear catchment, North Carolina, USA *Sci. Total Environ.* **524–525** 166–77
- Hansen M C, Potapov P V, Moore R, Hancher M, Turubanova S, Tyukavina A, Thau D, Stehman S, Goetz S and Loveland T 2013 High-resolution global maps of 21st-century forest cover change *Science* **342** 850–3
- Hijmans R J, Cameron S E, Parra J L, Jones P G and Jarvis A 2005 Very high resolution interpolated climate surfaces for global land areas *Int. J. Climatol.* **25** 1965–78
- IUCN 2014 The IUCN Red List of Threatened Species, version 2014.1 (<http://iucnredlist.org>) (Accessed: 22 April 2015)
- IUCN and WRI 2014 *A Guide to the Restoration Opportunities Assessment Methodology (ROAM): Assessing Forest Landscape Restoration at the National or Sub-National Level* (Gland)
- Koenker R 2009 quantreg: quantile regression R package version 5.19 (<https://cran.r-project.org/web/packages/quantreg/index.html>) (Accessed: 14 February 2016)
- Kraybill D and Kidoido M 2009 Analysis of relative profitability of key Ugandan agricultural enterprises by agricultural zone
- Uganda Strategy Support Program (Washington, DC: International Food Policy Research Institute)
- Lamb D, Erskine P D and Parrotta J A 2005 Restoration of degraded tropical forest landscapes *Science* **310** 1628–32
- Lautenbach S, Volk M, Strauch M, Whittaker G and Seppelt R 2013 Optimization-based trade-off analysis of biodiesel crop production for managing an agricultural catchment *Environ. Modelling Softw.* **48** 98–112
- Lehner B, Verdin K and Jarvis A 2006 *HydroSHEDS Technical Documentation* (Washington, DC: World Wildlife Fund US)
- Millennium Ecosystem Assessment (MEA) 2005 *Ecosystems and Human Well-Being. Millennium Ecosystem Assessment* (Washington, DC: Island Press)
- Monfreda C, Ramankutty N and Foley J A 2008 Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000 *Glob. Biogeochem. Cycles* **22** 1–19
- Nelson E, Polasky S, Lewis D J, Plantinga A J, Lonsdorf E, White D, Bael D and Lawler J J 2008 Efficiency of incentives to jointly increase carbon sequestration and species conservation on a landscape *Proc. Natl Acad. Sci.* **105** 9471–6
- Obua J, Agea J G and Ogwai J J 2010 Status of forests in Uganda *Afr. J. Ecol.* **48** 853–9
- Oren R *et al* 2001 Soil fertility limits carbon sequestration by forest ecosystems in a CO<sub>2</sub>-enriched atmosphere *Nature* **411** 469–72
- Polasky S, Nelson E, Camm J, Csuti B, Fackler P, Lonsdorf E, Montgomery C, White D, Arthur J and Garber-Yonts B 2008 Where to put things? Spatial land management to sustain biodiversity and economic returns *Biol. Conservation* **141** 1505–24
- Posner S M, McKenzie E and Ricketts T H 2016 Policy impacts of ecosystem services knowledge *Proc. Natl Acad. Sci.* **113** 1760–5
- Ramankutty N and Foley J A 1999 Estimating historical changes in global land cover: croplands from 1700 to 1992 *Glob. Biogeochem. Cycles* **13** 997–1027
- Saatchi S S, Harris N L, Brown S, Lefsky M, Mitchard E T, Salas W, Zutta B R, Buermann W, Lewis S L and Hagen S 2011 Benchmark map of forest carbon stocks in tropical regions across three continents *Proc. Natl Acad. Sci.* **108** 9899–904
- Seppelt R, Lautenbach S and Volk M 2013 Identifying trade-offs between ecosystem services, land use, and biodiversity: a plea for combining scenario analysis and optimization on different spatial scales *Curr. Opin. Environ. Sustainability* **5** 458–63
- Sharp R 2015 InVEST 3.2 User's Guide (<http://data.naturalcapitalproject.org/nightly-build/invest-users-guide/html/>) (Accessed: 7 December 2015)
- TEEB Foundations 2010 *The Economics of Ecosystems and Biodiversity: Ecological and Economic Foundations* (London and Washington: Earthscan)
- Uganda National Planning Authority (NPA) 2007 Uganda Vision 2040 (<http://npa.ug/uganda-vision-2040/>) (Accessed: 2 December 2015)
- Veldman J W, Overbeck G E, Negreiros D, Mahy G, Le Stradic S, Fernandes G W, Durigan G, Buisson E, Putz F E and Bond W J 2015 Where tree planting and forest expansion are bad for biodiversity and ecosystem services *Bioscience* **65** 1–8
- Vrieling A, Hoedjes J C and van der Velde M 2014 Towards large-scale monitoring of soil erosion in Africa: accounting for the dynamics of rainfall erosivity *Glob. Planet. Change* **115** 33–43
- Yang D, Kanae S, Oki T, Koike T and Musiak K 2003 Global potential soil erosion with reference to land use and climate changes *Hydrol. Process.* **17** 2913–28