

SUPPLEMENTAL MATERIALS

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

Jesse D Gourevitch, Peter L Hawthorne, Bonnie L Keeler, Craig R Beatty, Michelle Greve, and Michael A Verdone

Optimizing restoration for multiple objectives

Landscapes have the potential to provide multiple beneficial services, ranging from crop production to carbon storage to habitat for biodiversity. When landscapes are degraded, their ability to provide these services declines. Restoration offers an opportunity to enhance the potential for lands to support biodiversity and ecosystem services. How can decision-makers and planners best target restoration to areas that are most likely to deliver the greatest benefits to biodiversity and ecosystem services? What are the tradeoffs among these potential restoration benefits?

The Restoration Opportunities Optimization Tool (ROOT) is designed to help answer these questions. The tool is motivated by three assumptions:

- 1) Landscapes vary spatially in their potential to provide ecosystem services. Some regions are better suited for biodiversity protection, whereas restoration in other regions is more likely to deliver water quality benefits to downstream communities.
- 2) Landscapes provide multiple benefits or services. Different users may emphasize different services, but most users expect landscapes to provide a suite of benefits.
- 3) Restoration involves tradeoffs. Restoration may generate multiple services, but there will also be tradeoffs among services. For example, a restoration strategy designed to minimize soil loss will be different than a strategy designed to maximize habitat protection for biodiversity.

ROOT can be downloaded from here:

<http://forums.naturalcapitalproject.org/index.php?p=/discussion/833/restoration-opportunities-optimization-tool-root-release>

The objective of ROOT is to illuminate the tradeoffs inherent in prioritizing areas for landscape restoration. The tool is designed to be flexible and customizable - users upload their own data including service maps and restoration opportunities. ROOT provides an interface to visualize service maps and explore tradeoffs in terms of the potential benefits of restoration based on different service objectives (carbon, water, biodiversity). Finally, the tool also allows users to generate optimal restoration strategies based on defined objectives and constraints.

The outcomes of ROOT are:

- 1) Service maps representing how alternative restoration strategies would affect the provision of multiple ecosystem services.
- 2) Tradeoff curves depicting the relationship between two alternative restoration objectives to assist users in identifying their optimal restoration strategy.
- 3) Restoration portfolios that identify optimal restoration strategies based on user-defined weights and constraints.

ROOT Inputs

To take full advantage of the functionality of ROOT, users should have completed the following tasks:

- 1) Generate service maps for their area of interest. ROOT does not generate ecosystem service maps. Rather, ROOT uses user-defined maps of multiple services to assess tradeoffs and generate optimal scenarios. The service maps represent “scores” assigned to each pixel on the target landscape that reflect their potential to provide a given service. These maps can be in biophysical units (e.g. kg of pollutant) or indices (e.g. 0-1). For more information about ways to create service maps using open source ecosystem services models (e.g. InVEST) or other free global data resources see Data Sources section.
- 2) Identify and map restoration opportunities. ROOT assumes that the user has already identified a set of potential restoration opportunities. These opportunities may be parcels of degraded or deforested land identified through land use change mapping exercises or remote sensing (see Data Sources section), or they could be parcels or plots identified by stakeholders. In ROOT, this layer is called the “opportunity map” and it acts as a constraint or mask on the landscape such that only lands identified as opportunities will be considered by the model as available for restoration.
- 3) Select an aggregation or decision unit for prioritizing restoration. ROOT is best suited for regional or national scale analyses where a user is identifying sub-regions to prioritize for restoration. The model requires a layer identifying the parcels or sub-regions (“parcel map”) for which restoration prioritization decisions will be made. For example, a user may upload service maps for an entire country, including a map of all of the degraded lands (“opportunity map”). However, the user is most interested in identifying which districts or watersheds across the country are the highest priority areas for restoration (based on their potential to provide valuable ecosystem services). The parcel map defines the boundaries of these districts or watersheds.

If you have more than one service map, an opportunity map, and a parcel map then you are ready to run ROOT.

ROOT Outputs

At the core of ROOT is an optimization algorithm that identifies the parcels that are most likely to deliver the greatest benefits under restoration. The model selects parcels based on the scores for each “opportunity” within each parcel, where the scores are given by the values in the service maps. Each run of the model can consider two different services. For example, one run could compare a restoration strategy for biodiversity vs. a strategy for improved water quality. The tool outputs maps that reflect the amount of land within each parcel that should be allocated to restoration under each objective. The user can explore how the restoration strategy changes as the relative weights on each objective shift.

The user can also explore how the restoration strategy changes with a defined constraint. For example, the user can set a target or limit on the amount of land available for restoration. The tool will output the restoration strategy and impacts to services based on the optimal solution for each defined constraint.

ROOT Workflow

ROOT is designed to be interactive and iterative; therefore there is no single correct workflow to follow when running the tool. That said, there are four main elements to the ROOT workflow:

- 1) Loading data
- 2) Selecting variables
- 3) Exploring curves
- 4) Viewing and exporting data

Here we describe a hypothetical ROOT user and walk through how they would interact with these four elements of the ROOT workflow:

Marta works for the Ministry of Planning in Uganda. She has been tasked with developing a restoration plan for the country informed by national targets for reforestation and participatory processes driven by local stakeholders. Marta has assembled spatial data on the three restoration benefits of greatest interest to the government and stakeholders - water quality, biodiversity protection, and carbon sequestration. The next step in the restoration planning process is to identify which Ugandan districts should be prioritized for further investments in data collection and fundraising for restoration. The country has limited resources, so future work must target areas with the greatest restoration opportunities and the greatest likelihood of delivering the services of interest.

Service maps: Water quality, Biodiversity, Carbon storage

Opportunity map: Known areas of deforestation

Parcel map: Map of the districts of Uganda

Loading data: *Marta will start by loading her data into ROAM, naming each service map, and clicking “process data”. All further runs will be based on these data layers and maps.*

The Files Tab is where the user specifies and uploads data. There are three types of files the user provides: Service Maps, a Parcel Map, and an Opportunity Map. Clicking the ‘Browse’ button in any section will open a dialog to select maps to add.

- a. Service Maps (at least two required). Must be GeoTIFF (.tif) files. These layers define the objectives for the optimization. Since the optimization assumes the decision-context has multiple objectives, at least two services map are required. There is no constraint on the maximum number of service maps, but each service map must be given a unique name. Each pixel value represents a “score” for each service or objective that represents the potential benefits obtained if restoration occurs in that particular location. For example, the per pixel values in a water quality service map would represent the potential for that pixel to provide water quality benefits (relative to other pixels). Higher values represent higher potential future benefits under restoration. For more information on creating service maps, see Data Sources section. Service Maps can be given a title after they are loaded that will be used to identify them in the analyses.
- b. Parcel Map (required). Must be a shapefile (.shp). This is a layer that delineates the spatial areas that are used as decision units. The optimizer will assign restoration area to each decision unit based on the values of the service maps the unit contains. The shapefile must have a field named ‘PARCEL_ID’ that distinguishes the parcels. It is not required that parcels are contiguous, but each feature must have an integer ‘PARCEL_ID’ value that is greater than or equal to zero.
- c. Opportunity Map (required). Must be a GeoTIFF (.tif). This layer helps define decision scenarios by allowing the user to restrict the optimization to particular subregions of each decision unit. Pixels with zero or no data values in the Opportunity Map will be ignored in the Service Maps by the optimizer so that the decisions will reflect only available restoration opportunities.
- d. Setting the Reference Raster (required): Before proceeding, the user may select which of the input rasters to use as the reference. In the analysis, the Parcel Map and other service rasters will be automatically aligned and converted to the same resolution as the selected raster. All rasters will be cropped or extended to match the extent of the Parcel Map. To do this, click the ‘A’ near

the upper right and select a raster from the pop-up. The first raster loaded is selected by default if the user skips making a manual selection.

- e. Process Maps: After the desired data is loaded, the user clicks the “Process Maps” button at the bottom of the Files Inspector. The application then aligns all the spatial data and performs some initial computations to speed up the rest of processing. If other data is added later, the user must click the Process button again to deal with the new data. The processed versions are saved to folders titled ‘Intermediate’ in the directories containing the original files.

Selecting variables: *Marta is first interested in comparing the carbon sequestration and biodiversity benefits of restoration. She selects these services from the library and drags them to the X and Y axes. Marta knows that the government has set a target of 100,000 hectares of restoration. She converts this into pixels (based on the size of base raster), enters this value into the constraints box, and clicks “run”.*

Configuring and executing runs of the optimizer is done from the variables tab. In this tab, the user will create a number of different runs, assign the objectives for each optimization, set constraints, and run the model.

Basic setup: The simplest way to use the optimizer is to pick two services from the Library section, drag one to the X axis section and one to the Y Axis section, and hit Run. This will generate a trade-off curve showing how potential restoration could be placed in ways that generate different mixes of the two services. Note that the default upon opening the Variables Tab after processing data sets the restoration area to $\frac{1}{2}$ of the land area listed as an opportunity in the Opportunity Map. Changing the value in the area constraint and then hitting Run will generate results with different amounts of restoration, and hence different benefits and trade-offs.

Create and rename runs: When the user opens the variables tab, the first run (Run 1) will be automatically created. Create additional runs by clicking the ‘+’ in the Runs bar. The user can rename a run by double-clicking on its name in the Runs list. Each run has its own configuration of objectives and constraints, allowing the user to explore different trade-offs. When a run is created, services the user provided data for in the Files tab will appear in the Library tab. Click and drag the name of a service to assign it to a trade-off curve axis (as an objective in the optimization) or to the constraints.

More than one service per axis: It is possible to have more than one service assigned to an axis. In this case, each service must be given a weight. These weights are used to aggregate the two listed services together as a composite objective. The services will be normalized before these weights are applied, so the weights should reflect relative importance, and not differences in units or general orders of magnitude.

Setting constraints: Constraints allow the user to add additional requirements on the optimization solutions. The user must provide an area constraint, which specifies the desired reforestation area. The default value is 50% of available area, that is, area indicated as the opportunity map as available for restoration. The total maximum restoration opportunity area is shown. Constraints must be written in a particular fashion. The first character must be >, =, or <, followed by the numerical value of the constraint. The optimizer will ensure that solutions meet these constraints. Note that it is possible for the user to specify mutually incompatible constraints, in which case the optimization will fail. The program will attempt to provide a helpful message in this case, but the user will need to experiment with different values in order to find potential compromises. Finally, note that a service may be an objective or a constraint, but not both.

Running the optimization: Once the run is configured, click the run button at the bottom of the Variables tab to execute the run. The run button will be inactive until the run configuration is valid. In some cases the run may take a long time to complete.

Exploring curves: Marta navigates to the “curve” tab to explore the tradeoff frontier between carbon and biodiversity. Each point on the curve represents one possible scenario of restoration based on the defined constraint and underlying opportunity map. Marta clicks on a point near the right-hand side of the X axis, labeled “carbon sequestration”. This point represents a restoration strategy that prioritizes carbon at the expense of biodiversity. The map to the left displays the allocation of restoration in each district based on this “carbon priority” strategy. The color of each district represents how much land should be restored in each district to achieve the best outcome for carbon.

Now Marta clicks on the point at the far upper left of the plot. This point represents a restoration scenario that maximizes biodiversity protection. She notes that the allocation of restoration land in the map on the left changes - different districts emerge as being higher priority for restoration under a “biodiversity priority” strategy.

Finally Marta clicks on a point on the curve that is in the middle of the plot. This point represents a restoration strategy that seeks to maximize both carbon and biodiversity. Marta now returns to the “Variables” tab to set up a second run where she will compare the biodiversity and water quality services.

The curve tab allows the user to navigate the solutions found by the optimizer along the trade-off curve and control which points are selected for views. The plot in the top right shows the estimated service gains from each optimized restoration allocation. The points are arranged to show the trade-offs between the services on the X and Y axes. At one end of the curve, the solutions highly favor the services on axis, and at the other end of the curve, they favor the other objectives. In the figure shown, the upper-left-most points maximized biodiversity, while the lower-right points maximized carbon sequestration.

Selecting single solutions: The user can select points by clicking them on the curve, which highlights the appropriate row in the table below, or by clicking on a row in the table, which highlights the point on the curve. Either way will update the view on the left to show data associated with the selected solution.

Creating and customizing views: Views allow the user to see how the restoration area was allocated between the decision parcels for each point on the curve, or what service improvements this allocation leads to. One view is open by default, but extra views can be created by clicking the ‘+’ in the view tab bar.

As mentioned above, the solution displayed on the map can be changed by selecting different points from the curve tab. The values displayed on the map can be changed using the dropdown menu. The different options are:

- a) Allocation - this displays the restoration area assigned to each decision unit for the selected solution
- b) Curve - this creates a view that replicates the curve from the curve tab
- c) Services - selecting a service name shows the total value of that service obtained in each decision unit. Note that this is represented as a sum of the values for individual pixels. For some services, the average may be more meaningful, but the user will need to perform these calculations after exporting the data.

Selecting multiple points: If multiple points are selected from the table in the Curve tab, the map will display the average values for the selected quantities.

Viewing and exporting data: *Marta has explored multiple combinations of services and their associated tradeoffs and maps. She has also shared the tool with colleagues to solicit their feedback on how to weigh different services. In the end, the team has decided on a strategy that places relatively equal weight on biodiversity and carbon. Marta selects this solution from the curve tab. She views the allocation map which shows how much land to restore in each district. On the export tab, Marta selects the allocation map to be exported as a shapefile so she can share the result with her colleagues and stakeholders. She also exports maps for each service that show the provision of each service under that allocation strategy.*

Saving and opening projects: The user can save a project and any executed runs to return to in a later session using the standard save and open commands.

Exporting solutions: Solutions can be exported as shapefiles (.shp) or as comma separated (.csv) for use in other applications. To export a particular solution, the user must create a view with that solution selected, then go to the export tab. Each currently open view is shown with a checkbox, preview, and filename box. The user must select the checkbox and provide a name for each file he or she wishes to export (leaving the file extension off the name). Next, the user clicks the Export button and chooses the location for the exports to be saved.

Potential Data Sources

As mentioned above, the tool does not require any specific data inputs. The user instead must define their decision objectives and input spatial layers that reflect the value of making a decision in a particular area.

This section is a compilation of globally-available data sources and suggestions about finding, compiling, and formatting data. It is not an exhaustive or prescriptive list. Although we strive to update this section regularly with new data sources and methods, users are encouraged to seek local data to improve the quality of model inputs and make relevant to the objectives of the decision-context.

In general, the [FAO GeoNetwork](#) can be a valuable data source for different GIS layers for users outside the United States.

Service Maps (GeoTIFF or shapefile)

InVEST Models

The InVEST software suite provides flexible and generalizable models to map and quantify multiple ecosystem services under different LULC scenarios. These models can be used as static indicators of ecosystem service provision under a current or baseline scenario or can detect marginal changes in ecosystem service values under future LULC scenarios.

More information on the InVEST models and the software download can be accessed here:

<http://www.naturalcapitalproject.org/models/models.html>

Carbon storage

Among ecosystem service mapping studies, climate regulation is the most commonly mapped service (Martinez-Harms and Balvanera 2012). There are several global carbon storage maps available at varying resolutions and encompassing different time periods. The InVEST carbon model can also be used to estimate carbon storage and sequestration across a landscape.

Free carbon storage data are available from:

- [Pantropical National Level Carbon Stock Dataset](#) (Baccini et al. 2012)
- [Benchmark map of forest carbon stocks in tropical regions](#) (Saatchi et al. 2011)
- [New IPCC Tier-1 Global Biomass Carbon Map for the year 2000](#) (Ruesch and Gibbs 2008)

Biodiversity

There are many metrics and models to quantify biodiversity and estimate changes in biodiversity under various scenarios. These range in complexity and data requirements. Here, we suggest globally-available data for distribution of species that can be used to derive species richness. This is a simple and generalizable method that provides a baseline for spatial variation in biodiversity.

Global biodiversity data are available from:

- [IUCN RedList](#)
- [BirdLife International](#) (must request access to data distribution)

These data sources provide vector-based maps of distributions for individual species. To create a map of species richness for a particular taxonomic group, an overlay analysis of intersecting polygons is suggested. This can be done using the `vectorize_datasets` function in PyGeoprocessing or for smaller datasets the 'Count Overlapping Polygons' toolbox in ArcGIS may be sufficient.

Terrain Indices

There are several terrain indices that provide proxies for prioritizing areas that contribute to surface water quality. Such indices are simpler than other hydrologic models, such as the InVEST water quality models or SWAT, and may be better suited to data-sparse decision-contexts or where land use land cover data is not available. The compound topographic index (CTI), for example, identifies areas that receive a disproportionate amount of runoff and therefore have a greater potential to improve water quality if restored. Calculation of the CTI only requires the input of a DEM and is estimated using the following formula:

$$W = \ln(A_s/\tan B)$$

where A_s is the upslope contributing area and B is the slope angle. The CTI identifies areas of a watershed that are more likely to become saturated and therefore contribute to runoff and pollutant loads (Moore et al. 1993). Restoration should be prioritized in areas with high values for CTI because these pixels are likely to have a disproportionate impact on water quality. There are other more complex terrain indices, many of which require soils datasets, such as saturated hydraulic conductivity (K_{sat}) and soil depth.

DEM data are available globally and at varying resolutions. Since terrain indices are sensitive to the resolution of the DEM, the appropriate resolution should be selected based on the decision-context and extent of the study area. It may also be necessary to remove sinks from the DEM to ensure correct hydrological routing. TauDEM or multiple passes of the ArcGIS 'Fill' tool have shown good results.

Global DEMs are available from:

- [HydroSHEDS](#)
- [Shuttle Radar Topography Mission](#)
- [ASTER](#)

Global soils data are available from:

- [Harmonized World Soil Database](#)

Opportunity Costs

Optimal investments in conservation require consideration of opportunity costs of conservation activities across the landscape. Opportunity costs of conservation can be mapped and quantified in several ways. Here, we suggest data sources to estimate net economic returns from agricultural production, a common foregone benefit of conservation. Estimating economic benefits of agriculture requires data on cropland area, crop yields, enterprise budgets, and crop prices. Cropland area and crop yield data are globally available, but enterprise budgets and crop prices must be derived from national or sub-national datasets.

Global data for potential opportunity costs data are available from:

- [International Food Policy Research Institute](#)
- [Global cropland](#) (Fritz et al. 2015)
- [Mapping the world's degraded lands](#) (Gibbs and Salmon 2015)
- [Cropland and pasture area in 2000](#) (Ramankutty et al. 2008)
- [Harvested area and yield for 175 crops](#) (Monfreda et al. 2008)
- [Global distribution of livestock](#) (Robinson et al. 2014)
- [Spatial Production Allocation Model](#) (You et al. 2014)
- [Global-scale mapping of economic benefits from agricultural lands](#) (Naidoo and Iwamura 2007)
- [LandScan](#)

Socioeconomic/Demographic Indices

Depending on the decision-context, socioeconomic and demographic indices may be a key component of the decision-making process. Quantifying and mapping demand for ecosystem services is often service-dependent and may contribute to more equitable and efficient allocation of resources. Population density maps are one simple metric that can be used as a proxy for demand for ecosystem services. Demographic and socioeconomic data can also be used to quantify exposure and vulnerability to changes in ecosystem services. Since beneficiaries and demand for ecosystem services are spatially heterogeneous and are often spatially segregated from supply of ecosystem services, it may be important to delineate spatial flows of services from provisioning areas to benefitting areas. The data suggested below may be used to quantifying demand for ecosystem services. Although globally-available, data are sparse in some regions and may require extensive processing.

Global demographic and socioeconomic data are available from:

- [TerraPop](#) (under development)
- [International Public Use Microdata Series, International](#)
- [Demographic and Health Surveys Program](#) (must request access to data distribution)
- [Gridded Population of the World](#)

Parcel Maps (Shapefile)

A parcel map that delineates spatial decision-units is required. The parcel map should be relevant to the decision-context and can be delineated with any polygon layer. For example, parcels can be defined as administrative or political boundaries or biophysically derived units, such as watersheds or other forms of servicesheds. Watersheds and other servicesheds can be generated from points of interest using the InVEST 'DelineateIt' tool. Depending on the spatial heterogeneity among objectives, the optimization may be sensitive to the configuration of the parcel map.

Global administrative and watershed boundary data are available from:

- [FAO Global Administrative Unit Layers \(GAUL\)](#)
- [GADM database of Global Administrative Areas](#)

- [HydroSHEDS](#)

Opportunity Maps (GeoTIFF or shapefile) - optional

The opportunity map masks out areas of the parcel map that are potential locations for implementation of a decision. Depending on the decision-context and source of the opportunity map, it may be more logical to delineate opportunities as polygons or pixels in a raster. In either case, any the input opportunity map will be converted to a binary classification, where one is a location of an opportunity and zero is a location that will not be considered by the optimization. Examples of opportunity maps include degraded or deforested lands, protected areas, cropland, pasture, or high-risk areas.

Global data for potential opportunity maps are available from:

- [Global Forest Change 2000 – 2013](#) (Hansen et al. 2013)
- [World Database on Protected Areas](#)
- [Global cropland](#) (Fritz et al. 2015)
- [Mapping the world's degraded lands](#) (Gibbs and Salmon 2015)
- [Cropland and pasture area in 2000](#) (Ramankutty et al. 2008)
- [Harvested area and yield for 175 crops](#) (Monfreda et al. 2008)
- [Global distribution of livestock](#) (Robinson et al. 2014)
- [Spatial Production Allocation Model](#) (You et al. 2014)

References

- Baccini A, Goetz S J, Walker W S, Laporte N T, Sun M, Sulla-Menashe D, Hackler J, Beck P S A, Dubayah R, Friedl M A, Samanta S and Houghton R A 2012 Estimated carbon dioxide emissions from tropical deforestation improved by carbon-density maps *Nature Climate Change* **2** 182-185
- Fritz S, See L, McCallum I, You L, Bun A, Moltchanova E, Duerauer M, Albrecht F, Schill C and Perger C 2015 Mapping global cropland and field size *Global Change Biology* **21** 1980-1992
- Gessler P E, Moore I, McKenzie N and Ryan P 1995 Soil-landscape modelling and spatial prediction of soil attributes *International Journal of Geographical Information Systems* **9** 421-432
- Gibbs H and Salmon J 2015. Mapping the world's degraded lands *Applied Geography* **57** 12-21
- 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** 850-853
- 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 *Global Biogeochemical Cycles* **22** 1-19
- Moore I, Lewis A and Gallant J 1993 *Terrain attributes: estimation methods and scale effects* Modeling Change in Environmental Systems (London)
- Naidoo R and Iwamura T 2007 Global-scale mapping of economic benefits from agricultural lands: implications for conservation priorities *Biological Conservation* **140** 40-49
- Ramankutty N, Evan A T, Monfreda C and Foley J A 2008 Farming the planet: 1. Geographic distribution of global agricultural lands in the year 2000 *Global Biogeochemical Cycles* **22** 1-19
- Robinson T P, Wint G W, Conchedda G, Van Boeckel T P, Ercoli V, Palamara E, Cinardi G, D'Aiotti L, Hay S I and Gilbert M 2014 Mapping the global distribution of livestock *PLoS ONE* **9**
- Ruesch A and Gibbs H K 2008 New IPCC Tier-1 global biomass carbon map for the year 2000
- 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 *Proceedings of the National Academy of Sciences* **108** 9899-9904

You L, Wood S, Wood-Sichra U and Wu W 2014 Generating global crop distribution maps: From census to grid *Agricultural Systems* **127** 53-60