Landscapes, at your service

Applications of the Restoration Opportunities Optimization Tool (ROOT)

Craig R. Beatty, Leander Raes, Adrian L. Vogl, Peter L. Hawthorne, Miguel Moraes, Javier L. Saborio and Kelly Meza Prado

First edition

IUCN GLOBAL FOREST AND CLIMATE CHANGE PROGRAMME

Federal Ministry for the Environment, Nature Conservation and Nuclear Safety

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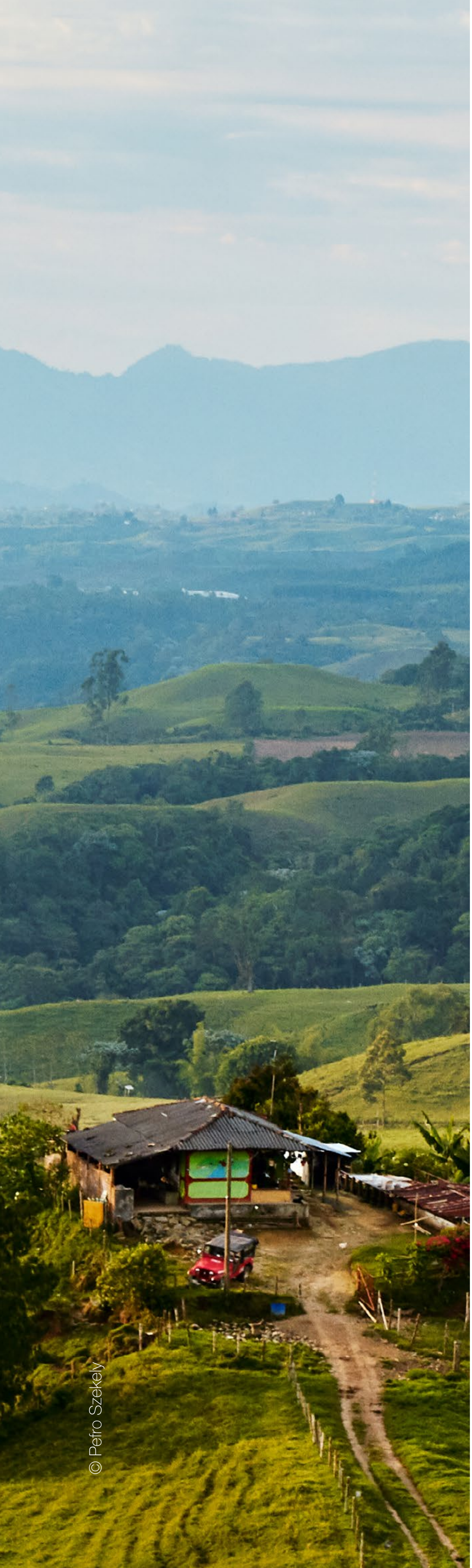

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Key messages

- Ecosystem services and their impacts on livelihoods can be helpful in justifying large-scale investments in landscape restoration.

- ROOT provides an assessment of ecosystem service trade-offs and facilitates the effective communication of this information to decision makers.

- Knowing where restoration can have the greatest impact on multiple ecosystem services for multiple beneficiaries can help make restoration more cost-effective and increase its success.

- ROOT builds support for forest landscape restoration and facilitates the mobilisation and direction of funding; it helps people visualise potential landscape benefits and define recommendations.

- Investments in restoration have the potential to be optimised such that relatively small interventions can have large and compounding benefits across landscapes.

- ROOT can demonstrate how restoration generates multiple benefits beyond just the biophysical realm—it connects those services and their provision to people and restoration processes in specific places.

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Executive summary

The Restoration Opportunities Optimization Tool (ROOT) was developed out of a need to more efficiently and effectively communicate the importance of ecosystem services to decision makers. IUCN's collective experience working to increase ecological productivity and improve human well-being through forest landscape restoration (FLR) demonstrated that although stakeholders were interested in generating ecosystem services from proposed restoration activities, the many services and their interactions with each other were often too complicated to communicate clearly. Furthermore, as a social process, decision makers working towards restoration were interested in more than just the biophysical gains from restoration for different services; they wanted evidence for how restoration might benefit agricultural production, access to jobs or different sources of income, and how investments in restoration might help underserved or marginalized groups.

ROOT was developed as the cornerstone of a three-year collaboration with The Natural Capital Project to support ecosystem services decision-making in forest landscape restoration. It is intended to help translate the technical details of ecosystem services analysis into elegant outputs that can easily communicate the potential impact of nature-based restoration solutions on people's lives. Critically, ROOT also provides the underlying data and analysis that permits technical experts to evaluate ecosystem service trade-offs and the aggregation of quantifiable ecosystem service benefits within a landscape or jurisdiction.

The following case studies demonstrate examples of the practical applicability of ROOT in different contexts, using ROOT in several different ways. Each of the case studies illustrate one technical component of a large, inclusive process under the Restoration Opportunities Assessment Methodology (ROAM), which is a flexible, iterative and inter-sectoral approach taken by stakeholders to identify the best places to restore degraded landscapes (IUCN & WRI, 2014). As such, the data used in these cases has already been verified by diverse groups of national and international stakeholders in FLR.

The case studies were chosen based on ongoing FLR assessments as well as the existence of ecosystem services data, and are intended to demonstrate the applicability of ROOT to both technical and non-technical audiences. An additional requirement was the inclusion of a restoration scenario upon which projected changes in ecosystem services from restoration actions could be modelled. In each case, ecosystem services have been modelled using the Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) suite of ecosystem service modelling tools. It is, however, important to note that ROOT is agnostic to the source of ecosystem services data. Any number of ecosystem service modelling tools are available and any that produce spatially explicit ecosystem service values can be a source for ROOT analysis. Running ROOT requires spatial data on ecosystem services, an area of interest or priority for restoration, spatial data on whom or what restoration is intended to benefit (ecologically or socially), a monetary or geographic constraint within the area of interest, and a concern for optimal solutions. The process will require someone familiar with geographic information science and people knowledgeable about the biophysical, social, and economic considerations within the target landscape. These have generally been provided within ROAM processes at national or subnational scales in the case studies that follow, but could be generated by any interested committee of technical and non-technical restoration practitioners.

Still relatively new, ROOT has undergone extensive testing and refinement prior to its release in 2017. However, there are some limitations to its applicability. ROOT should be used in situations where an optimal solution is desired or warranted. It requires not only that ecosystem services information be available, but that projected changes in ecosystem services from a restoration scenario be calculated as well. In many cases this is not possible or practical. Additionally, optimisation results are aggregated based on 'decision units', and the size of these units is limited by the processing power of desktop computers. Therefore, results may be demonstrated at a resolution that is too coarse for specific local planning, though they may still be useful to guide decision making.

Finally, each of these applications of ROOT exist within assessments of forest landscape restoration opportunity, not the implementation of restoration itself. The results presented in these case studies cannot yet be validated due to the duration of restoration interventions within large landscapes; it may take some time to effectively validate these results and demonstrate that restoration has produced the estimated changes in ecosystem services and increased cost-effectiveness. That said, ROOT has established the baseline for ecosystem services provision in these areas, and calculating changes in the provision of these services or the livelihoods of beneficiaries will be an ongoing process embedded in IUCN's approach to forest landscape restoration for years to come.

While designed to support FLR assessments at national or subnational scales, the applicability of ROOT beyond these assessments and at different scales is an exciting frontier. Many landscape challenges exist where optimisation can help deliver impactful investments for intended benefits. Future applications of ROOT will include economic assessments, including opportunity costs and trade-offs in net present values. ROOT can conceivably be used by the private sector to direct capital investments to areas that may streamline sustainable supply chains or provide increases in natural resources while also demonstrating the environmental and social responsibility that consumers increasingly demand. Finally, as a relatively simple tool, ROOT has the capacity to facilitate a broader integration of ecosystem services analysis beyond an inventory of services to better include the social, cultural, and economic considerations within functioning landscapes.

Introduction

Ecosystem services are a framework for understanding the ecological interactions among people and their environments. This framework helps quantify large and dispersed natural processes in terms of how they contribute to human prosperity and well-being. Landscape and policy decisions that have direct and indirect bearing on species increasingly rely on ecosystem services information. As a result, ecosystem services are becoming a critical component of landscape planning and management and now form a cornerstone for how decision makers assess the productivity and potential of landscapes.

For places suffering from landscape degradation, ecosystem service analysis and forecasting can inform decision makers both about the current ecosystem services that flow through a landscape and about the potential for how different management and restoration activities may increase these services. Where people are experiencing drought, ecosystem services information can provide a window into where and how the effects of drought may be mitigated or reversed; for carbon sequestration it can provide figures for the potential of landscapes to store carbon; and, for areas abnormally affected by sedimentation of rivers, streams and reservoirs, ecosystem services analysis can demonstrate where this sediment originates and can provide clues for where investments could be made to reduce sedimentation.

There are many ways to approach utilising ecosystem services in a restoration assessment or implementation context. For example, in addition to biophysical ecosystem service benefits, decision makers can also prioritise restoration based on projected economic returns (Birch et al., 2010), non-market benefits of ecological restoration (Martin-Lopez et al., 2014), or measures of improved social resilience (Reyers et al., 2013). However, these attempts to prioritise restoration based on benefits to ecosystem services have generally considered one service at a time or tend not to include more than two interacting services. In practice, ecosystem services are often assessed individually and then qualitatively evaluated to identify ecosystem service 'hotspots', which are then overlaid with other ecosystem services to show where high priority areas overlap with each other (review in: Trabucchi et al., 2014). Alternatively, some studies have attempted to group ecosystem services to demonstrate trade-offs in provision of services based on different scenarios (e.g. Bryan & Crossman, 2013; Willemen et al., 2017), yet, by necessity these approaches ultimately use qualitative classifications of ecosystem service distributions (high to low) instead of quantitative data.

Integrating ecosystem services in policy

De Groot et al. (2010) have outlined some of the challenges of integrating ecosystem services information in landscape planning and note that "at the landscape level, the main challenge is how to decide on the optimal allocation and management of the many different land use options." There remain few available tools for the spatial prioritisation of landscape interventions to support benefits from multiple concurrent and interacting ecosystem services that can be weighed by how these services may support specific beneficiaries (Nelson et al., 2009; Birch et al., 2010), and none that do so by optimising spatially explicit ecosystem service delivery from projected restoration actions to support identified beneficiaries.

What current prioritisation approaches also struggle to achieve is an efficient method of communicating optimal solutions among the underlying complexities of landscape restoration. Where time and funding are limited to assess, decide and implement landscape restoration actions, the capacity of decision makers to know the technical details and variations in the economic, social and ecological components of proposed restoration actions is also limited. What decision makers seek is clear and understandable decision support that allows them to visualize the results of an ecosystem service assessment that includes the ecological and social returns that can help them make the best decisions.

Decision makers within restoration always look for low-cost and effective solutions to the impacts that landscape degradation has on their constituents. Through decades of research and analysis, the ability to measure ecosystem services and provide recommendations on how to improve landscapes to increase ecosystem services is now relatively strong. Furthermore, in assessing the opportunities for landscape restoration, as IUCN has facilitated in well over 40 jurisdictions so far using ROAM (IUCN & WRI, 2014), ecosystem services are often one of the main analytical requests of policy-makers and stakeholders in these assessments.

Despite the wealth of knowledge on how to model ecosystem services, a curious thing happens, when decision makers are asked which ecosystem services are most important to them. Instead of selecting one ecosystem service to focus on (e.g. water provision or cleanliness, sedimentation of waterways, etc.) the typical answer is "all of them." Most current ecosystem services models are designed specifically to solve an ecosystem service problem or to generate a value for one ecosystem service at a time. While this information remains critical for ROOT, what interested decision makers was an ecosystem services solution that included as many ecosystem services as possible. They were understandably keen to make sure that the investment of their limited funds for landscape restoration would achieve the most impact for the least cost.

The long-term and sustainable delivery of ecosystem services from restored landscapes is the ultimate objective in many places. Ecosystem services generated from restoration remain one of the few quantitative ways of measuring restoration success; these assessments, especially when combined with socio-economic attributes, bring strong evidence for the utility of restoration for competing land parcels (Wortley et al., 2013). One of the primary considerations faced by decision makers in allocating effort and resources to restoration is a quantification of the projected economic, ecological, or social returns from political and economic investments in forest landscape restoration. Landscape-scale choices today will have lasting consequences for ecosystem services and will ultimately involve trade-offs in the restoration of ecosystem services (MEA, 2005; Raudsepp-Hearne et al., 2010).

The development of ROOT

To address this issue, IUCN and The Natural Capital Project formalized a partnership to explore how an ecosystem services decision-support tool could be integrated into the FLR assessment process. The overarching goal was to provide a tool for restoration practitioners working on the assessment of multiple ecosystem services that could be quickly understood by decision makers. Specifically, the result was intended to provide an easily communicable map that integrated ecosystem services and human livelihoods. In its current form, ROOT is a decision-support tool that demonstrates ecosystem service trade-offs among a number of ecosystem services; ROOT then optimises the delivery of these ecosystem services for their biophysical benefits as well as for their benefits to the people who are of interest to decision makers.

ROOT moves beyond analysing scenarios and presenting results to decision makers based on the three typical scenario tracks (i.e. business as usual, partial intervention, full intervention) to provide suites of optimised restoration portfolios based on the direct input of stakeholders and decision makers into the ecosystem service value chain. Placed within a decision context such as an FLR assessment, ROOT allows a multi-stakeholder process to define which ecosystem services are important across many sectors, where and how landscapes are degraded, and who should benefit from the augmentation of ecosystem services.

ROOT has emerged as a demand-driven solution to a need of stakeholders in FLR assessments to translate ecosystem services information into a format that is easy for decision makers to gauge and modify based on iterative consultation with stakeholders. ROOT does not replace the ecosystem service analysis process through any of the dozens of spatially-explicit ecosystem service modelling tools available. It was designed to specifically support the restoration decision-making process within the context of forest landscape restoration to support the generation of ecosystem services from restoration for intended beneficiaries. It provides decision makers with concise and clear figures, maps, and baseline data to generate confidence in the landscape restoration decisions that will optimise human and economic investments in restoration.

Making landscape trade-offs more explicit

Formerly, there were several barriers to this approach, not least of which was a lack of opportunity for decision makers to collect, assess and weigh information to decide how their sector's landscape context would benefit from the restoration of ecosystem services in a particular area — a 'silo mentality'. This is not necessarily a lack of capacity with regard to understanding of the importance of ecosystem services, but a difficulty in weighing landscape choices, based on the inherent opportunity costs of restoration and the number of other available landscape choices. In other words, forestry sectors tend to identify forestry solutions, agricultural sectors tend to identify agricultural solutions, and water sectors tend to identify water solutions. Each sector tends to view ecosystem service information as either supporting the aims of their sector or imposing opportunity costs that compete with their goals.

In FLR assessments, a significant amount of spatial data is gathered and generated to provide guidance on where restoration might be feasible and what it is intended to achieve. Within this process it is possible to include prioritisations based on the thematic goals of restoration, but these are relatively simple and additive. Priorities are based on the inclusion or exclusion of static spatial data layers. For instance, if the goal of restoration is to increase the quality of water by decreasing erosion, priority could be given in planning restoration actions to areas where erosion is having a negative effect on water quality — typically areas of high slope with little vegetative cover. For example, restoration in these areas would conceivably mitigate poor water quality.

While basic prioritisation will remain a part of restoration assessments due to its relative ease and ability to target specific issues, what this prioritisation cannot accomplish is a broader assessment of where landscape interventions can be identified that will lead to increases in multiple ecosystem services. The opportunity cost for ecosystem services of prioritising one area over another for restoration and the effect of this prioritisation on the ecosystem services generated is not only key in planning restoration actions, but also important for estimating the benefits that restoration may have for people.

Due to variation in how ecosystem services respond to restoration in different areas, there are trade-offs between the benefits provided by different types of restoration activities and the value of the ecosystem services that flow from implementation decisions. ROOT uses these trade-offs to model where practitioners might invest in restoration within their priority areas in order to maximise the procurement of two or more ecosystem services. ROOT builds a body of knowledge regarding the interaction among the benefits or costs of restoration for ecosystem services such that a decision-maker is not required to choose between, for example, restoring for carbon sequestration or water yield.

Communicating the results of ROOT

One of the primary outputs of ROOT is a map that distils the trade-offs among two or more ecosystem services and provides a clear and understandable index of these trade-offs. This 'agreement map' demonstrates the frequency with which the model selects a specific area among the multiple iterations of the model. Areas that are selected 100% of the time indicate that no matter the parameters of the optimisation model, these areas are consistently selected as important for ecosystem services and their delivery to beneficiaries. Alternatively, areas that are not selected in any of the optimisation scenarios display little or no potential for an increase in ecosystem services that would flow to beneficiaries.

While the inputs of ROOT are grounded in spatial analysis and geographic information science, and require such expertise to employ, the outputs are designed to provide decision makers with information that is easy to translate into policy recommendations. ROOT provides practitioners with the capacity to optimise trade-offs in multiple spatially explicit ecosystem service benefits, opportunity costs, or quantified social benefits within a user-defined decision context. This analysis generates multiple optimised solutions based on randomized variations in input data, a summary table containing all totals for all solutions, and an aggregation map that displays where in the projected restoration landscape the multiple randomized optimisations agree on optimal selection for ecosystem services and beneficiaries.

The following case studies demonstrate the first applications of ROOT in five different geographies, each with different combinations of services and beneficiaries. ROOT can go beyond the prioritisation inherent in assessing the opportunities for landscape restoration to provide optimal locations to begin restoration. More than an analysis of how ecosystem services could be improved, ROOT provides decision makers with actionable information on where restoration could benefit multiple ecosystem services and beneficiaries.

Technical details of ROOT

ROOT applies linear programming optimisation to identify optimal areas for restoration. It allows the user to specify multiple objectives of interest, combining expected changes in biophysical values and maps of ecosystem service demand, and generates a range of activity allocations by performing many optimisations varying the weight placed on each objective. ROOT synthesizes the results of these separate analyses with an agreement map that identifies areas that are a high priority for intervention across the range of potential priority weights. These are the key landscape locations for the provision of multiple ecosystem services. ROOT has been designed to be scale-independent and to appeal to users within the environmental, agricultural, economic and business sectors.

ROOT utilises a series of input tables which contain pathways to GIS rasters and shapefiles. Within the optimisation, ROOT orchestrates an integrated linear optimisation algorithm that randomly assigns weights to each objective for each model iteration using a multivariate normal distribution, which is then normalised so the weight vectors equal 1. ROOT requires six main inputs: 1) impact potential rasters of marginal ecosystem service values, 2) ecosystem servicesheds, 3) composite factors, 4) activity masks, 5) objectives, and 6) targets.

1. Impact potential rasters of marginal ecosystem service values represent differences in biophysical processes between a baseline and restored landscape scenario. Depending on context, users could consider the theoretical maximum of each potential ecosystem process change (e.g. when all degraded land is restored to native ecosystem), or they may consider incremental ecosystem process changes based on adaptation within a land use class (e.g. the sediment retention potential of agroforestry as a restoration practice).

2. Ecosystem servicesheds are the spatial data (polygons) that capture which areas of the landscape are more or less important for providing services to potential beneficiaries of the ecosystem services measured. For water-related services, these could be the catchments of identified points of interest.

3. Composite factors allow the user to specify the combinations of impact potential rasters and servicesheds that connect the biophysical supply and beneficiaries to form the ecosystem services of interest.

4. Activity masks are rasters that represent areas where the restoration activities could be implemented. These are the areas that ROOT will decide among in the optimisations (as aggregated in the spatial decision unit maps).

5. Objectives allow the user to specify which composite factors to include as objectives in the analysis and whether optimal values should be minimized or maximized. For instance, users would generally maximize a value calculated as sediment retention, but minimise the related value calculated as sediment export.

6. Targets allow the user to specify constraints that the optimised solutions must meet. For instance, Bonn Challenge commitments for a given area of restoration can be captured as a target, as well as targets for particular services or budget limits.

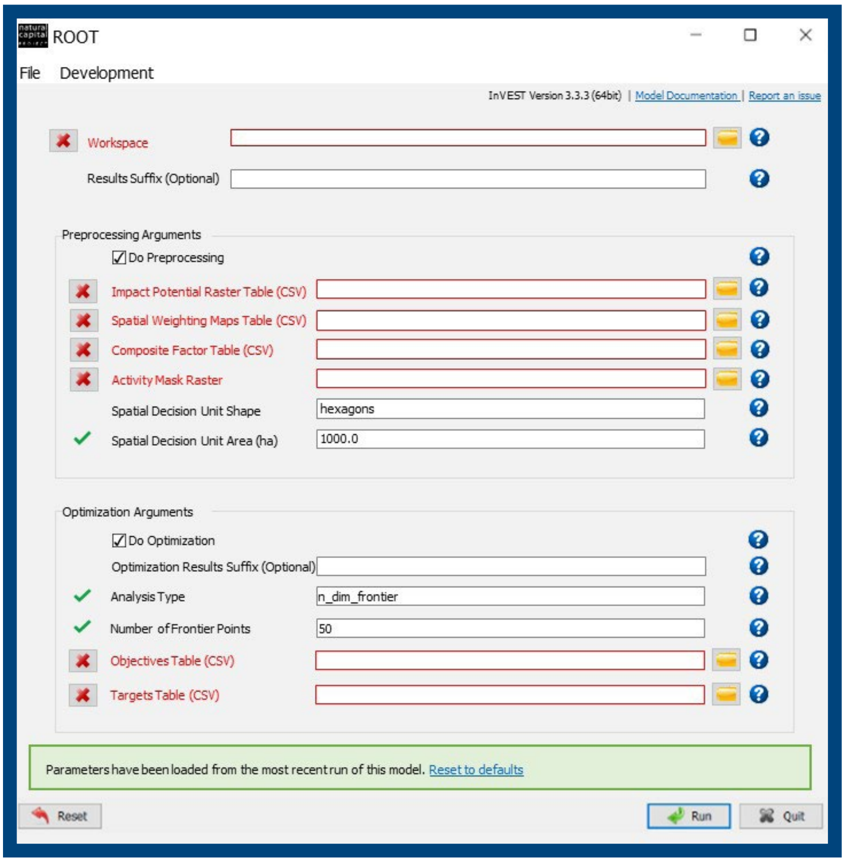


__Figure 1__ shows the graphical user interface of ROOT. Though developed with the same look and feel of InVEST, ROOT does not require that ecosystem service values be calculated in the InVEST suite of tools; ROOT can use any spatial ecosystem services information in raster form from any spatially explicit ecosystem services model.

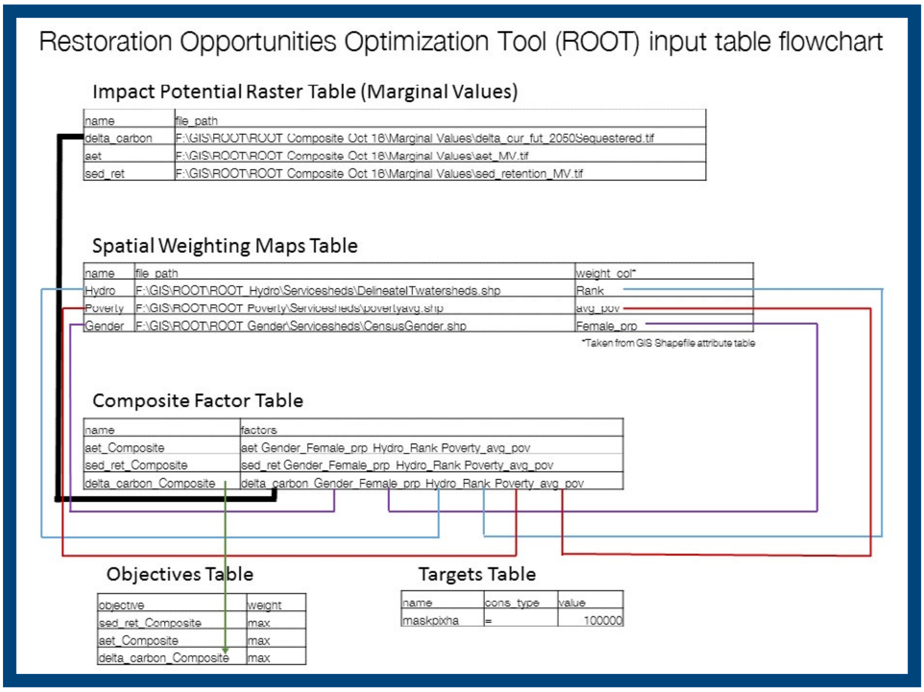


***Figure 2** provides an example of the data inputs for ROOT. The values represented in each table can be used as objectives in the optimisation. The composite factor table, though, combines the results of the impact potential raster data with spatial weights for different beneficiaries to capture the full service value. There are three composite factors in this figure, though only the components of one is highlighted for clarity. The 'delta_carbon_Composite' factor is a combination of the marginal increases in carbon sequestration combined with spatial weights for gender, hydroelectric/irrigation potential and poverty level. As indicated in the Objectives Table, ROOT will optimise to achieve areas where the maximum values for this composite are achieved within the map.*

The user must also decide what the spatial decision unit will be. These can be defined as hexagons or squares within the area of interest, or the user may include a file path to a shapefile (.shp) for political, watershed or other boundaries. The user may also select the area of each of the decision units (squares or hexagons). The ROOT workflow is divided into two distinct steps: pre-processing and optimisation. This division allows the user to use the same input data to run multiple optimisations using different objectives, targets, or the number of times the model iterates using different randomised objective weights.
The result of the analysis will demonstrate the decision units that are most optimal for improving multiple ecosystem services for the specified beneficiaries based on 'agreement' among the model iterations. ROOT will decide for each iteration whether a decision unit is an optimal location for restoration based on the ecosystem services gains and the randomised beneficiary weights. The frequency with which a decision unit is chosen as optimal can then be expressed in a map.

Additionally, ROOT provides data tables for each model iteration that quantify the ecosystem service results for that specific optimized activity allocation. This allows analysts to explore the mechanics of ROOTs optimisation process and examine the ecosystem service provision to particular beneficiaries among different iterations.

Applications of ROOT

The following case studies demonstrate several ROOT applications and explore several contexts where optimisation was helpful and where trade-offs were predicted, to illustrate how decisions utilising ecosystem services information were made. These cases cover examples from Brazil, Malawi, Myanmar, Colombia and Costa Rica, and they demonstrate both the explanatory and predictive capabilities of ROOT in FLR assessments using spatially explicit models to show what decision makers and landowners might expect regarding both ecosystem service benefits and how those benefits are distributed to people. These cases also cover examples of where governments have expressed specific interest in ROOT's ability to optimise restoration investments for established actions or programmes that are primed for implementation as well as exploratory analyses of the optimal trade-offs in ecosystem services for different social priorities where the specific restoration activities have not yet been defined.

Brazil: Espirito Santo State

The Espirito Santo case revolves around a subnational FLR assessment that was undertaken 2015–2017. The State had been suffering from significant drought that had drastically affected agricultural production, especially coffee. This drought led to economic hardship for many of the people of Espirito Santo, and the State worked with IUCN and its members to develop an FLR assessment using ROAM. Following the identification of approximately 120,000 hectares of opportunity area in the State (40,000 hectares more than its Bonn Challenge commitment), the State was interested in identifying where within this opportunity area restoration could optimally support more retention of water and reductions in sediment delivery to streams. Additionally, it was important to implement restoration actions in areas that supported these services in priority watersheds and in municipalities where incomes were low. ROOT was used to calculate the areas for optimal investment in restoration to support these objectives within identified restoration opportunities.

Malawi

In 2016, Malawi began a national FLR assessment to determine the political, financial, geographical, social and economic rationale for a national strategy for restoration. This commitment was elevated to the international level at the IUCN World Conservation Congress, where Malawi announced a 4.5 million hectare commitment to the Bonn Challenge. This commitment was intended to support the restoration of Malawi's deforested and degraded lands. Malawi's objectives for restoration fell into three broad categories: food security, resilience and biodiversity. The national FLR assessment identified both general restoration intervention activities and priority areas for the implementation of these activities.

The ROOT analysis completed for Malawi uses high priority areas identified through the National Forest Landscape Restoration Assessment along with ecosystem services assessments of actual evapotranspiration, carbon sequestration, and sediment retention to determine where investments could be made in restoration to support these ecosystem services in areas where there are proportionally more women, in water resource units that have high poverty levels, and in areas important for hydropower generation and irrigation.

Myanmar

In 2016, Myanmar completed a national assessment of several key ecosystem services led by WWF and the Natural Capital Project (Mandle et al., 2017). This analysis, the first of its kind in Myanmar, resulted in several key recommendations that included recognising the importance of natural ecosystems in water quality, the availability of water based on forest regulation of flow, the reduction in flood risk through the existence of natural ecosystems, and the protection of coastal infrastructure and people through intact coastal ecosystems like mangroves. It also demonstrated important overlaps in 'high-value' ecosystem service areas and areas important for biodiversity. These analyses provided the baseline ecosystem service information that IUCN and the Natural Capital Project would use to model the optimal areas for restoration in Myanmar using ROOT.

The ROOT analysis for Myanmar used the results from a national forest landscape opportunities assessment map, developed in collaboration among IUCN, The Myanmar Ministry of Natural Resources and Environmental Conservation — Forest Department, and The Nature Conservancy. The objective of ROOT was to maximise the ecosystem services of sediment retention in municipalities most affected by the 2015 flooding, and in areas with high unemployment and heavy reliance on fuelwood.

Colombia

Colombia is facing rapid urbanisation, with current projections showing that nearly 84% of Colombians will be living in urban areas by 2050 (United Nations, 2014). Ongoing urban growth presents significant challenges to providing services and funding investments in infrastructure to ensure sustainable incomes, food, water, energy and shelter for all citizens, 27.8% of whom remain in poverty (World Bank, 2015). Colombia's 2015 National Development Plan (NDP) and additional legislative and institutional mandates such as Regional Autonomous Corporations (CARs) support investments and payments to landowners for ecosystem services and include requirements for hydropower companies to transfer a percentage of their earnings from energy production to municipalities and CARs for watershed protection.

To support and finance FLR activities, The Nature Conservancy suggested the implementation of a collaborative finance and governance mechanism that connects downstream beneficiaries of water purification and habitat restoration services to upstream landholders who provide those services — a water fund. Because water funds often need to allocate limited budgets to restoration activities while achieving specific ecosystem services targets, ROOT was applied to optimise the locations of four types of interventions (agricultural best management practices, forest restoration, riparian restoration, and protection of native vegetation) in the source watersheds of six of the largest cities in the country (population >500,000) to reach targeted changes in ecosystem services, including sediment retention, nitrogen retention and carbon storage.

Costa Rica

To support Costa Rica in achieving its one million hectare commitment to the Bonn Challenge, IUCN facilitated the implementation of a ROAM assessment with government and other stakeholders in August 2014. As part of the process a technical committee of restoration experts was established. This technical committee made a first proposal of restoration actions and targets related to those actions. The proposal was based on unifying existing programmes in Costa Rica that have a restoration component, specifically Costa Rica's national Payments for Ecosystem Services Program (PPSA for its abbreviation in Spanish), the Nationally Appropriate Mitigation Actions (NAMAs), and the programmes for the implementation of Good Agricultural Practices (GAP).

ROOT was used to optimise areas for the implementation of each of the restoration actions within these existing programmes, to consider the impact on ecosystem service provision, and to ensure the activities would have positive benefits for potential beneficiaries. This use of ROOT included national scale ecosystem services assessments of nutrient export and sediment export, and assessments of the impact potential of restoration actions within each of these ecosystem services. These ecosystem service benefits were then considered for hydropower production, drinking water supply, wetlands and biological corridors.

The following examples demonstrate the utility of ROOT in answering landscape-scale questions, which can help direct decision makers towards options that are grounded by empirical analysis and help them optimise decisions to achieve both ecosystem service and livelihood goals of restoration activities.

Table 1: The primary ecosystem services, opportunity area, beneficiary objectives and constraints for each of the five ROOT case studies.

	Main ecosystem services	Identified area of restoration opportunity or priority	Beneficiary objectives	Constraints
Espirito Santo, Brazil	Sediment retention and water yield	120,000 ha FLR opportunity area	Groundwater recharge, payments for environmental services, income generation, watershed risk management	Land use type (pasture/ macega), 80,000 Bonn Challenge Pledge
Malawi	Sediment retention, actual evapotranspiration, carbon sequestration	100,000 ha highly degraded land	Hydropower generation, poverty alleviation, gender-responsive restoration	50,000 ha to begin restoration project
Myanmar	Sediment export	713,400 ha of forest loss	Flood mitigation, job creation, reduction in reliance on unsustainable natural resources	25,000 ha to begin restoration
Colombia	Sediment delivery ratio model ('sediment'), nutrient delivery ratio model ('nutrient'), forest carbon edge effect ('carbon'), seasonal water yield	88,000 ha restoration potential surrounding six urban areas	Watershed protection for urban area water sources	Monetary/budget constraints
Costa Rica	Sediment export, nitrogen export, phosphorus export	1 million ha of degraded and deforested land	Increased agricultural production and carbon sequestration, potable water, wetlands, hydroelectricity, biodiversity corridors	25,000 ha for coffee restoration, 70,000 ha for plantations outside livestock areas

Brazil: Espirito Santo

Drought and coffee: planning restoration in Espirito Santo, Brazil

Craig R. Beatty[1] and Miguel Moraes[2]

South-eastern Brazil has recently experienced the most severe droughts in living memory (NPR, 2016). Usually receiving ample rain to support a large agricultural sector, Espirito Santo experienced extreme flooding and damage in 2013 followed by reductions in rainfall throughout south-eastern Brazil of up to 70% below average values (Nobre et al., 2016). This, combined with record high temperatures, devastated many of the State's farmers along with the cities that rely on rural water sources. Within south-eastern Brazil, this caused a water crisis for over 40 million people. Steep declines in coffee production led farmers to either accept their losses or shift to other crops such as pepper. Many coffee producers went bankrupt and were required to close their facilities, some of which had existed for generations. COOABRIL, a coffee cooperative within Espirito Santo, explains that while drought may be a natural phenomenon, deforestation and landscape degradation, especially on hilltops, have prohibited the infiltration of water into the ground (NPR, 2016). Furthermore, the impacts of climate change make seasonal rainfall predictions less accurate, and new research indicates that it may no longer be possible to grow coffee in Espirito Santo by the end of this century (Bunn et al., 2015; Bragança et al., 2016).

To combat the immediate effects of drought, Espirito Santo's State Sanitation Company (CESAN) instituted strict water conservation activities that helped to reduce water use. However, an unpredictable climate and some of the more dire forecasts have led the State government to seek long-term solutions to what may be increasingly frequent and unpredictable drought events. In 2015, Espirito Santo enlisted the help of IUCN to undertake an FLR assessment using ROAM (IUCN & WRI, 2014). Forest landscape restoration represents one of the most economically feasible pathways for generating multiple benefits for people and ecosystems to explore nature-based solutions[3] to many of the landscape challenges faced by the people of Espirito Santo.

Within the broader FLR assessment process and to help assess solutions to long-term drought, IUCN initially facilitated a spatial analysis of water yield and sediment delivery using the Integrated Valuation of Ecosystem Services and Trade-offs Tool (InVEST). These ecosystem service models helped to quantify the current delivery of two important ecosystem services and were then instrumental in helping to model the projected delivery of these services under a restored scenario. The analyses looked at different scenarios of resource allocation in Espirito Santo to help define priority areas for investment in FLR activities. The results of these analyses are the foundation for amplifying the existing Payments for Ecosystem Services (PES) program, since they provided the basis for prioritizing areas where FLR can deliver ecosystem service gains for each of the services, considered separately.

However, this approach was not entirely clear in terms of helping decision makers prioritise areas based on their own evaluation and comparisons of ecosystem service gains. What they needed to know was, "Which areas should be considered for restoration in order to obtain optimal results for both water yield and sediment retention simultaneously?" With this specific focus, ROOT was employed by IUCN to optimise the trade-offs between these two ecosystem services to help determine where the proposed PES systems would have the highest impact.

Improving water quality and quantity remains one of the main challenges for ensuring long-term productivity in landscapes. In this context, efforts are being undertaken to invest in reductions to surface runoff in water recharge areas. These areas are normally marked by rugged slopes and decades of unsustainable agricultural activities. Years of severe rainfall on these degraded areas have led to high sediment delivery indices and water yields, especially in areas where the native vegetation cover has been significantly altered, such as degraded grassy weed areas (macega) and pasture lands. Beyond the technical assumptions that led to a focus on two specific land uses (macega and pasture land), a strategic rational was carefully developed to unite divergent stakeholders and develop landscape cooperation and compromise. As normally occurs in subnational governmental agencies, each sector was concerned mainly about its own attributions, namely water supply, biodiversity loss, silting, food production and income generation, among others. In this sense, FLR was framed as a convergent solution that could provide cost-effective results for different problems, bringing together key stakeholders under a positive agenda. Moreover, communication and engagement has focused on the water crisis, taking advantage of government attention to propose nature-based solutions that could tackle problems while putting the state of Espirito Santo in the vanguard of United Nations' 2030 agenda.

At the political level, the aforementioned rationales were used to underpin initial dialogues with state-level decision

[1] International Union for Conservation of Nature, Washington D.C.
[2] Formerly, International Union for Conservation of Nature, Brazil. Currently, Conservation International, Brazil.
[3] IUCN defines Nature-based solutions (NbS) as actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits.

makers to ensure a coherent message that could provide the political support needed to carry out a comprehensive FLR assessment. At the technical level, stakeholders decided that land uses currently classified as degraded pasture or macega would be the most opportune areas to implement restoration activities, since these land uses were already accounted as unproductive and the political attention was focused on reduction of sediment delivery and water yield. To quantify the maximum potential ecosystem services that could be generated, these land uses were transformed within a GIS to native forest, of significant interest due to Espirito Santo's commitment to the restoration of the Atlantic Forest, through the Atlantic Forest Restoration Pact (PACTO). Using the same input values for both InVEST models (SDR and Water Yield), the models were re-run with the modified land use land cover layer to show where within the landscape FLR activities might have the largest potential benefits for proposed restoration. The result is a maximum potential impact map of increases in ecosystem services within the land uses identified for restoration activities.

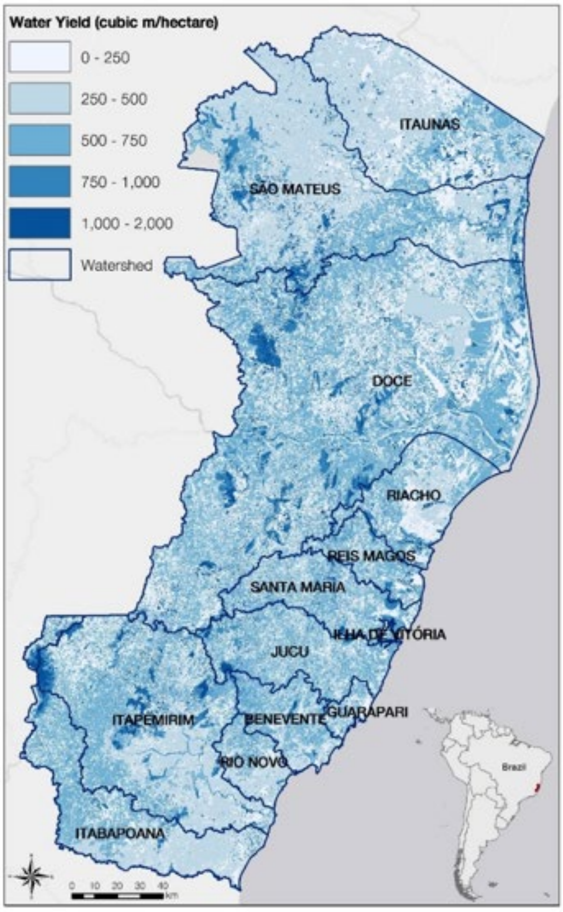
Though baseline ecosystem service information is helpful, the analysis of ecosystem service scenarios is intended to make the case for investments in areas that could produce multiple benefits through FLR. In addition to a clear definition of political strategies that orient efforts to maintain and improve ecosystem services related to resilience to drought and agricultural productivity, there is an underlying priority for supporting social groups more impacted by the current drought. As a result, the analysis of ecosystem service potential focused on alternative restoration models that could increase income for rural households. This is especially the case for identifying areas where families affected by the drought could participate in a PES programme that would provide monetary benefits for their conservation or restoration efforts.

The following case provides an overview of how InVEST and ROOT were used to support the Espirito Santo state government in building a comprehensive FLR framework. Since IUCN worked to facilitate the participation of key stakeholders within a participatory process, the final results of these analyses are owned by local organisations that are working to guarantee political uptake and unlock investments to scale up action. This section will also present the ROOT methodological framework, main results and conclusions. The material hereby presented may help others interested in analytical tools that can change perspective, while fostering stakeholders' engagement and scaled-up action.

Methods

The outputs of InVEST sediment delivery and water yield analyses were used as inputs for ROOT. (For detailed information on InVEST please see the Appendix.) Herein focus will shift to how ROOT was applied to define scenarios that optimise results for specific target audiences

Figure 3 *shows the ecosystem service values for sediment delivery ratio (left) and water yield (right) used in a preliminary assessment of ecosystem services in Esprito Santo State, Brazil. These values were used to inform the development of a potential PES scheme in the State.*



The purpose of using ROOT in Espirito Santo was to demonstrate where restoration interventions could be made that would decrease water yield (i.e. more water is retained in each pixel) and increase sediment retention (i.e. lower the amount of sediment exported from a pixel). Interventions in these areas have a high potential for generating the landscape-scale benefits desired by Espirito Santo.

Table 2: *ROOT requires six main inputs: 1) impact potential rasters with marginal ecosystem service values, 2) ecosystem servicesheds, 3) composite factors, 4) activity mask, 5) objectives, and 6) targets. ROOT input categories*

ROOT input categories	Espirito Santo details
Impact potential maps (marginal values of ecosystem services resulting from restoration activities)	Sediment Retention (Mg/ha/year) Water Yield (m^3/ha/year)
Servicesheds	Watershed risk (watersheds of high priority due to drought) Average income by municipality
Composite factors	Sediment retention and income average Water yield and income average Sediment retention and watershed risk Water yield and watershed risk
Activity mask	120,000 ha of forest landscape restoration opportunity within the State that had been identified and validated as 'high priority' areas for FLR through the ROAM.
Objectives (must account for positive or negative input values since objectives are multiplied in the analysis)	Maximize sediment retention and income average Minimize water yield and income average Maximize sediment retention and watershed risk Minimize water yield and watershed risk
Targets	Espirito Santo Bonn Challenge target of 80,000 ha

To generate additional confidence in the agreement patterns indicated in the ROOT agreement map, we performed an optimised hotspot analysis and cluster and outlier analysis. The hotspot analysis uses the Getis Ord Gi* algorithm (Getis & Ord, 1992) to calculate the optimal fixed distance band threshold for the analysis of spatial clusters. In this case, the optimal fixed distance band for the ROOT analysis of Espirito Santo was calculated to be 14,417 m. This figure was rounded to 15,000 m for subsequent analysis. This figure was then used as the distance threshold in a cluster and outlier analysis algorithm (Anselin, 1995) to determine the degree to which agreement values were significantly different from neighbourhood values. The outputs of this analysis are a cluster and outlier analysis that can be seen in Figure 5, below.

Results and discussion

ROOT generates results for each of the individual optimisations. These values are indicated in a summary table output that provides a solution value for each optimisation in case stakeholders are interested in exploring quantitative differences among optimisation solutions. The model also produces a table that outlines the randomised weights applied in each of the optimisation runs. Finally, ROOT generates a map that demonstrates the frequency of agreement among all of the individual iterations of the model (Figure 4). This agreement map can help stakeholders visualize ROOT results and can be used to help develop key recommendations as part of an FLR assessment.

Figure 4 *shows the results of the ecosystem services optimization using ROOT for Espirito Santo State, Brazil. One of the many outputs of ROOT is a spatial agreement map. This map demonstrates the frequency with which a spatial decision unit (e.g. hexagon) is chosen among multiple simultaneous executions of the optimisation model. Generally, some units are chosen as optimal for ecosystem services and their benefits in nearly every model run (very high agreement) and some spatial decision units never contain optimal areas (no agreement). Areas that show higher agreement are indicative of areas where restorative actions would provide optimal benefits in ecosystem services.*

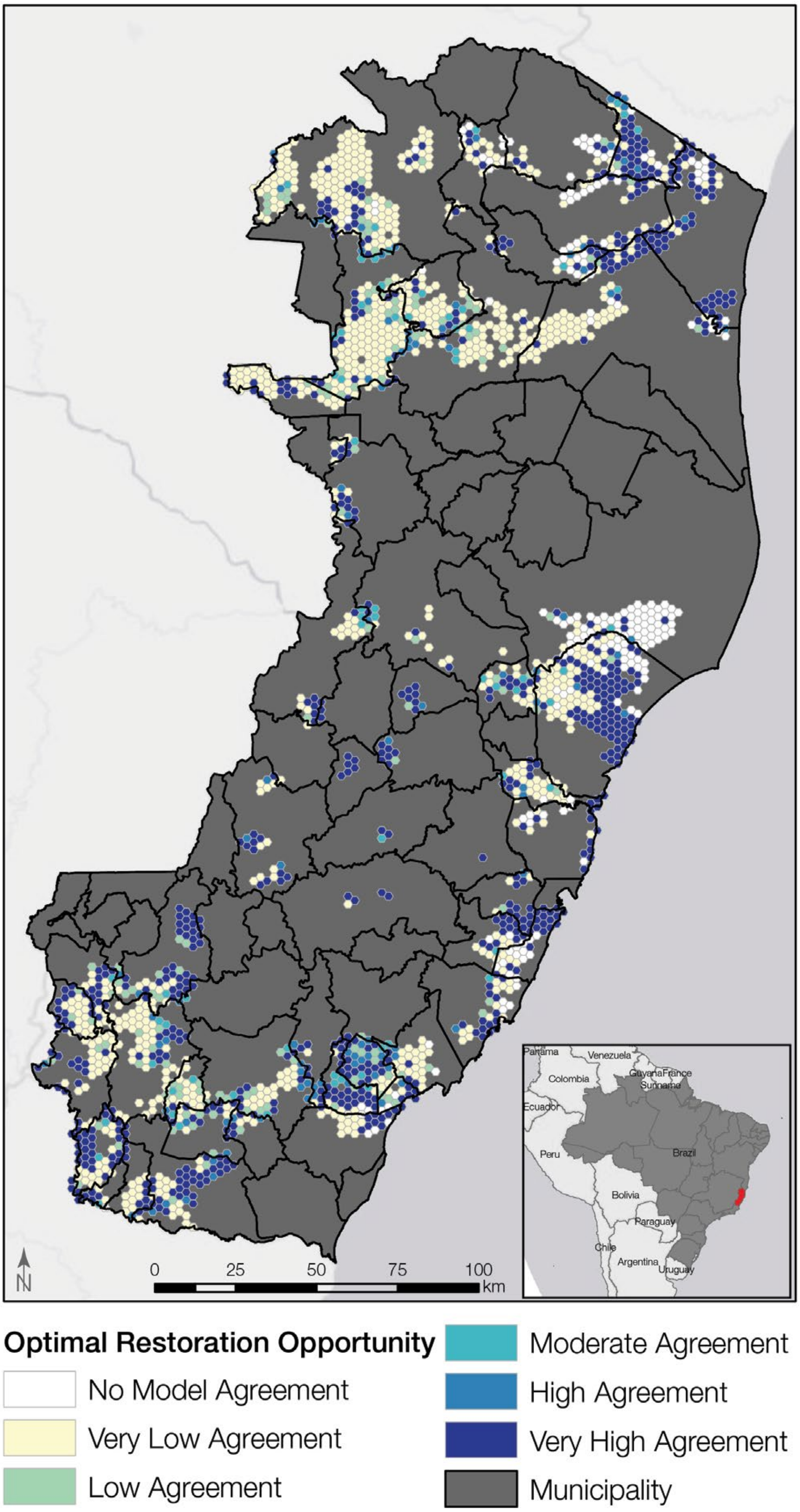


Figure 5: *Anselin Local Moran's I cluster and outlier analysis of ROOT results. This figure demonstrates the significance of optimal restoration clusters. In the previous map, many areas were identified as being optimal in a high proportion of model iterations, and this analysis demonstrates the confidence possible in whether adjacent areas are optimal as well. This should assist in determining the extent to which restoration strategies should seek to take a wide or smaller landscape approach in each of these clusters.*

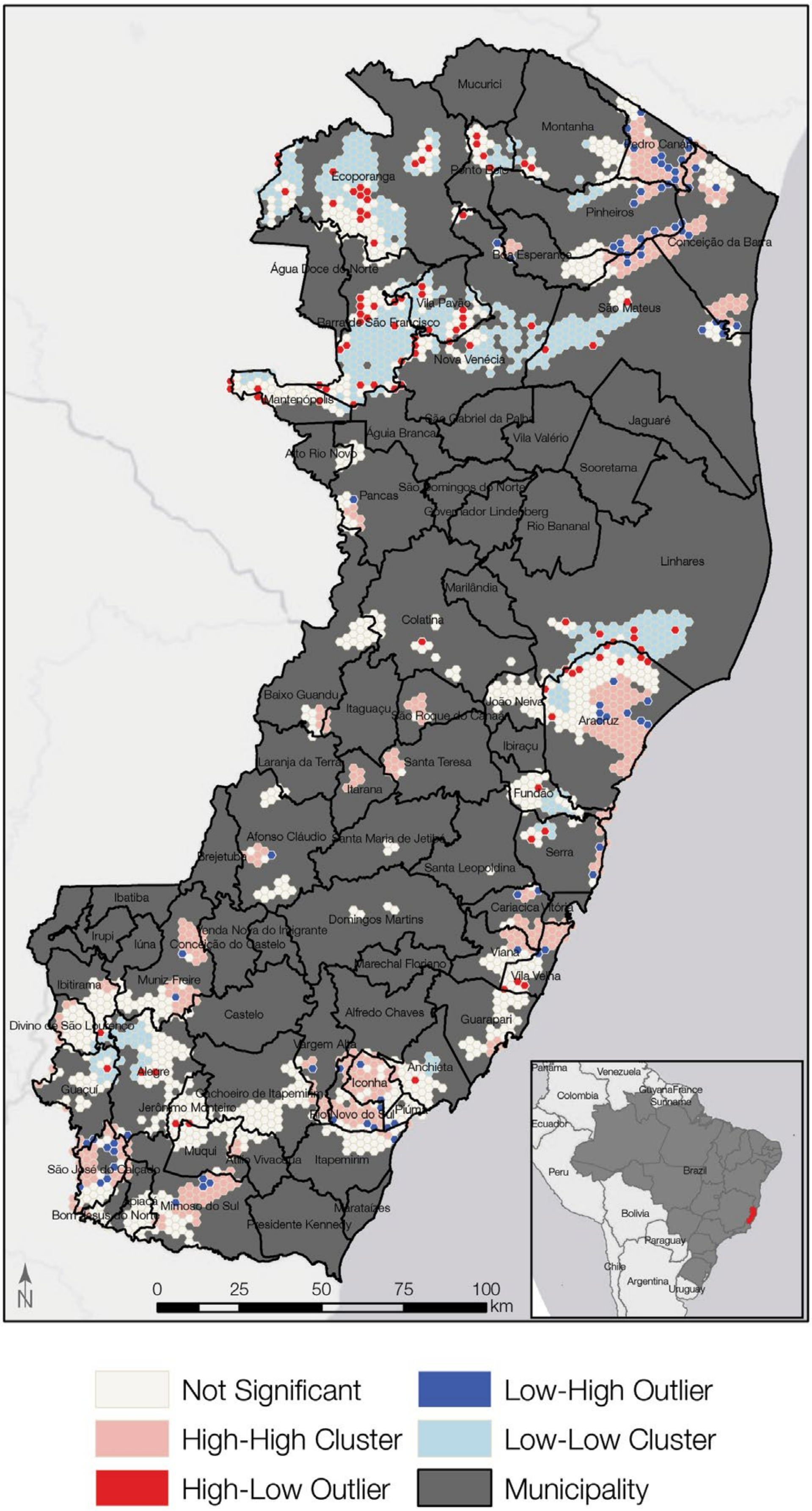


Table 3 *displays the total hectares of FLR opportunity area identified for each municipality that were calculated as optimal by ROOT. These include areas of high and very high model agreement. This represents the FLR area in these municipalities that would contribute the most to ecosystem services provision.*

NAME	ha	NAME	ha	NAME	ha
Aracruz	5,465	João Neiva	1,320	Nova Venécia	521
São José do Calçado	5,011	Vila Velha	1,266	Itarana	500
Pedro Canário	4,988	Guarapari	1,251	Alto Rio Novo	499
Rio Novo do Sul	4,761	Ibitirama	1,151	Mantenópolis	454
Conceição da Barra	4,592	Guaçuí	1,135	Colatina	435
Muniz Freire	4,405	Apiacá	1,115	Serra	431
Ecoporanga	4,042	Fundão	1,058	Vila Pavão	409
Alegre	2,696	Montanha	1,037	Jerônimo Monteiro	158
Mimoso do Sul	2,680	Baixo Guandu	994	Santa Maria de Jetibá	153
Iconha	2,192	Pancas	944	Domingos Martins	90
Pinheiros	1,897	Divino de São Lourenço	925	Santa Leopoldina	70
Viana	1,800	Cachoeiro de Itapemirim	877	Iúna	39
Piúma	1,598	São Roque do Canaã	866	Alfredo Chaves	25
Boa Esperança	1,552	Muqui	862	Castelo	25
Afonso Cláudio	1,514	Bom Jesus do Norte	827	Vitória	13
Ponto Belo	1,492	Santa Teresa	761	Água Doce do Norte	11
Anchieta	1,479	Vargem Alta	726	Conceição do Castelo	6
Cariacica	1,372	Barra de São Francisco	580	Águia Branca	1
Itapemirim	1,345	Linhares	577	Total ha 'very high' and 'high' agreement: **78,903**	
São Mateus	1,327	Atilio Vivacqua	577		

The cluster analysis identifies 42,173 hectares of FLR opportunity that occur in high-high cluster areas. This indicates that at least half of Espirito Santo's Bonn Challenge commitment of 80,000 hectares can be implemented in areas that are highly optimal for ecosystem service provision and clustered with similar high priority areas. Conversely, since contiguity is not a requirement in ROOT, restoration opportunities have the potential to be widely distributed. The cluster analysis shows that over 50% of the optimal restoration opportunity occurs in high value clusters. This lends itself well to intervention actions and investment scenarios that can be tailored to these high value clusters. It also provides municipalities with confidence in the design and implementation of restoration strategies.

Also interesting is that ROOT has identified nearly 80,000 hectares of FLR opportunity area that is in high or very high agreement for ecosystem service optimisation, including the hectare totals of this opportunity by municipality. If implemented, this would achieve Espirito Santo's commitment to the Bonn Challenge and do so in a manner that most optimally increased ecosystem services within the State, especially for low-income people in priority watersheds.

Conclusion

The objective of FLR assessments is to provide a decision context for landscapes whereby both ecological and economic productivity can be increased. To accomplish this for the ecosystem services of concern in Espirito Santo, these services were placed into the context of FLR activities that would occur in two main land uses (pasture and macega) and calculated to include the highest possible ecosystem services provision based on a restoration to native forest (in support of Atlantic Forest restoration efforts). The results from the ecosystem services assessment in Espirito Santo have been used to build political support for restoration. Quantitative approaches such as this for ecosystem services offer reference numbers that can be used for analysing scenarios. In other words, these scenarios provide a baseline for understanding eventual gains and losses from FLR when moving away from business as usual. Showing how people can benefit from restoration actions both in terms of societal benefits and specific economic benefits derived (or avoided) from the investment in ecosystem services through restoration is useful. Furthermore, it is an effective strategy to search for a middle ground where convergent interests can be accommodated in one single common vision. If on one side such an approach can demonstrate how forest landscape restoration can generate benefits beyond the ecological realm, on the other it can help to translate ecosystem services improvements into general terms that can be understood by different sectors of society. The ecosystem services information is also key for engaging decision makers from many different sectors and management groups, as the allocation of resources for restoration programmes can be more objectively distributed based on the potential to accumulate multiple cross-sectoral benefits from one intervention action. Moreover, the quantitative approach adopted has been shown to influence agenda-setting at the state level; as decision makers understood all the benefits related to forest landscape restoration, they started to incorporate other agendas such as food security, ecosystem-based adaptation and gender equity, among others, into discursive propositions.

In this context, these ecosystem service results have allowed the State to strengthen the existing PES program, incorporating quantified ecosystem services into planning. Such effort can guide the programme towards promoting long-term water conservation. Despite a successful trajectory and the sound results obtained so far, defining clear targets and audiences can help to improve the programme, moving away from blind decisions based mainly on opportunistic coincidences. While this water conservation programme currently includes the water yield and sediment delivery ratio information as ecosystem services on which payment systems can be allocated, ROOT intends to provide a more comprehensive assessment of where PES schemes could be optimised. The ecosystem services analyses are a snapshot of service potential and do not necessarily indicate the dynamics of these services within scenario planning.

The assessment of ecosystem services for PES schemes using ROOT can go beyond assessing areas as either high priority or low priority for increasing the delivery of ecosystem services. ROOT allows the stakeholders and decision makers within the Espirito Santo FLR assessment process to build faith in optimised restoration activities that have the potential to deliver the ecosystem service benefits (namely, increased water retention and reductions in the erosion of topsoil) in the best areas to support specific social benefits. This information provides decision makers at the state and local levels with confidence that restoration actions can deliver optimised benefits. This increases the accumulated potential benefits achieved through landscape restoration and directs investment to places where these benefits will have the most impact for people and nature.

Malawi

Maize, power and gender: balancing restoration decisions in Malawi

Craig R. Beatty

In 2016, at the IUCN World Conservation Congress in Honolulu, Hawai`i, the government of Malawi committed to placing 4.5 million hectares of degraded and deforested land under restoration by 2030, in support of the Bonn Challenge. Malawi has since worked to identify and address possible pathways to achieving these commitments through the national forest landscape restoration assessment (NFLRA) (Ministry of Natural Resources, Energy and Mining – Malawi, 2017a) and subsequent implementation strategy (NFLRS) (Ministry of Natural Resources, Energy and Mining – Malawi, 2017b). Malawi's high population density, having more than quadrupled since 1964, has placed considerable strain on natural resources, and poverty and inequality remain persistent despite a relatively stable democratic government (Bone et al., 2016; World Bank, 2017). Malawi's main challenges continue to be food security and socio-ecological resilience to natural and economic variability. At the heart of many of Malawi's social and ecological challenges is a significant reliance of the rural poor (85% of Malawi's population) on natural resources. Unsustainable use of these common resources has led to drastic reductions in the function of ecosystems across Malawi and the products and services they provide to people, further reinforcing a lack of social and ecological resilience. Therefore, There are many opportunities in Malawi for addressing wide-scale landscape degradation through restoration.

The role of ecosystem services and biodiversity featured prominently in Malawi's NFLRA. The NFLRA had three primary objectives for what forest landscape restoration interventions were intended to achieve. Any restoration activities ideally would support at least one of the following objectives: 1) to strengthen food security, 2) to increase resilient landscapes, and 3) to support biodiversity. To help define the areas where each of these themes could be addressed through restoration, IUCN and The Natural Capital Project completed a national analysis of several ecosystem services using InVEST (Sharp et al., 2016).

In preparation for the NFLRA, IUCN, with assistance from The Natural Capital Project, completed a national ecosystem services analyses using the InVEST tool to model carbon sequestration, sediment delivery/retention, actual evapotranspiration and water yield. The choice of these ecosystem services was originally intended to support the national assessment of degradation and so utilised ecosystem service components that had a degradation component. In the assessment, actual evapotranspiration, especially low values, were used to indicate dry areas. Where these areas were not historically dry, this assessment was used as a proxy for landscape degradation. This was similar for sediment export to streams. These assessments of ecosystem services for Malawi are, to our knowledge, the first to be completed at the national level, and represent a significant new information source for landscape managers, especially within the Ministry of Natural Resources, Energy, and Mining and the Department of Forestry. Within the NFLRA, portions of these new data sets were used as criteria within a multi-criteria analysis of degradation (see Figure 6). Especially important were the roles that actual evapotranspiration (as a function of the yield potential for maize (Koffi Djaman et al., 2013)) and sediment export to streams played in the assessment of landscape degradation for Malawi. Each of these ecosystem services alone can be powerful in helping landscape managers determine the level of degradation that they can expect within Malawi, and when combined with other proxies for degradation they can build a representative picture of the intensity of degradation.

Additionally, low water yield was also used in assessing the potential for addressing resilience in a similar multi-criteria analysis. This service indicated that above a minimum threshold, low values for water yield indicated areas that were typically dry and where FLR activities could have a positive effect on building more resilient landscapes through increasing the potential of water to be held by plants and soil, resulting in more yield of water from pixels across the landscape.

While the quantification of these ecosystem services provided new information for the landscape restoration assessment, they only provide a snapshot of ecosystem services at one point in time. The ecosystem services assessments using InVEST provide vital information on where knowledge or information about ecosystem services are strongest and where they may be weakest, but these assessments do not assess the trajectory of these ecosystem services further than to say that Malawi consistently battles ecosystem degradation and it can be inferred that in a business-as-usual scenario, ecosystem services would continue to decline.

Through the following analysis using ROOT, InVEST modelled the maximum potential increases in ecosystem services that would result from the restoration of degraded land to forest for each of the ecosystem services. For the purposes of this analysis, the restoration of these areas to forest was independent of underlying land use and land cover, such that all priority areas identified as degraded (categories 4–8 in Figure 6 below) were converted to forest in restoration the ROOT scenario.


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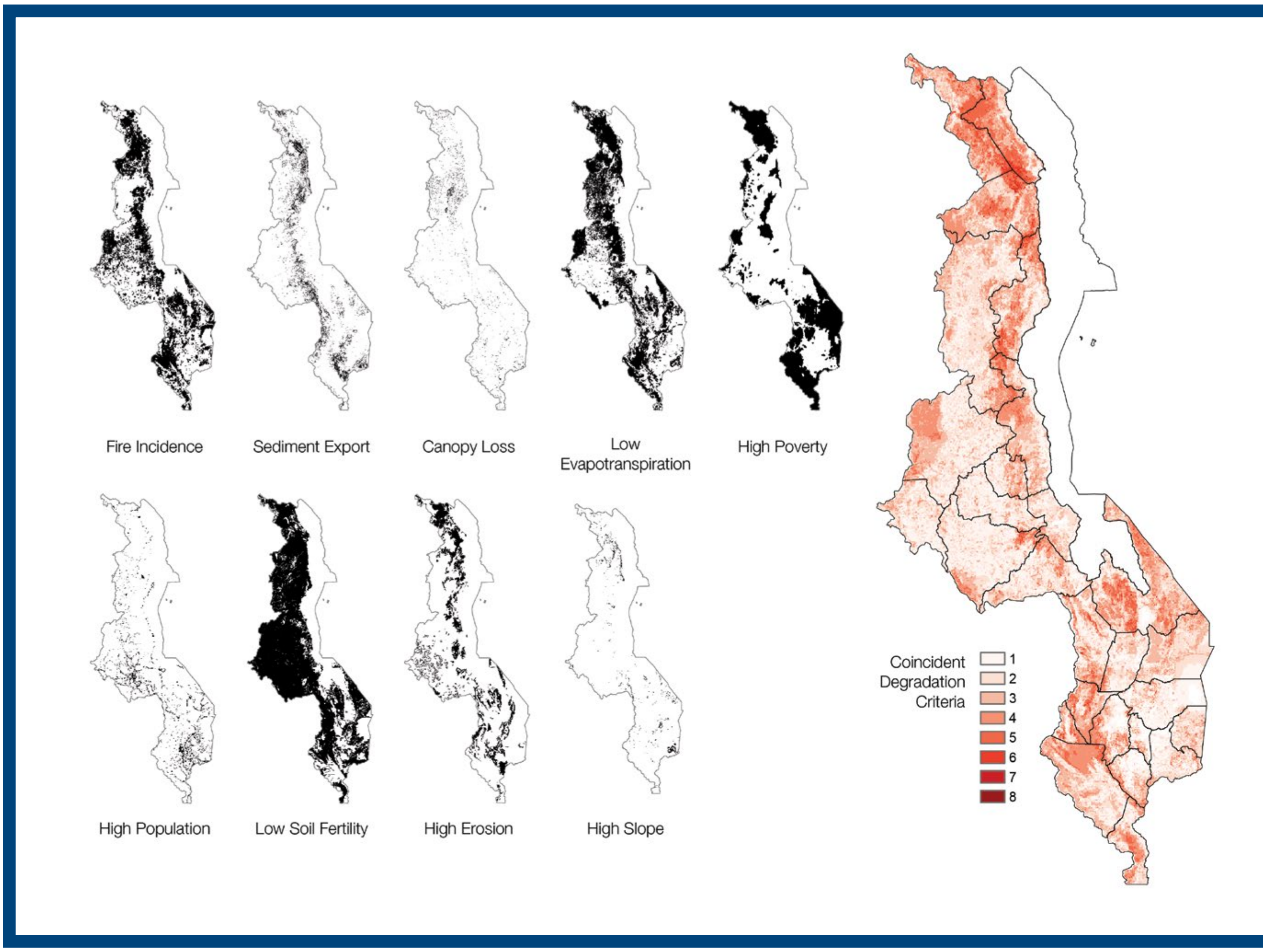
Figure 6 *shows the full multi-criteria degredation assessment for Malawi. Darker red indicates more overlapping degradation criteria*
Source: Ministry of Natural Resources, Energy and Mining - Malawi (2017a)



Utilising ecosystem services information

The Ministry of Natural Resources, Energy and Mining can now utilise this baseline ecosystem services information for any number of questions. However, the analysis was incapable of demonstrating one critical reality: there are spatial trade-offs for where forest landscape restoration could contribute to increasing different ecosystem services. One common example is the trade-off among restoration for increased carbon stocks and for increased water yield. As carbon stocks increase (through forest restoration, for example) the available water is often used by growing forests, sometimes leading to lower water yields (Filoso et al., 2017), (although the relationships between restoration and hydrology are far from clear (see Lamb, 2018)). Many current ecosystem services modelling approaches attempt to demonstrate these trade-offs by comparison, whereby each service (carbon and water yield) is visually compared to each other service. Though there are a few examples of quantitative trade-off analysis (e.g. Bryan et al., 2015; Bryan & Crossman, 2013), this typically leads to qualitative assessments of trade-offs in ecosystem services benefits, but it does not provide a spatially explicit quantitative assessment of these trade-offs, except when aggregated by administrative level.

In Malawi, the priorities of the Department of Forestry were to explore optimal solutions for restoration actions that would create ecosystem service benefits for a combination of increased sediment retention, increased carbon sequestration and increased actual evapotranspiration. Not only was it important to demonstrate where restoration interventions could contribute to increases in ecosystem services, but it was also important to identify the locations where people would realise increases in the benefits from all of these ecosystem services. IUCN engaged with the Department of Forestry on three main questions to facilitate the application of ROOT in Malawi:

- Which of the modelled ecosystem services are most important to include in the optimisation?
- What are the highest priority areas for restoration and why?
- What is a reasonable number of hectares on which the government of Malawi can start planning FLR interventions?

The government of Malawi was interested in including all of the ecosystem services calculated for the NFLRA, which included results from three InVEST models (Sediment Delivery Ratio, Water Yield and Carbon Sequestration). Particularly important to the Department of Forestry was the sediment export to streams due to its detrimental effects on hydropower generation in Malawi. Landscape degradation, especially due to unsustainable farming practices, charcoal, and firewood production occurring upstream of power stations, lowers the potential and efficiency of hydropower generation (Eales et al., 2017). Specifically, a study by Mzuza et al. (2017) determined that the majority of sediments affecting the Nkula Dam on the Shire River originated from the western side of the Shire River, presumably due to the effects of large-scale landscape degradation.

Nearly 100% of Malawi's electricity is generated by large hydropower stations (Eales et al., 2017). However, only 12% of Malawi's rural population had access to electricity in 2012 (IEA and World Bank, 2015). Consequently, the majority of the energy needs for the people of Malawi are met primarily by unsustainable use of firewood, charcoal and kerosene. Despite the current energy situation, significant potential exists to increase the application of small-scale hydropower systems (Kaunda, 2013; Japan International Cooperation Agency, 2003). However, the impacts of climate change on the electricity potential of large and micro-hydropower schemes are significant. While research has indicated that rainfall volumes have remained relatively constant over the past 30 years, increasing temperature trends may drive additional evapotranspiration, reducing power generation (Kachaje et al., 2016). Landscape restoration has many positive implications for hydropower generation in Malawi, including reductions in landscape and watercourse temperature, reductions in sediment, and supporting sustainable access to traditional energy sources while national energy programmes are designed and implemented.

Methods

Table 4: *ROOT inputs and their corresponding details for what was included in the Malawi scenario.*

ROOT input categories	Malawi details
Impact potential maps (marginal values of ecosystem services resulting from restoration activities)	Sediment retention (Mg/ha/year) Actual evapotranspiration (m^3/ha/year) Carbon sequestration (Mg/ha/year to 2050)
Servicesheds	Hydropower: watersheds that feed rivers and streams with important hydropower facilities or irrigation potential Poverty: average poverty percent for each water resource unit Women: proportion of women in each census tract (areas with higher proportions of women granted higher priority)
Composite factors	Sediment retention *(hydropower, poverty, women) Actual evapotranspiration *(hydropower, poverty, women) Carbon sequestration *(hydropower, poverty, women)
Activity mask	This was classified as areas where 6–8 degradation criteria overlapped. Within these degradation categories there are 91,100 ha of 6 overlapping criteria in Malawi, 8100 ha of 7, and 100 ha of 8, totalling an estimated 99,300 ha of high priority area. With the permission of the Forest Department, this figure was rounded to 100,000 ha and considered a reasonable area constraint for the optimisation.
Objectives (must account for positive or negative input values since objectives are multiplied in the analysis)	Maximize composite factor of [sediment retention *(hydropower, poverty, women)] Maximize composite factor of [actual evapotranspiration *(hydropower, poverty, women)] Maximize composite factor of [carbon sequestration *(hydropower, poverty, women)]
Targets	50,000 ha

Ecosystem service modelling

This analysis applied the InVEST sediment delivery ratio ('sediment') model, water yield model, and carbon sequestration model (Sharp et al., 2016, version 3.3.3). The potential impact of forest restoration on ecosystem service provision for each of these ecosystem services was calculated by analysing the difference in values between the ecosystem service delivery under baseline conditions and then under an FLR scenario derived from the 2017 NFLRA. These values represent the potential changes in ecosystem service provision following a restoration scenario. For additional information on how these ecosystem services and the restoration opportunity areas were calculated, please refer to Malawi's NFLRA report (2017a).

For this analysis, the ecosystem service of sediment export refers to the mass of sediment that is carried into stream and river networks within Malawi, expressed as the mean annual sediment export in tons per year. Through restoration of landscapes, it is expected that sediment export to streams will be reduced, leading to increases in water quality and reductions in both the destructive flow of water across landscapes and the mass of sediment that can be captured by flowing water.

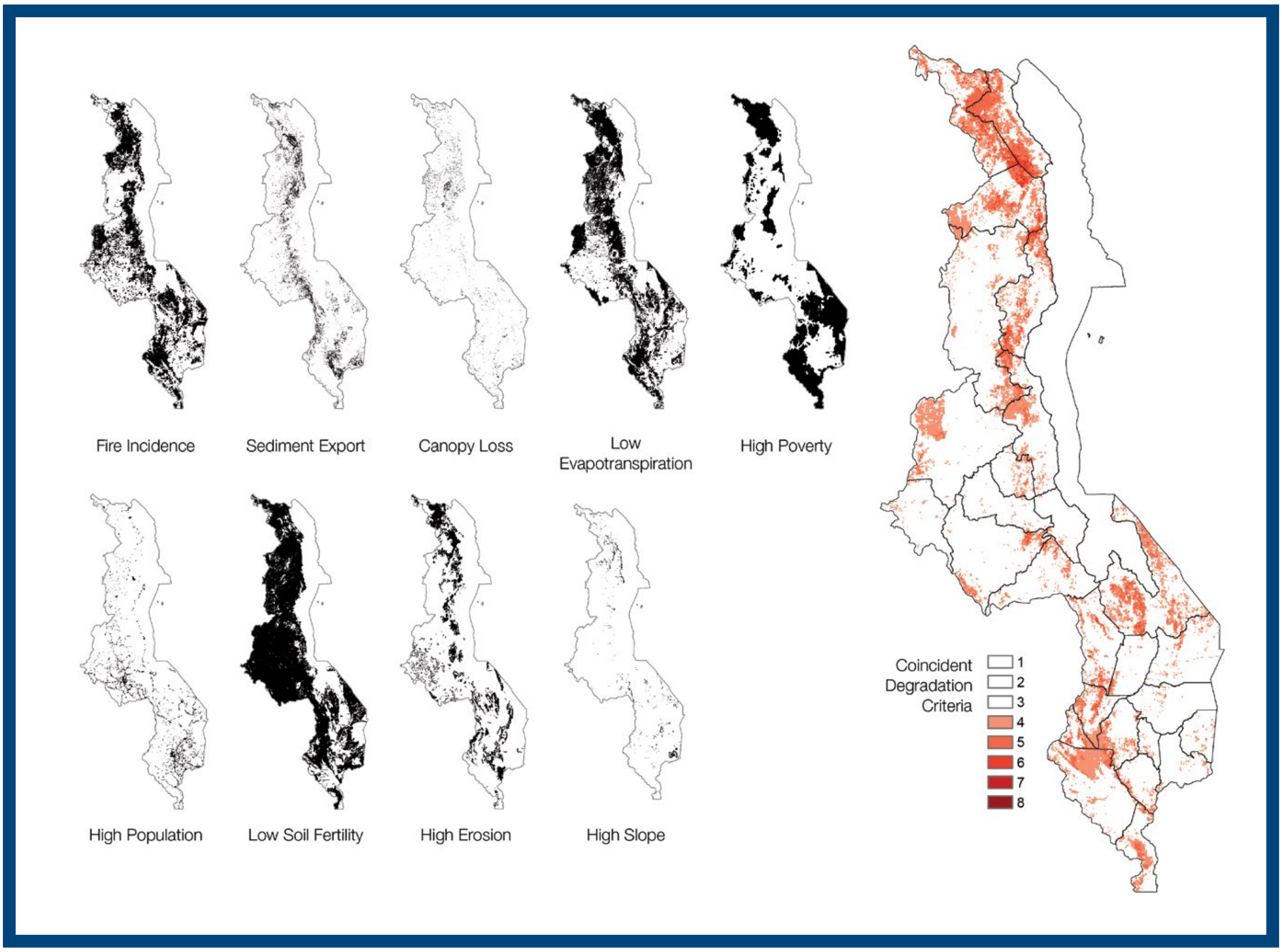
To create maps of restoration potential for carbon sequestration, an InVEST model was run to determine the potential mass of sequestered carbon from forest restoration activities 2010–2050. The InVEST Carbon model shows where carbon sequestration can be improved outside of the current protected areas system, forgoing any implication of FLR activities in protected areas, though these areas may ultimately require consideration for restoration actions.

Impact potential maps were created based on a condensed version of the FAO LULC dataset (see Annex) used in the InVEST analysis for Malawi's ecosystem services. For each of the three ecosystem service models (sediment delivery ratio, water yield, carbon sequestration), underlying land use/land cover categories that overlapped with the area of interest were converted to forest. The InVEST analysis for each service was then recalculated using the 'restored' land use/land cover. The difference in ecosystem services values between the original InVEST analyses and the values calculated from the restored scenario indicate the potential maximum gains in ecosystem services for these areas were they restored or converted to forest.

Activity mask

The activity area for this optimisation was calculated based on the number of coincident degradation criteria (as described in the NFLRA, 2017, pp. 33). Based on a consultation with the Department of Forestry, areas that contained 4–8 overlapping degradation criteria within Malawi were extracted, and this area was considered the operating activity area for forest landscape restoration in Malawi for this exercise. This layer represents the 'opportunity area' in Malawi for addressing high-level functional degradation through FLR interventions, and forms the areas within the ROOT model where ecosystem services are optimised.

Figure 7 *demonstrates the input criteria (black maps) and the resulting overlaps in these inputs where more than 3 criteria overlap. All black areas indicate the presence of an appropriately parameterized input criteria (as defined in the NFLRA 2017). Red areas indicate 'restoration opportunity' used as the potential area for restoration in ROOT. Source: Ministry of Natural Resources, Energy and Mining - Malawi (2017a)*



Beneficiaries

Watersheds supporting hydropower generation

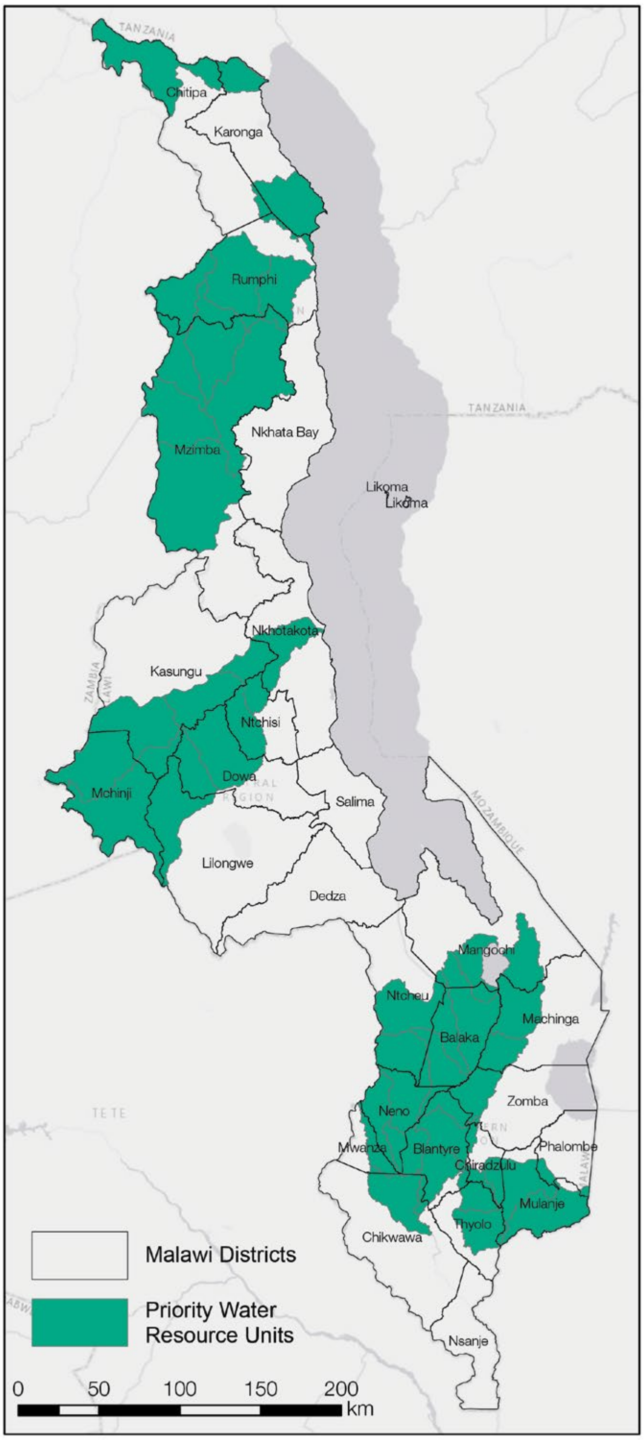
Serviceshed were based on a need to identify areas where ecosystem services could be generated to support hydropower/irrigation dams and where they could best support the rural poor. The first prioritisation was including watersheds that support actual or potential hydropower generation. This was based on spatial data on dams that was available through the Malawi Spatial Data Platform[4] as well as the location of dams from AquaSTAT's geo-referenced dams database[5]. These dams were used as pour points during a typical watershed model delineation process using the Hydrology toolset within ArcMap 10.3.1 (ESRI, 2016). It should be noted, however, that the quantity of dams and hydropower facilities in Malawi is certainly larger than the number included in this analysis. Kaunda (2013) outlines the vast potential for small-scale hydropower systems in Malawi and includes several examples of small-scale projects used to generate electricity that are not included in national reports or plans or in this analysis.

The servicesheds for hydropower were drawn from the DelineateIT tool (InVEST 3.3.1), which used the location of hydropower facilities in Malawi and a digital elevation model to delineate the watersheds that contribute water to the large hydropower facilities in Malawi. These delineated watersheds were then compared to results from Malawi's National Water Resources Master plan and the nationally defined water resource units. Spatial overlaps between watersheds delineated from the digital elevation model (DEM) and the nationally defined water resource units were used as the priority water resource units within ROOT. Water resource unit ranks, based on a summary implementation schedule of irrigation development area (5000ha/year) from Malawi's National Water Resources Master plan (JICA, 2014, Table 3.5.15) were then joined to the spatial layer of priority hydropower watersheds to provide a magnitude of priority for each water resources unit, to provide both hydropower and irrigation. Ranks were based on a composite additive ranking score based on project cost efficiency, development effect area, and water supply potential. Higher ranks indicated higher potential for additional irrigation capacity within the water resource unit—conferring higher restoration priority.

High poverty areas

In addition to the support landscape restoration can provide to watersheds that provide hydropower, restoration in water resource units with high average levels of poverty were also included as a priority for augmenting ecosystem services. Poverty data was acquired through the National Forest Landscape Restoration Stocktaking & Mapping working group and sourced from Regional Centre for Mapping of Resources for Development (RCMRD) and Malawi Department of Disaster Management Affairs (DoDMA). These data were then aggregated and averaged by water resource unit to provide a measurement of poverty level by watershed. The inclusion of poverty as an appropriate serviceshed aims to guide the optimal delivery of increased ecosystem services both towards areas that are important for hydropower/irrigation as well as towards areas where these ecosystem services will more profoundly benefit the rural poor.

***Figure 8** shows the main water resource units within Malawi that support major hydropower and irrigation sites. Within these areas restoration to support the provision of water quantity and reductions in sediment*



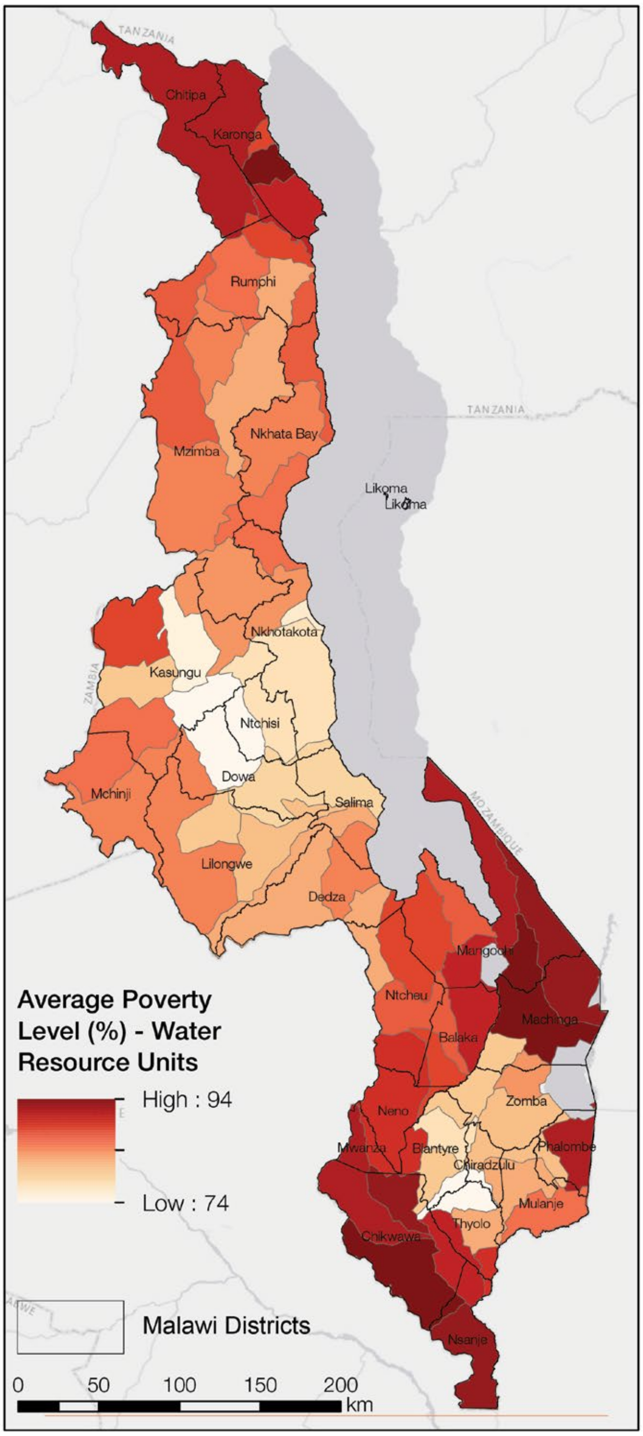
Areas with proportionally more women

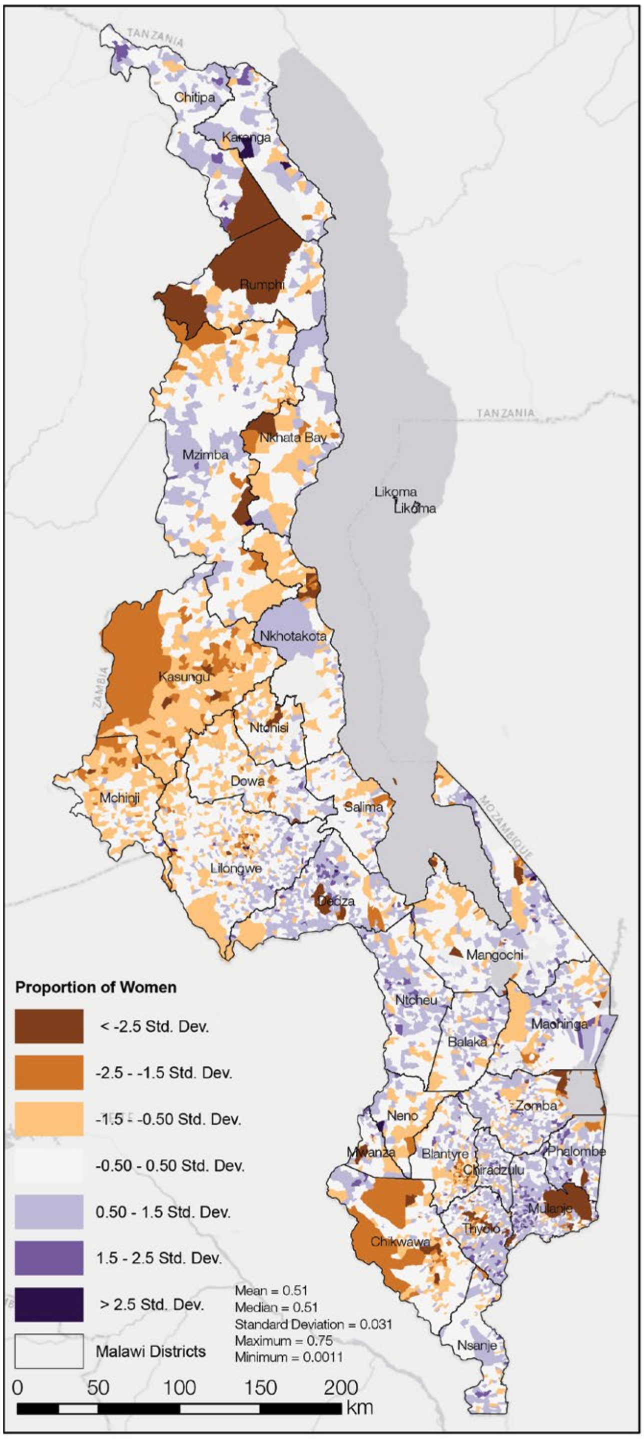
Last, but not least, the proportion of women within an enumeration area formed the final beneficiary consideration in the model. These data were sourced from Malawi's National Statistical Office and represent gender proportions from the 2010 National Census. Values of proportion of women were calculated for each enumeration area and then used as priority weights in the optimisation. Higher proportions of women were granted higher priority in the analysis to indicate a higher preference for restorative actions in areas where benefits have a higher mathematical potential to accrue for women.

[4] Malawi Spatial Data Platform (MASDAP). http://www.masdap.mw/
[5] AQUASTAT is FAO's global water information system http://www.fao.org/nr/water/aquastat/dams/index.stm

Figure 9 *demonstrates the average poverty level of people living in Malawi's water resource units. Darker red indicates a higher density of people living in poverty.*

Figure 10 *utilises Malawi census data to calculate the proportion of women for each enumeration area in the census. Purple areas indicate proportionally more women.*





TIP

If ecosystem service values or factor (serviceshed attribute) values are negative, it is important to determine whether the result of combining these factors through multiplication would produce negative or positive values and then determine if the objective of restoration is to increase values or decrease values. ROOT will optimise based on minimising or maximising values, so it is key to determine through an assessment whether higher negative values are sought and if so to indicate in the ecosystem services objectives table that ROOT should choose minimised values during the optimisation.

Data processing for ROOT

Biophysical

While it is possible in ROOT to combine all servicesheds and ecosystem services into one composite factor, this analysis intended to demonstrate how optimal areas for increasing ecosystem services might change based on the beneficiaries indicated in the model. For this reason, three separate but parallel ROOT applications using the three different beneficiary servicesheds were completed. For each of these 'composite factor' rows in Table 4 (pp. 15), ROOT multiplies the indicated factor components and produces a result labelled with the 'name' indicated in the table. Actual evapotranspiration (aet) ecosystem service values were multiplied by the weight of hydropower priority watersheds based on their ranking for irrigation potential as well. The ecosystem service objectives allowed for the possibility of informing the model whether the composite factor values should be minimized or maximised. This is dependent on both the type of ecosystem service under analysis and the factors with which it is combined. In this case, each of the three ecosystem services would ideally be maximised by restoration actions: evapotranspiration would increase as more vegetation covered the landscape, sediment retention would increase and roots would stabilize run-off and soils, and carbon sequestration would increase due to increases in biomass.

Opportunity areas

A constraint is a necessary component of the optimisation model, as it forces the optimisation algorithm to find a solution that includes some areas and excludes others. In restoration, area constraints can be commitments to a defined number of hectares, as under a Bonn Challenge contribution. Alternatively, they can represent the maximum calculated area that can be restored based on an available budget and an estimate of the cost of restoration per unit area. Still further, constraints can represent an estimation of the feasible area to begin restorative activities. In the case of Malawi, having a large Bonn Challenge pledge (4.5 million hectares) and an undermined budget for FLR in the short term, Malawi indicated that the area of the most intensely degraded areas in Malawi could serve as a reasonable constraint. These were classified as areas where 6–8 degradation criteria overlapped. Within these degradation categories there are 91,100 hectares of 6 overlapping criteria in Malawi, 8100 hectares of 7, and 100 hectares of 8, totalling an estimated 99,300 hectares of high-priority, highly degraded area. With the permission of the Forest Department, this figure was rounded to 100,000 hectares and considered a reasonable area constraint for the optimisation.

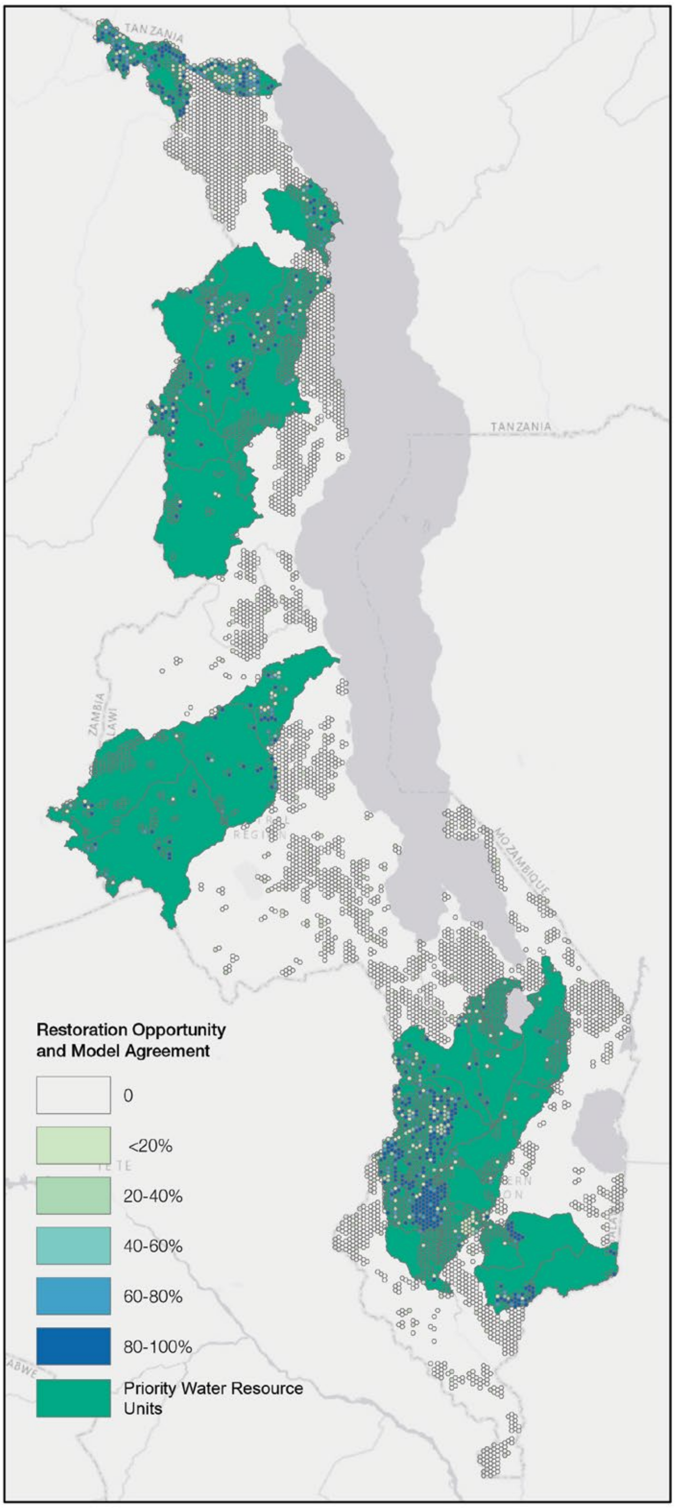
Results

Hydropower/Irrigation:

The composite analysis of ecosystem service benefits for power and irrigation beneficiaries identified priority areas for restoration. This analysis considered only water resource units that supply water for hydropower and their irrigation potential, which tend to cluster to the west of the Lower Shire River (Balaka,Ntcheu, Neno, and Blantyre Districts) and in Northern Malawi (northern Chitipa and Karonga Districts). These areas have the highest potential to support both hydropower production and irrigation projects in areas that are currently classified in the National Forest Landscape Restoration Assessment and Strategy as moderately or highly degraded. Additionally, there are high quality restoration opportunities in each of the priority water resource units, many of which are less clustered than in the North and Lower Shire. Additionally, Anselin Local Moran's I cluster analysis of ROOT agreement data confirms the significance of clustering for priority restoration areas in these regions (see figure 12).

Figure 11 *shows the areas most often selected by ROOT as optimal for restoration to support increases in all three ecosystem services within watersheds important for irrigation and hydropower generation.*

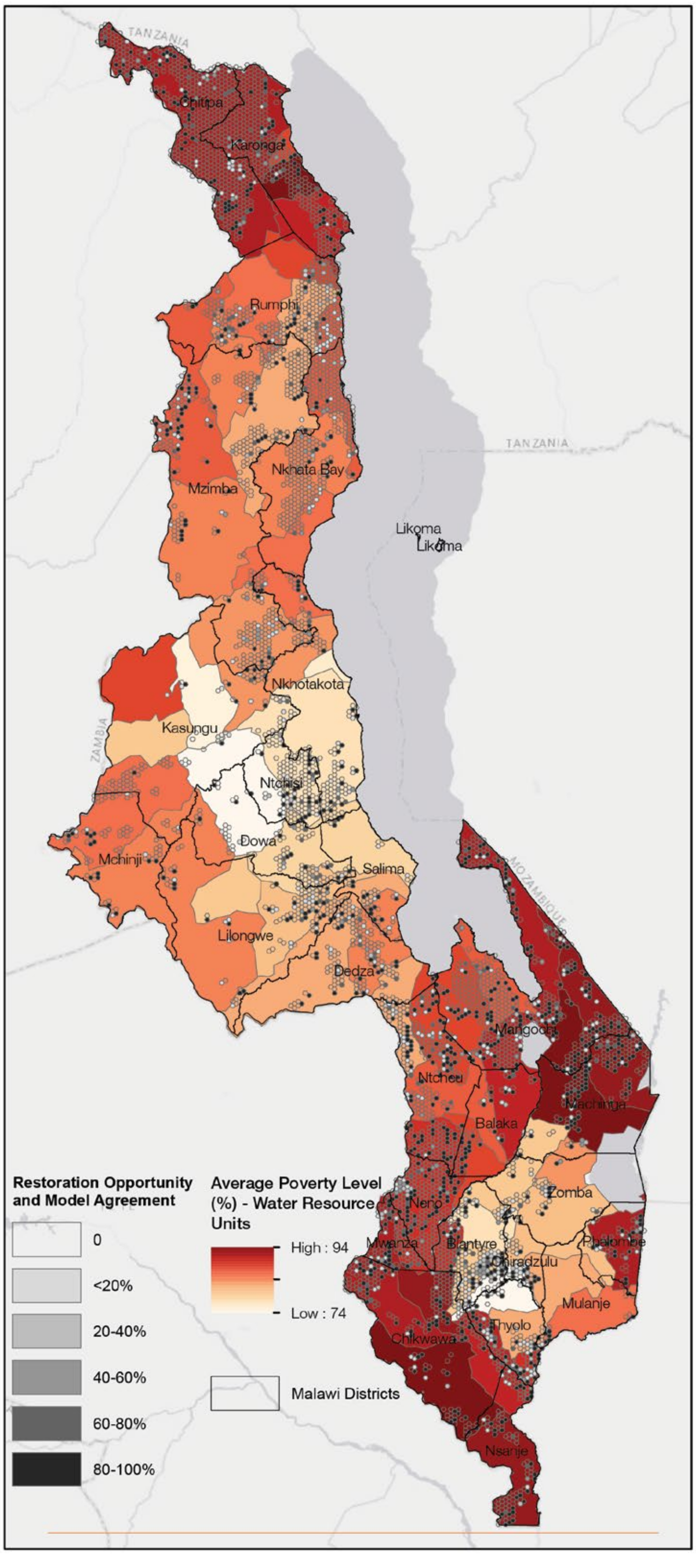
Figure 12 *shows the results of a statistical cluster analysis. This analysis provides statistical confirmation of clustering patterns observed in ROOT results and gives confidence of the priority areas to implement restoration for optimal ecosystem service and beneficiaries' benefits.*



Poverty: The optimal areas for ecosystem service augmentation when prioritised based on poverty averages in water resource units is far more distributed across Malawi than when based on any other beneficiary input. Every district has at least 1000 hectares of highly optimal area for FLR interventions to support increases in ecosystem services within high poverty areas. Since the lowest poverty level in a water resource unit is 74% and most districts have poverty levels upwards of 85%, a wide distribution of optimal ecosystem services opportunity is expected. Despite the distributed optimisation, Anselin Local Moran's I cluster analysis shows significant clustering of optimal results within areas where poverty is high in Blantyre and Neno Distrcits and along the border between Machinga and Mangochi Districts, and a small but distinct cluster in Southern Chitipa District (see figure 14).

***Figure 13** demonstrates the distribution of optimal areas for restoration to support increases in ecosystems services, weighed towards areas with high average poverty levels which may disproportionally benefit the poor.*

***Figure 14** shows the results of a statistical cluster analysis. This analysis provides statistical confirmation of clustering patterns observed in ROOT results and gives confidence of the priority areas to implement restoration for optimal ecosystem service and beneficiaries' benefits.?*

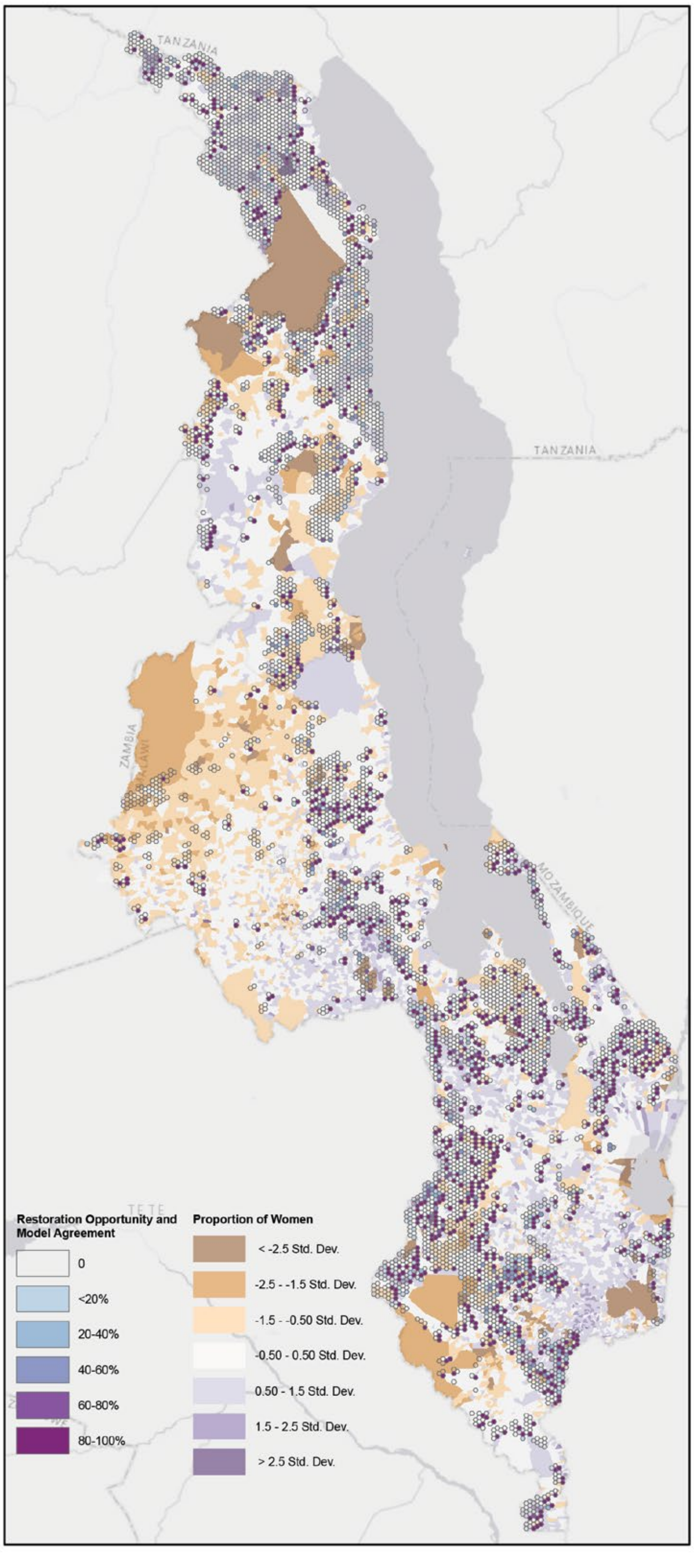


Proportion of women:

Agreement within the 50 iterations of the ecosystem service optimisation for proportion of women, similar to average poverty optimisation, produces a widely distributed map of optimal areas for increasing the values of many ecosystem services in areas where the proportion of women is high. This points to the necessity of including cosmopolitan, gender-based approaches in FLR planning and implementation throughout each district and in any intervention. Further cluster analysis using Anselin Local Moran's I demonstrates that the distribution of clusters of areas significant based on the proportion of women present is wide.That said, there are a few notable clusters, including areas along the southern borders of Ntchisi and Nkhotakota Districts, along the southern border of Blantyre and Chiradzulu Districts, and within Neno District (Figure 16).

Figure 15 *shows the areas where restoration would optimally benefit ecosysetm services, weighed towards areas where there are proportionally more women*

Figure 16 *shows the results of a statistical cluster analysis. This analysis provides statistical confirmation of clustering patterns observed in ROOT results and gives confidence of the priority areas to implement restoration for optimal ecosystem service and beneficiaries' benefits.*

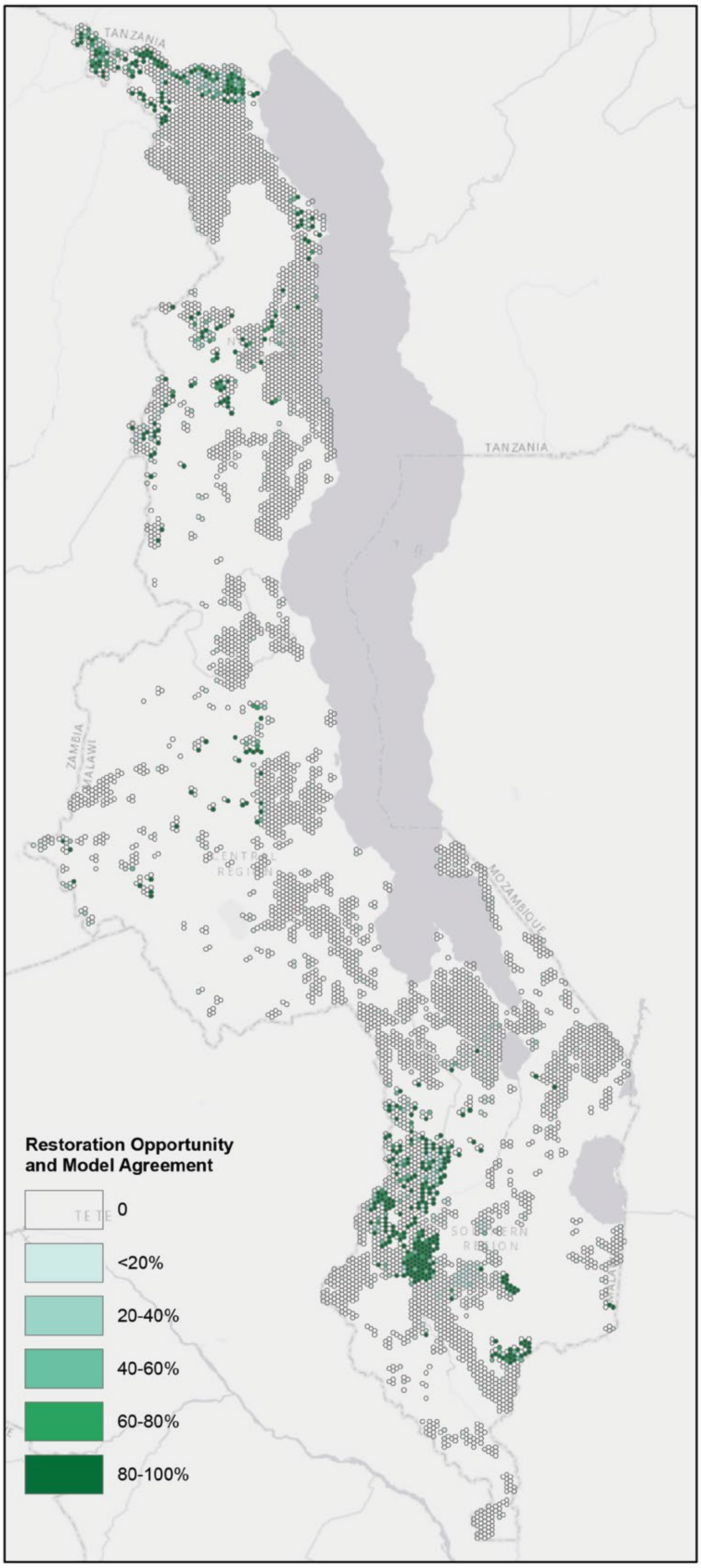


Composite map:

The results of the composite analysis of all three ecosystem services and all three beneficiary layers clearly show priority areas for forest landscape restoration along the Lower Shire River in the districts of Neno, Ntcheu, Blantyre, and Thyolo and Malawi's northern border with Tanzania in Chitipa District. Apart from these clusters, there are several smaller areas with 500–2000 hectares of optimal areas. Again, Anselin Local Moran's I cluster analysis of ROOT agreement data confirms statistically significant clustering for optimal restoration (Figure 18).

***Figure 17** shows a composite optimisation based on all three ecosystem services and all three beneficiaries.*

***Figure 18** shows the results of a statistical cluster analysis. This analysis provides statistical confirmation of clustering patterns observed in ROOT results and gives confidence of the priority areas to implement restoration for optimal ecosystem service and beneficiaries' benefits.*



Conclusion

This case study, drawn from basic ecosystem services data calculated for Malawi during the NFLRA, demonstrates how spatial data on ecosystem services can be placed within a decision context and optimised to further refine and guide the decision-making and implementation process of landscape restoration. The results of these analyses were delivered to the government of Malawi for use in planning the implementation of the National Forest Landscape Restoration Strategy. With a significant amount of identified restoration opportunity throughout Malawi, these analyses provide a refined analysis of where the most highly degraded areas coincide with areas that have the most potential for increases in ecosystem services for specific beneficiaries.

These analyses demonstrate that even within optimisations for ecosystem services, hotspots can be identified where landscape-scale restoration would benefit people and ecological productivity. Taking these analyses individually, decision makers can see where investments in restoration could be made to optimise the benefits delivered for hydropower and irrigation, where increases in ecosystem services could help alleviate extreme poverty, and where increases in ecosystem services might disproportionately flow to women based on their proportion of the population. Individually, each of these approaches would have merit in the landscape and restoration planning process.

However, as a composite, these analyses provide an index of value for supporting increases in multiple ecosystem services for many beneficiaries at a national scale. As a result, some of the specificity of beneficiaries is averaged into indexed values, which allows for a broad assessment of optimal areas for restoration (Figure 17), but dulls the specificity available in the single-beneficiary optimisations (Figures 11, 13, 15). The composite optimisation represents a modelled index of restoration value for the selected ecosystem services and beneficiaries. If restored, these areas would contribute the highest ecosystem service gains for the beneficiaries included. From a policy perspective, these areas represent geographies where restoration could be most efficiently employed to address the underlying drivers of degradation and support increased ecological productivity for people and processes.

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CHINA
BHUTAN
BANGLADESH
INDIA
MYANMAR
VIETNAM
LAOS
THAILAND
CAMBODIA

Myanmar

A landscape approach to reducing disaster risk and improving livelihoods in Myanmar

Craig R. Beatty[6] and Adrian L. Vogl[7]

Myanmar remains one of the most heavily forested countries in the world;over 45% of Myanmar's land surface is forested despite significant deforestation in the last several decades. Local fuelwood extraction and the expansion of agriculture and aquaculture, in addition to international demand for high-quality timber – including illegal logging – has largely driven land use change. Recognizing the rapid decline in forest and mangrove cover and its implications for people and landscapes, the Government of Myanmar Forest Department of the Ministry of Natural Resources and Environmental Conservation (MONREC) enlisted the assistance of IUCN in supporting efforts to assess opportunities to restore degraded and deforested landscapes.

This process began in November of 2016 and included a three-day workshop to focus on forest landscape restoration as a comprehensive approach[8]. This workshop assembled key stakeholders from government, civil society, non-governmental organisations, and inter-governmental organisations to explore the current status and trends of landscape degradation, restoration goals and needs, technical products and methodologies, and an in-depth presentation on ROAM (IUCN & WRI, 2015) and its potential in Myanmar. This workshop defined a list of objectives for restoration in Myanmar as well as an assessment of the steps required to assess and scale up the use of data, economics and policies to support practices that contribute to landscape restoration and sustainable development.

Furthermore, this workshop intended to build upon Myanmar's 10-year Restoration and Rehabilitation Programme, which includes preliminary details on the locations, objectives and projected outputs of large-scale restoration of deforested landscapes (MONREC, 2016). This plan and the results of the workshop demonstrated a need for inter-sectoral collaboration and the input of stakeholders at multiple administrative levels. It also highlighted the need for accurate data and spatial analysis to support restoration planning, especially for ecosystem services, and the alignment of environmental, trade and agricultural policies – including financing strategies – to create the conditions upon which a restoration initiative could achieve long-term success.

Broadly, the objectives of FLR defined by the workshop participants included increasing and protecting ecosystem services (fuelwood, watershed regulation, climate change adaptation/mitigation and biodiversity), increasing community development, supporting economic development and income diversification, and a more comprehensive inclusion of stakeholders for many sectors, especially women and youth, in the landscape planning and decision-making process.

Additionally, severe flooding from June through September 2015 affected millions of people, destroyed an estimated 1.2 million hectares of rice, and led to, among other adaptation initiatives, a national ecosystem services assessment led by WWF-US, WWF-Myanmar and The Natural Capital Project. These assessments were undertaken at the request of the President of Myanmar as a means of both testing the potential of developing a green economy and providing basic ecosystem services information that would conceivably be helpful for landscape planning and decision-making. The results of these analyses[9] jump-started a conversation on Myanmar's sustainable development and natural capital, including how regional and landscape planning could help alleviate some of the challenges of landscape degradation and help Myanmar adapt to the effects of climate change, especially regarding flooding and water sedimentation.

In terms of forest landscape restoration, the ecosystem services data and reports developed by WWF-Myanmar and the Natural Capital Project permit advanced scenario-building around the restoration of forests and mangroves and the implications of these activities for ecosystem services and the beneficiaries that rely on them. In the following analysis, ROOT used these ecosystem service data from the Natural Capital Project/WWF initiative along with spatial data resulting from a national ROAM to evaluate the agreement among ecosystem service beneficiaries for a particular ecosystem service (sediment export). Sediment export was chosen as the ecosystem service to focus on due to its applicability to forest landscape restoration intervention types in Myanmar (typically tree-based restoration activities) and the devastating effects sediment-laden water had on the people of Myanmar during the 2015 floods. The beneficiaries optimised in the following analysis are townships that were heavily impacted by flooding, districts that rely heavily on fuelwood as an energy source, and townships with high levels of unemployment. The value of this analysis is that it demonstrates trade-offs among beneficiaries for the ecosystem service that is most important in dealing with Myanmar's demonstrated water sedimentation and flooding problems.

The optimisation of current restoration opportunities using ROOT required a scenario analysis of the difference between ecosystem service provision and ecosystem service provision under a future restoration scenario. It then used a linear programming optimisation to identify areas with the highest potential to improve the provision of ecosystem services for the beneficiaries of interest. In this case, only one ecosystem service was used and was optimised against three different sets of beneficiaries. The results should demonstrate which watersheds in Myanmar would most benefit from FLR investments to address high sediment export, and where these investments would most optimally support all of the three beneficiary groups.

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[6] International Union for Conservation of Nature
[7] The Natural Capital Project – Stanford University
[8] Workshop report : workshop on restoring Myanmar's degraded and deforested landscapes, Thingaha Hotel, Nay Pyi Taw, Myanmar, 9-11 November 2016. https://portals.iucn.org/library/node/46653
[9] Myanmar's Natural Capital: The foundation for a green economy http://www.myanmarnaturalcapital.org/en

Methods

In order to generate an estimate of the optimal locations for FLR to support sediment retention in areas where people could most benefit, the process required several inputs. These include an assessment of the change in ecosystem services based on projected restoration scenario, a series of geographic decision units (e.g. districts, watersheds, etc.), and spatial data on beneficiaries that could benefit from restoration activities. The restoration opportunities assessment for Myanmar provided information on the desired decision units, the beneficiaries that were of interest, and the restoration opportunity areas that would act as the activity mask in ROOT. Prior ecosystem services modelling for Myanmar, completed by The Natural Capital Project in 2016, provided the ecosystem services assessment for sediment delivery.

Ecosystem service modelling

This analysis applied the InVEST Sediment Delivery Ratio model (Sharp et al., 2016, version 3.3.3) derived from Myanmar's 2016 National Ecosystem Services Assessment. The potential impact of forest restoration on ecosystem service provision for sediment export was then calculated by analysing the difference in values between the ecosystem service delivery under baseline (2013) conditions and under a scenario of forest restoration from the 2017 national forest landscape restoration opportunity assessment. These values represent the potential ecosystem service gains and losses following a scenario of the restoration of forests that have disappeared since 1990. For this analysis, sediment export refers to the mass of sediment that is carried into stream and river networks within Myanmar, expressed as the mean annual sediment export in tons per year. Through restoration of degraded and deforested land, it is expected that the export of sediment to streams will be reduced, which will, in turn, increase water quality and reduce both the fast flow of water across landscapes and the volume of sediment that can be captured by this movement of water. In addition to damage caused by floodwaters themselves, the sedimentation of villages, streams and reservoirs is a lasting consequence.

Beneficiaries

The selection of beneficiaries to prioritise in Myanmar was based the potential to generate socioeconomic benefits through the creation of rural restoration economies and/or the augmentation of resources on which rural communities rely. Restoration can provide jobs and income and can increase the natural resources available for people. With this in mind, data were acquired that could be used in identifying the location of people who would benefit from restoration activities and the ecosystem service benefits of reductions in stream and reservoir sedimentation.

Flood-affected villages

Of the potential beneficiaries of FLR, those municipalities most heavily affected by the 2015 floods are of high priority. Not only were villages inundated with severe floodwaters, but this water was loaded with enormous quantities of sediment that filled reservoirs, rice paddies, watercourses and towns. Data were available through the 2016 Natural Capital Project's ecosystem service assessment for Myanmar on the number of flood-affected villages for each of Myanmar's townships. The ROOT analysis uses these data to prioritise restoration in municipalities based on the number of flood-affected villages within each township. While not a strict measurement of the magnitude of damage that each village experienced, this analysis does provide a reasonable estimate of the intensity, location and distribution of flooding events by township.

Fuelwood reliance

A reliance on fuelwood has both environmental and economic implications. Communities that are reliant on fuelwood for cooking often depend directly on local natural resources, including trees and forests, and people (primarily women) must often spend long hours collecting and transporting fuelwood. Additionally, areas where the majority of people are dependent on fuelwood are often poor and rural, with no, or limited, infrastructure to support transitions to alternative fuel sources. Restoration in these areas has the potential to restore degraded lands to woodlots specifically designed and managed for the growth of fuelwood. Additionally, increased economic activity around forest landscape restoration could provide additional economic benefits to people. Where barriers to different energy sources are restricted by cost rather than available infrastructure, increased wages and employment from restoration activities may allow people to transition to alternative fuel sources. The data used in the analysis for fuelwood reliance are taken from Myanmar's census and are based on the percentage of households per district that rely on firewood as a fuel source.

Unemployment

When optimising the location of restoration action, the local population density is an important consideration. Areas with too few people do not have enough workers to actively restore the land; in areas with too many people, restoration may not be possible due to unceasing pressures on resources. Additionally important in considering where restoration could occur is the potential of restoration activities to provide employment opportunities, especially in rural areas. This analysis considers the number of individuals per township seeking work, not seeking work, and not paid for work. This number is taken as a percentage of the total population of the township to provide an unemployment or underemployment proportion.

Data processing

Biophysical data

Data inputs and parameters for the InVEST sediment model were taken from Mandle et al. (2017; see Table A.1). The current land use/land cover map was based on a custom classification of 2013 Landsat imagery using Google Earth Engine (Dixon, 2015). For this application, the land use/land cover data were resampled to 90 m and registered to the digital elevation model layer. The threshold flow accumulation parameter is used by the model to delineate streams, and was set at a value that will define major streams and rivers, as per Mandle et al. (2017).

***Table 5**: Data and sources for the InVEST Sediment Delivery Ratio ("sediment") model.*

SDR model input	Dataset source
Land use/land cover	Custom map made by WWF from Google Earth Engine, wherein agriculture is defined by administrative district, 150 m resolution (Landsat is 30 m)
Digital elevation model	SRTM, 90 m resolution (Jarvis et al., 2008)
Rainfall erosivity	Derived from precipitation data using the equation R = 38.5 + 0.35P where R is rainfall erosivity and P is annual mean precipitation (mm/year); from Thang et al. (2005). Historical precipitation data from CCSR.
Soil erodibility	Derived from the FAO Harmonized World Soil Database (FAO/IIASA/ISRIC/ISS-CAS/JRC, 2009) using information on sand/silt/clay/organic carbon
Threshold flow accumulation	Value: 10,000
USLE coefficients	From Mandle et al. (2017). Coefficients were set for agricultural land by district, reflecting data on crop areas from the Digital Agricultural Atlas for the Union of Myanmar (FAO, 2009).

Opportunity areas/ restoration scenario

To develop the restoration scenario, first the potential areas where restoration could take place were mapped. The potential opportunity areas were based on data on canopy loss from 1990 to 2000 (Leimgruber et al., 2005) and from 2001 to 2015 (Hansen et al., 2013). The merged dataset was obtained from IUCN Myanmar and represented an estimated forest cover loss of 2.3 million hectares (Figure 19). While this does not necessarily cover the extent of all possible forest landscape restoration opportunities within all land use types in Myanmar, it provides a sound analytical platform on which the optimisation analysis can take place. Within Myanmar, opportunities for restoration to support increased ecological productivity and to support livelihoods are not as developed as monitoring of forest loss, especially for the permanent forest estate.

Next, using data on watersheds from HydroBASINS (Lehner et al., 2011) and the Myanmar Information Management Unit (MIMU, 2014), areas within watersheds that contain no villages were excluded as potential restoration areas under the assumption that population in those areas would not be sufficient to support a restoration programme. Areas within lakes and on roads, which are not likely locations for forest restoration, were also excluded. Several large reservoirs were not included in the HydroSHEDS global lakes layer nor in the land use/land cover data. These reservoirs were derived based on data from Bhagwat et al. (2017). Roads data were obtained from MIMU.

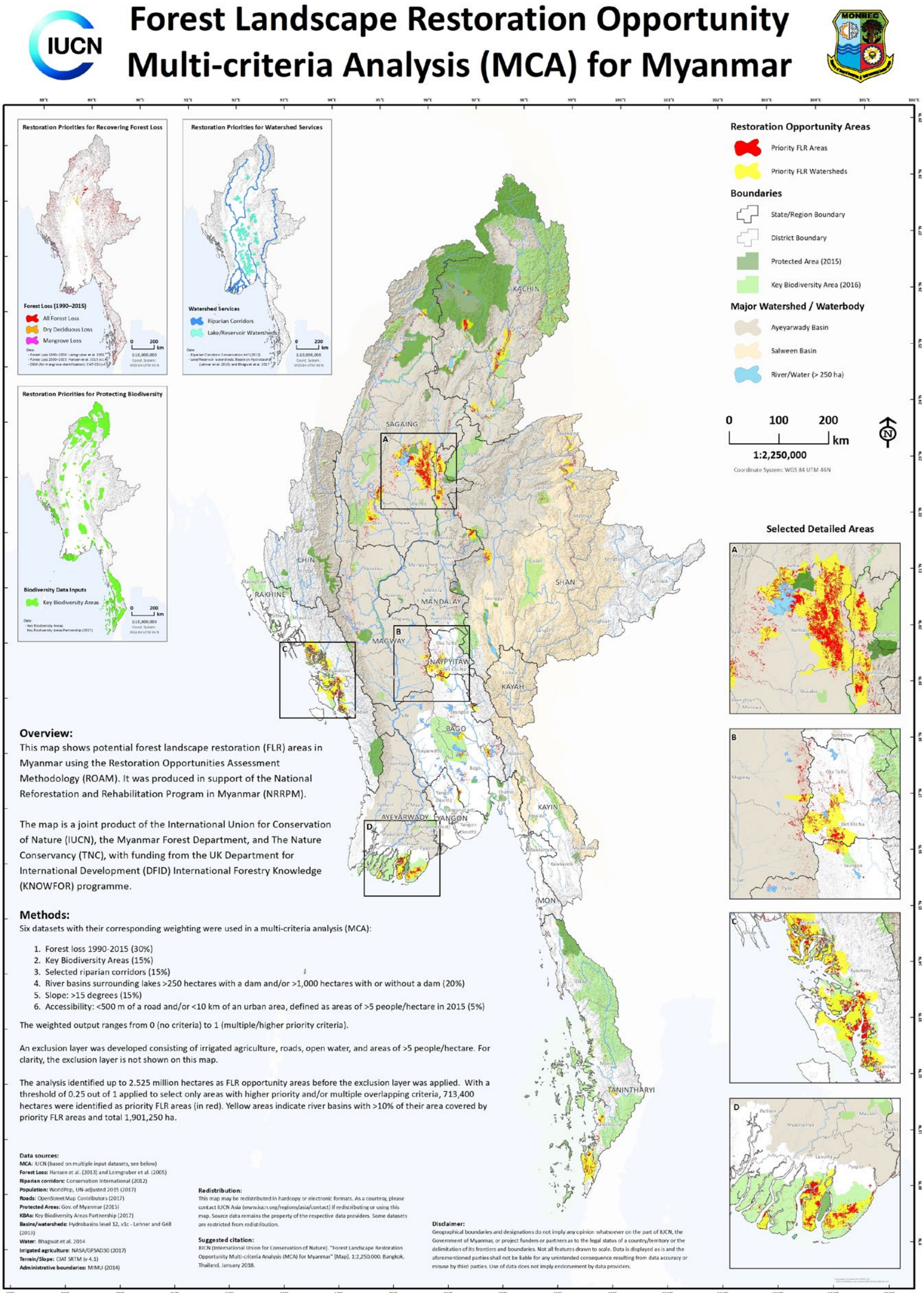
All data inputs were first resampled to 30 m, and the land use/land cover was changed to forest wherever canopy loss had occurred, except where a pixel was part of an excluded watershed, lake or road. The resulting restoration scenario was then resampled to 90 m and registered to the DEM, to preserve hydrologic routing in the InVEST model and to align with the baseline model runs.

The InVEST sediment model was run on the baseline and restoration scenarios, and the change in sediment load was calculated for each pixel as the baseline sediment export minus the restoration scenario sediment export.

Table 6: *ROOT inputs and their corresponding details for what was included in the Myanmar scenario.*

ROOT input categories	Myanmar details
Impact potential maps (marginal values of ecosystem services resulting from restoration activities)	Sediment Retention (Mg/ha/year)
Servicesheds	Floods: flood-impacted villages (number of villages within township heavily affected by floods) Fuel: households heavily reliant on fuelwood for energy (percentage of households per district that rely on firewood for fuel) Employment: individuals per township seeking work, not seeking work, or not paid for work (percentage of population unemployed or not paid for employment)
Composite factors	Sediment retention (floods, fuel, employment)
Activity mask	Myanmar forest landscape restoration opportunity assessment. Opportunity area for forest restoration 1,214,767 ha
Objectives (must account for positive or negative input values since objectives are multiplied in the analysis)	Maximize composite factor of [sediment retention *(floods, fuel, employment)]
Targets	50,000 ha

Figure 19: *The restoration opportunity areas for forest restoration in Myanmar*



Generating optimal portfolios

We used ROOT to perform the optimisation for restoration areas that would most contribute to reductions in watercourse sedimentation. The study area was divided into 2,752 sub-basins (i.e. watersheds), derived from the HYDROsheds dataset (Lehner at al., 2011) within which the ROOT model assessed whether restoration within this decision unit is optimal or not. The total sediment reduction within each sub-basin was the metric used for optimisation. The optimisation was run 100 times as an n-dimensional frontier type. The objectives were to minimise sediment export to streams and waterbodies in support of flood-affected villages, areas heavily dependent on fuelwood and areas of high unemployment.

The original restoration target area was summed from the restoration target areas given in the National Reforestation and Rehabilitation Programme for Objectives 1 (increase forest plantation area) and 2 (restore degraded forests) to arrive at the total national area to target for restoration (1,214,767 ha) (MONREC, 2016). This lumped-target approach assumes that during the process of implementation, the most appropriate restoration activities would be selected within the priority areas identified, and then this restoration would be credited towards the appropriate target. However, the results of this optimisation remained difficult to interpret since the total available area for restoration based on the national opportunities map was an estimated 2,525,000 hectares before applying area exclusions for roads, open water, irrigated agriculture and high population areas (>5 people per hectare). To allow ROOT to provide guidance on the most optimal areas to begin restoration, the current analysis selects the first 50,000 hectares that would be most optimal to restore for sediment retention for the beneficiaries indicated here.

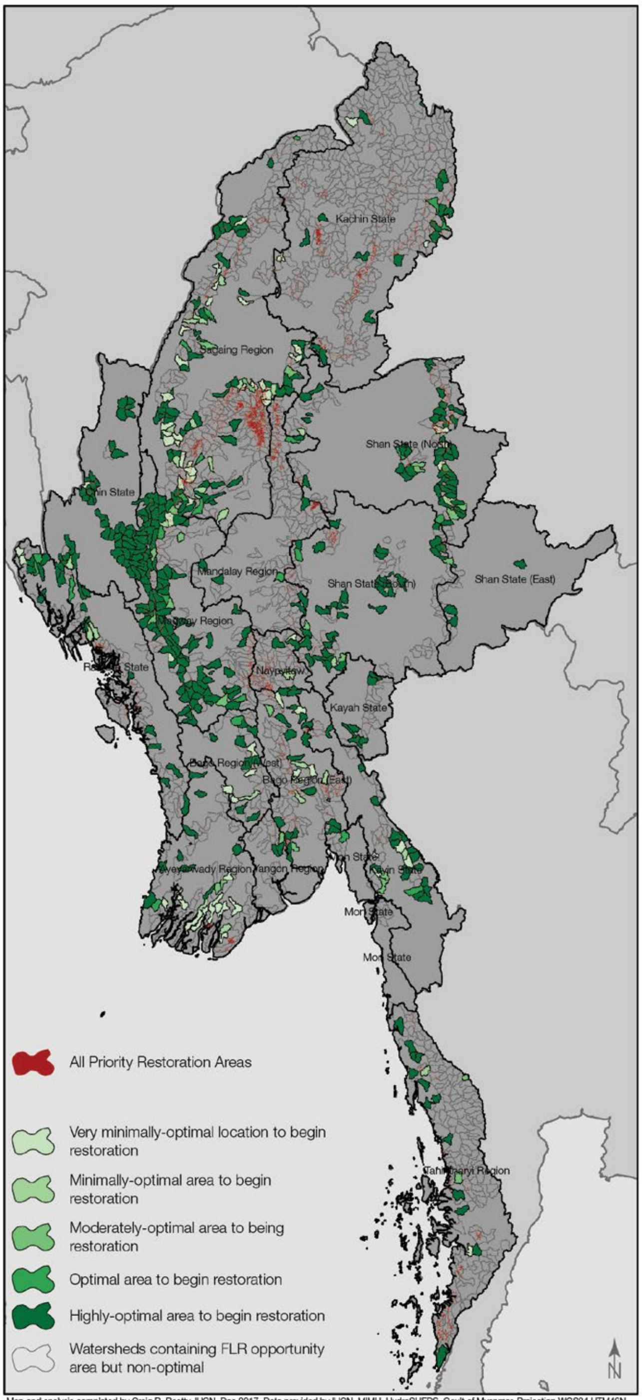
Results and discussion

The restoration opportunity agreement map (Figure 20) provides refined priority restoration areas based on the provision of an ecosystem service (sediment retention) for selected beneficiaries for the first 50,000 hectares restored. This complements the national FLR analysis in Figure 19 by demonstrating the optimal locations to begin landscape restoration within the 713,400 hectares of identified priority FLR areas from the national ROAM assessment. For the greatest landscape benefits in reduced sediment export from restoration, interventions can be prioritised within watersheds that are currently exporting large quantities of sediment.

This optimisation used 100 simulations and then aggregated the results based on how often ROOT decided that a sub-basin was an optimal area for restoration to support increases in sediment retention for the beneficiaries considered. The watersheds in darkest green (Figure 20) were selected by at least 80 out of the 100 separate simulations as optimal areas for reducing sediment export through restoration activities, while supporting flood-affected villages, households dependent on fuelwood, and places of high unemployment.

ROOT analysis indicates that, for the first 50,000 hectares placed under restoration, the sediment retention benefits important for the beneficiaries of interest would be most optimal in all green areas in Figure 19.

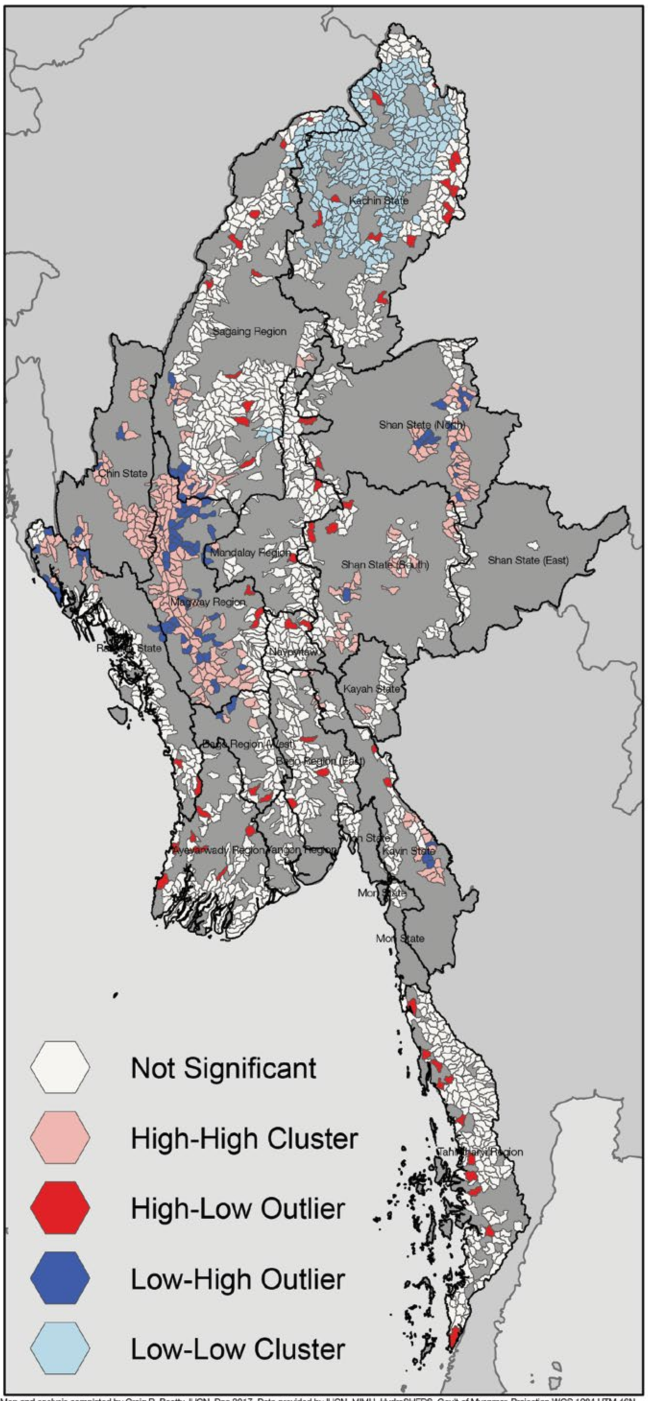
Figure 20: *Results of the ROOT forest restoration optimisation, shown as an agreement map. The agreement map shows the proportion of scenarios (out of a total of 100) where a given watershed decision unit was selected for optimisation, considering all objectives together. Note: the optimal watersheds are coloured in this figure, though all watersheds that contain priority restoration areas are indicated on the map (coloured or not). The actual restoration opportunities within each watershed are typically smaller areas and are indicated in red.*



Map and analysis completed by Craig R. Beatty, IUCN, Dec 2017. Data provided by IUCN, MIMU, HydroSHEDS, Gov't of Myanmar. Projection WGS84 UTM46N

Figure 21 *This map presents a cluster analysis of restoration opportunity areas for Myanmar. It shows where investments in restoration for optimized benefits are clustered. High-High clusters indicate areas that are repeatedly identified as optimal in ROOT and are significantly clustered together to form a hotspot for FLR implementation. High-Low outliers indicated areas that have high agreement values but are surrounded by watersheds with low agreement values. Low-High outliers are areas that have low agreement values but are surrounded by areas with high agreement values. Low-Low clusters indicate areas that were still significant in the cluster analysis but that contained significant clusters of low agreement values.*

This analysis used a 100km threshold calculated from a Getis-Ord Gi optimized hot spot analysis*



Map and analysis completed by Craig R. Beatty, IUCN, Dec 2017. Data provided by IUCN, MIMU, HydroSHEDS, Gov't of Myanmar. Projection WGS 1984 UTM 46N.

Of the most optimal areas (darkest green), there are 254 sub-basins that are always selected by the model as optimal for restoration out of 1982 possible sub-basins (13%). These watersheds were selected by ROOT as optimal places for restoration in each of the 100 iterations of the model, meaning that restoration of opportunity areas within these watersheds will reduce sediment export and will do so in areas where people can benefit the most. Since ROOT aggregates the ecosystem service benefits within a watershed, it is not necessary that the entire watershed undergo active restoration. In each of these 254 watersheds, less than 10% of the overall watershed area has been designated as an FLR opportunity area. Yet restoration of these areas would significantly contribute to sediment retention and offer the most benefits directly to people who would benefit from increases in fuelwood sources or employment opportunities.

The surface area covered by these 254 watersheds is 3,805,549 hectares; however, the specific FLR opportunity area, as defined by the priority restoration areas (Figure 22, red areas) within each sub-basin, is only 21,889 hectares. The remaining 28,111 hectares are distributed among sub-basins that are not selected by ROOT 100% of the time, but are selected 1–99% of the time. This may indicate that through an FLR approach that utilises holistic watershed restoration using an appropriate suite of restoration interventions and strategies, practitioners may physically restore slightly over 20,000 hectares of degraded land, but that nearly 4 million hectares of Myanmar's landscapes may end up "under restoration." The specific area for each region within Myanmar is indicated in Table 7, below.

Table 7 *shows the cumulative area of watersheds in Myanmar per region that were selected in each of the 100 iterations ROOT. The actual restoration opportunity in these hectares, as indicated by the red areas in Figure 18 and 19, is far less than the total area of the optimal watersheds.*

Region	Area of 100% Optimal Watersheds (ha)
Magway Region	958,374
Chin State	627,135
Saigaing Region	563,204
Shan State (North)	259,731
Shan State (South)	253,977
Kayin State	201,374
Rakhine State	200,552
Bago Region (East)	180,003
Tanintharyi Region	162,743
Ayeyarwady Region	119,180
Bago Region (West)	86,303
Mandalay Region	45,206
Kayah State	43,562
Yangon Region	33,699
Kachin State	30,412
Shan State (East)	27,124
Mon State	8,219
Naypyitaw	4,932
Total potential area "under restoration"	**3,805,730**
FLR "opportunity" ha within 100% optimal watersheds	**21,889**

Additional cluster analysis of the optimisation results (Figure 21) demonstrates a high agreement of restoration optimisation along Myanmar's rivers, especially following the confluence of the Irrawaddy and Chindwin Rivers along the border of Chin State and the Magway Region. Another significant cluster of optimised restoration opportunity is along the upper Salween River in North Shan State. Highly optimal areas for FLR exist in nearly all regions within Myanmar, and these results are not intended to negate the contributions that all degraded areas can make to landscape restoration. Instead, these areas represent the 50,000 hectares with the most optimal benefits for sediment retention for the identified beneficiaries. This is especially evident when comparing the multi-criteria analysis map for Myanmar (Figure 19) with the Anselin Local Moran's I analysis of optimisation results clusters (Figure 21). The priority areas recognized in the opportunity map do not align with the priority clusters in Figure 19. This does not mean that the priority areas in Figure 19 are incorrect; it simply means that based on the objectives of reductions in sediment export, the restoration practitioner might choose to restore these (Figure 19) optimal areas first and increase potential connectivity of restoration sites by prioritising the high-high clusters in Figure 21.

Conclusions

The intention to scale up restoration efforts does not necessarily mean that restoration practitioners must restore all degraded land; this is hardly practical or financially feasible. Investments in restoration have the potential to be optimised such that relatively small interventions can have large and compounding benefits across landscapes. Therefore, it may be possible through this ROOT analysis to demonstrate the effects of 21,889 hectares of restoration targeted for specific ecosystem services and beneficiaries on nearly 4 million hectares of land. These optimal investments would also be made where restoration can reduce sediment loads in streams, where unemployment is high, and where people are reliant on wood for fuel. Restoration in these areas will conceivable reduce sedimentation in watercourses and reservoirs, leading to increased hydropower potential for people reliant on fuelwood and others who might benefit from these local reductions in sediment. Secondly, restoration programmes in areas that are plagued by low employment could realise the benefits of restoration economies in rural areas through increased employment and enterprise opportunities.

While the restoration opportunities assessment will support Myanmar's national forest strategy and will help refine national and subnational restoration initiatives through targeted restoration activities in the highest priority areas for forest restoration in Myanmar, the ROOT analysis demonstrates where this restoration could be initiated for the most optimal benefits for sediment reduction for specific beneficiaries. As demonstrated, the most optimal areas for ecosystem services are different than the areas that appear as restoration priorities in the analysis of 1.2 million hectares of restoration opportunity. This analysis does not negate the importance of restoration in these areas, but it does refine the assessment to demonstrate that, based on an ecosystem service approach for reductions in stream and reservoir sedimentation, the most beneficial areas to start restoration can be identified in the assessment of national restoration opportunity.

Colombia

Water for cities: optimising the delivery of water resources based on forest landscape restoration in Colombia

Adrian L. Vogl [10]

Colombia is facing rapid urbanisation. Current projections show that nearly 84% of Colombians will be living in urban areas by 2050 (United Nations, 2014). Ongoing urban growth presents significant challenges to service infrastructure and resources. Funding investments in infrastructure to ensure sustainable incomes, food, water, energy and shelter for all citizens (27.8% of whom are in poverty) will be a priority (World Bank, 2015).

Colombia's National Development Plan (NDP) 2014–2018 includes comprehensive goals for the energy, housing and agricultural sectors, requiring them to incorporate substantial sustainable development approaches. The NDP also mandates the prompt and efficient implementation of a National Plan for Ecological Restoration, Rehabilitation and Recuperation of Degraded Landscapes, which was subsequently launched in 2015. In recent years, the government has also enacted legislative and institutional mandates that promote investment in watershed management services through local and regional environmental authorities, known as Corporación Autónoma Regional (CARs – Regional Autonomous Corporations). CARs support investments such as payments to landowners for ecosystem services and direct land acquisition in source watershed areas. The DNP also includes requirements for hydropower companies to transfer a percentage of their earnings from energy production to municipalities and CARs for watershed protection.

Local partners, coordinated by The Nature Conservancy (TNC), have been working on developing conservation and restoration plans in the source watersheds of most major cities in Colombia to support implementation of these ambitious national goals. One mechanism promoted by TNC to support and finance FLR activities is through a water fund, a collaborative finance and governance mechanism that connects downstream beneficiaries of water purification and habitat restoration services to upstream landholders who provide those services. To date, Colombia has six operational water funds, with a total investment of over US$ 9m in watershed conservation strategies (Bremer et al., 2016).

Water funds often can allocate only limited budgets to FLR activities, but must achieve specific ecosystem services targets. To reflect this decision context, we applied ROOT to optimise the locations of interventions in the source watersheds of six of the largest cities in the country (population >500,000). According to the 2005 national census, these cities have a combined population of over 13 million people (about 27% of the population of the country). We optimised activities – including agricultural best management practices (BMPs), forest restoration, riparian restoration and protection of native vegetation – to reach a target change in services, including sediment retention, nitrogen retention and carbon storage. These ecosystem services were chosen as key for water quality. We also analysed water regulation co-benefits using the InVEST seasonal water yield model, represented by how infiltration and baseflow regulation could change if selected interventions were implemented in the locations identified with the ROOT model.

Methods

Seven major cities in Colombia were initially selected, the populations of which exceeded 500,000 people per the 2005 national census: Bogotá (pop 6,840,000), Medellín (pop 2,214,000), Cali (pop 2,119,000), Barranquilla (pop 1,146,000), Cartagena (pop 892,500), Cúcuta (pop 587,000), and Bucaramanga (pop 516,500).

Figure 22. *Study areas: Source watershed areas analysed for the six cities in Colombia. For each city, the source watersheds were merged and analysed together as a single area.*

Source watershed delineation was done using the DelineateIT tool from InVEST and the 90 m DEM (Table 1; Sharp et al., 2016). Water intake locations for cities were obtained from TNC's Urban Water Blueprint project (McDonald & Shemie, 2014) and its underpinning City Water Map, and were used as outlet points for the initial source watersheds. The resulting source watersheds were then reviewed by TNC Colombia and, in some cases, modified based on additional local data

[10] The Natural Capital Project – Stanford University

on water intakes. Based on this feedback, and considering the feasibility of short-term implementation of water funds and FLR activities, we made the following modifications to the study areas:

- Cali: We eliminated the Cauca River basin, which supplies a portion of water to the city, and focused instead on the western tributary that has been identified by local stakeholders as the most likely place to begin FLR implementation.

- Cartagena: We eliminated the Magdalena River basin, which supplies part of the city's water supply, and focused instead on the watersheds to the north of the water intake on the Dique Canal, as more feasible areas for initial FLR implementation.

- Barranquilla: The source watershed for this city is the very large Magdalena River basin, which is not at a scale feasible for short-term FLR implementation through a water fund mechanism, so this city was eliminated from the final analysis.

The source watersheds for each of the six final cities were merged and analysed together as a single 'study area', so while there are more than 6 source watersheds, results are reported for the aggregated source areas per city.

Ecosystem service modelling

We applied the InVEST suite of models (Sharp et al., 2016, version 3.3.1) to calculate ecosystem service delivery in each of the source watersheds under baseline (2007) conditions and with activities implemented. Models included the sediment model, nutrient delivery ratio ('nutrient') model, forest carbon edge effect ('carbon') model, and seasonal water yield model. Ecosystem services are expressed as the total for each city's source watersheds in terms of mean annual sediment export (tons/yr), mean annual nitrogen export (kg/yr), and total carbon stored in above- and below-ground biomass, soil carbon, and litter (tonnes).

We estimated the benefits of implementing activities by running the InVEST ecosystem service models for each activity one at a time, using a set of input land cover rasters where the activity was implemented in every possible location. We restricted activities only to feasible locations under the following assumptions: forest/páramo protection was restricted to natural forests, páramo and mangroves; agricultural BMPs were restricted to croplands and pasture; restoration was restricted to shrublands, croplands, secondary vegetation, pasture, degraded/bare areas and other highly impacted areas; riparian restoration was additionally restricted to within 90 m buffers on both sides of streams.

For agricultural BMPs, forest restoration and riparian restoration, the differences between the baseline scenario and full implementation in all possible locations were used to calculate marginal benefits. Protection was calculated by changing all possible natural land covers to a degraded state, in this case pasture. The marginal benefit of protection (avoided degradation) is the proportion of the change in service on a protected landscape, relative to the total change on a fully degraded landscape:

Avoided degradation = (degraded – protected)/ (degraded – baseline) * 100

We applied two types of targets for each study area and ecosystem service: for restoration activities (forest/ páramo restoration, riparian restoration and agricultural BMPs), the target was defined as a 10% improvement (-10% for sediment and nitrogen and +10% for carbon storage); for protection, the target was set to avoid 17% of potential future degradation, following the CBD's Aichi Target 11 of 17% protection for lands and inland waters.

Marginal values for each activity in each location were then calculated based on the degree to which the activity helps to reach the target change in each ecosystem service. Expressing the marginal value relative to the target change means that when activities are prioritised, the optimisation is not choosing the activity that has the highest absolute change (which would be influenced by the units of analysis), but rather choosing the activity comes closest to achieving the goal. Final marginal values were expressed as a proportion of the change from each activity relative to the total city-level target change in each service, and were used to generate optimal portfolios in the next step.

Generating optimal portfolios

ROOT first summarises the changes in each service in a series of tables listing the marginal value of each activity within each' spatial decision unit' (SDU); calculated as the sum of pixel-level marginal values within each SDU. SDUs are spatial regions representing the smallest area on which an activity will be implemented; here we used a hexagonal grid of 120 hectares as a feasible target area for local implementation.
The optimisation problem was to find the cost-minimising management activity in each SDU while achieving watershed-level environmental targets. The optimisation was completed for nitrogen and sediment loading and carbon storage targets individually, and for all three together.

Return on investment

The InVEST models were applied on the optimal scenarios to calculate the total change in ecosystem services from implementation. To do this, we created new land cover input data by applying the selected activities to all possible land covers within each SDU selected for that activity, based on the same feasibility restrictions outlined above in "Ecosystem services modelling."

The InVEST seasonal water yield model contributed at this stage to estimate the change in contribution to dry season flow (index of slow flow contribution to streams). These results represent the co-benefit that portfolio implementation might have for water security. Change in the contribution to baseflow (Qb, mm) was calculated as the difference between Qb from the baseline to the optimal portfolio. The benefit of forest and riparian restoration, agricultural BMPs, and the avoided loss in Qb from protection were summed for each source watershed to give the total benefit to baseflow contribution. This total is expressed as percent change from the baseline Qb.

Data processing

Table 8: The modelling approach and all data sources were developed and compiled in close collaboration with the technical staff in the office of TNC Colombia. While some local datasets of higher quality were available (e.g., 30 m resolution DEM for some areas, updated land cover maps for others), we chose to apply national-level datasets, ensuring consistent results across the country.

Data type	Source	Model application
Digital elevation model (DEM)	SRTM (Jarvis et al., 2008)	Sediment, nutrient, seasonal water yield
Precipitation	WorldClim (Hijmans et al., 2005)	Sediment, nutrient, seasonal water yield
Minimum/maximum monthly temperature	WorldClim (Hijmans et al., 2005)	Seasonal water yield
Climate zones	Koeppen-Geiger climate zones (Kottek et al., 2006)	Seasonal water yield
Number of rain events per month	IWMI's Online Climate Summary Service Portal (IWMI, 2009)	Seasonal water yield
Soils	Soils map of Colombia (IGAC, 2003)	Sediment, nutrient, seasonal water yield
Hydrologic soil group	FutureWater HiHydro dataset (De Boer, 2015)	Seasonal water yield
Land cover and management	Map of continental, marine and coastal ecosystems of Colombia (IDEAM et al., 2007)	Carbon, sediment, nutrient, seasonal water yield
Land cover-based parameters: USLE C factor, USLE P factor	Peralvo and Coello, 2008	Sediment
Land cover-based parameters: Nitrogen load and nitrogen retention efficiency	Peralvo and Coello, 2008	Nutrient
Land cover-based parameters: aboveground, belowground, soil and dead carbon pools	Peralvo and Coello, 2008	Carbon
Land cover-based parameters: evapotranspiration coefficient	Peralvo and Coello, 2008	Seasonal water yield

Biophysical data

Annual precipitation data from Hijmans et al. (2005) were used in the nutrient model, and these data were converted to erosivity (used in the sediment model) based on the empirical formula in Pérez and Mesa (2002). Monthly precipitation events and minimum/maximum monthly temperatures (used in the seasonal water yield model) were also derived from Hijmans et al. (2005), and potential evapotranspiration was calculated based on the Modified Hargreaves method as described in Droogers and Allen (2002). Number of rain events per month (used in the seasonal water yield model) were obtained from International Water Management Institute (IWMI) Online Climate Summary Service Portal (IWMI, 2009).

Soil erodibility (used in the sediment model) was calculated from soil texture (IGAC, 2003) based on the procedure in Stone and Hilborn (2012).

Land cover data were obtained from the latest national ecosystems map of Colombia (IDEAM et al., 2007). This map is used most frequently by government agencies for national-scale planning and provides consistent classification across the entire study region. Biophysical parameters associated with land cover and management were derived from Peralvo and Coello (2008).

Activity costs

Per-hectare costs for activities were obtained from TNC Colombia staff based on historical data from implementing FLR programmes in Bogotá, Cali, and Medellín. Because we lacked location-specific data for all the study areas, we applied average per-hectare costs for each activity to all source watersheds. We did not have separate cost data for upland versus riparian restoration, so we used the same cost for both activities. Agricultural BMPs in our data set ranged from silvopastoral systems to agroforestry to pasture improvement. We averaged these costs together, assuming that when implemented, the programme would choose the most appropriate practice given local conditions.

We found that using average costs resulted in more conservative cost assumptions overall; however, costs can vary widely across the country due to factors such as labour and transportation costs, differing processes for negotiating compensation, landholder expectations and opportunity costs. In addition, land protection typically involves some additional compensation to landholders, negotiated on a case-by-case basis, which was not included in our portfolio costs due to issues of sensitivity around publishing this information. These variations mean that total portfolio budgets should be considered representative rather than definitive.

Activity effectiveness

Activity implementation results in changes to land cover and associated parameters. The following assumptions were made about parameter changes in areas where activities were implemented:

Forest protection: without protection, the alternative (avoided degraded state) is conversion to pasture.

- *Restoration:* we assume restoration is implemented on only 10% of the land areas chosen for implementation, based on the experience of TNC Colombia staff in negotiating restoration with landholders. We assume that restored areas are converted to natural forests.
- *Riparian restoration:* we assume that areas within a 90 m buffer on both sides of streams are converted to natural forest.
- *Agricultural BMPs on croplands:* we assume an average reduction in nitrogen load of 61% (McDonald & Shemie, 2014; USEPA, 2009); average reduction in USLE_C of 72% (McDonald & Shemie, 2014); USLE_P was set to the same value as mixed agriculture (from Peralvo & Coello, 2008); aboveground, belowground, and dead carbon were unchanged, but soil carbon was increased to match natural forest value.
- *Agricultural BMPs on pasture:* we applied parameters from Peralvo and Coello (2008) for 'silvopastoral systems' where available; others were set to equal natural grassland.

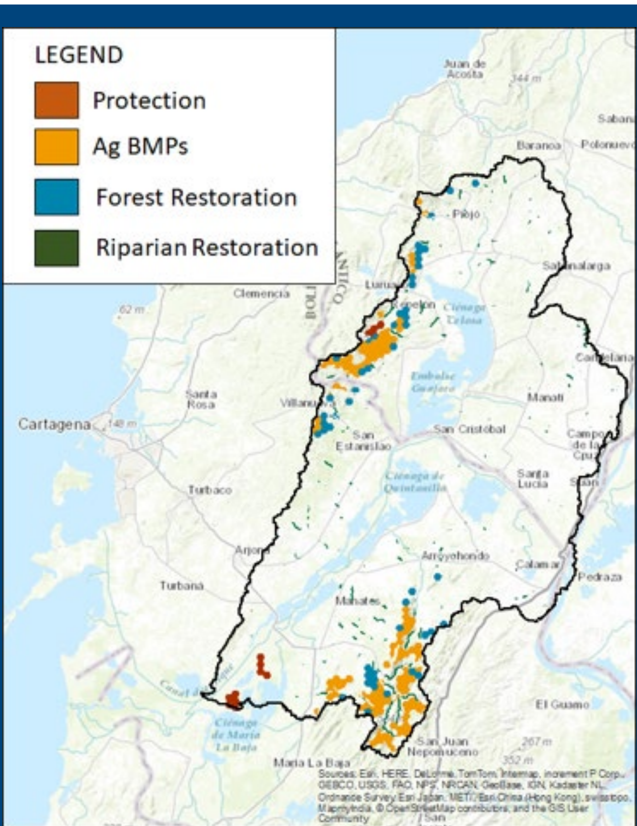
Cost savings from multi-benefit targeting

We also compared the costs of achieving sediment, nutrient and carbon benefits simultaneously with the costs of doing so individually. We used the same method described previously to develop separate optimal activity portfolios to reach each ecosystem service target one-by-one to represent what implementation would look like if different actors focused only on their individual mandates. Most important for this analysis is our comparison of costs within a given watershed for the multiple- versus individual-benefits portfolios.

Results and discussion

The maps below show the optimised FLR portfolios that meet the targets for improving and protecting sediment retention, nitrogen retention and carbon storage services. Because the scenarios were optimised to hit targets, there is only one optimal result for each city (no agreement maps).

Figures 23-28: *Optimal investment portfolio for the source watersheds of each of the Colombian cities in our analysis (left). The right panels detail the total portfolio cost and hectares chosen for implementation of each of the four activities, in order to meet the target ecosystem service change for the city's watersheds a whole.*

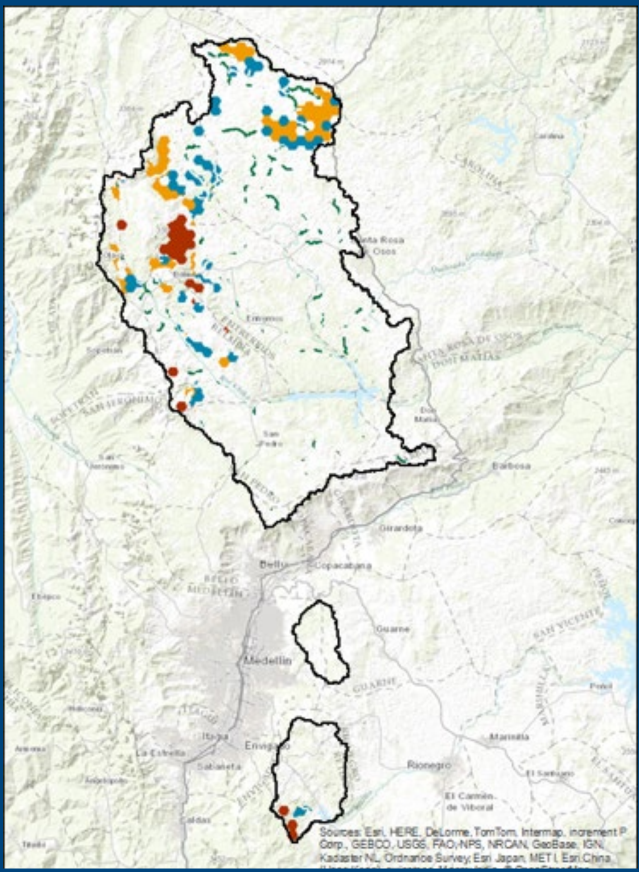


Cartagena

Portfolio cost = 43.4 million USD

Activity	Area (ha)
Agricultural Best Management Practices	9,723
Restoration	4,406
Riparian restoration	2,522
Protection	1,181
TOTAL	**17,832 (7% of total area)**

Figure 24

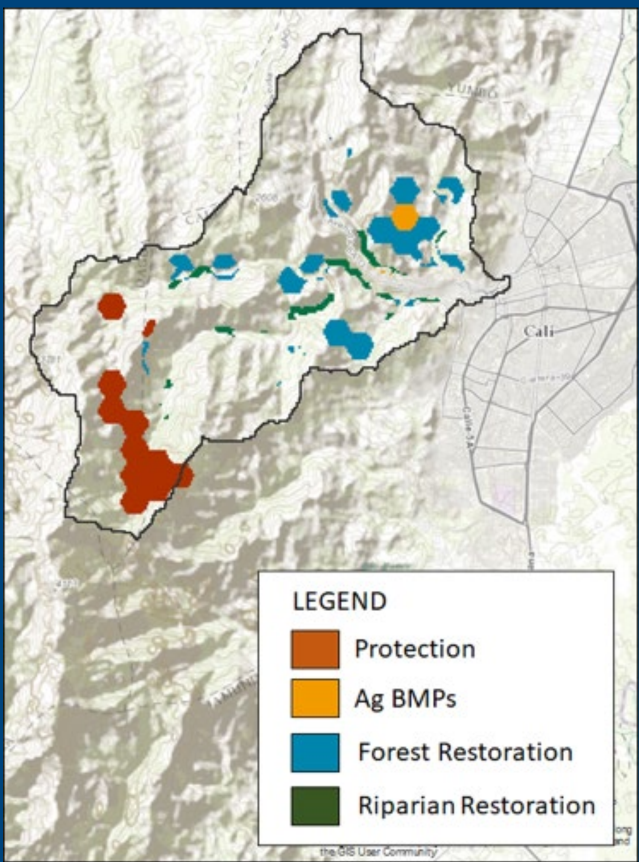


Medellín

Portfolio cost = 26.6 million USD

Activity	Area (ha)
Agricultural Best Management Practices	4,278
Restoration	4,195
Riparian restoration	1,581
Protection	1,978
TOTAL	**12,032 (10% of total area)**

Figure 25

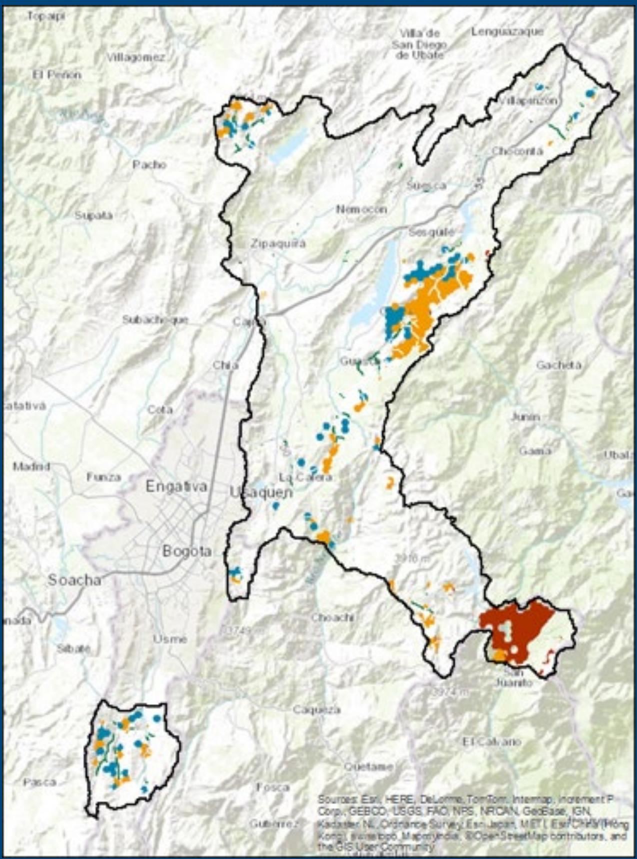


Cali

Portfolio cost = 5.1 million USD

Activity	Area (ha)
Agricultural Best Management Practices	100
Restoration	1,103
Riparian restoration	293
Protection	994
TOTAL	**2,491 (14% of total area)**

Figure 26

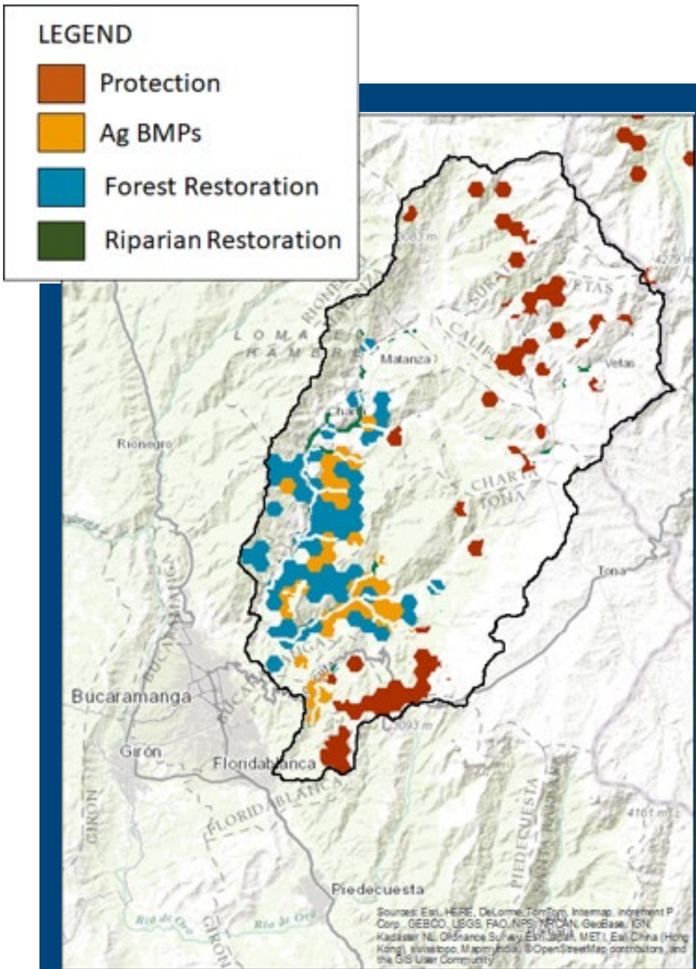


Bogotá

Portfolio cost = 53.8 million USD

Activity	Area (ha)
Agricultural Best Management Practices	9,142
Restoration	5,674
Riparian restoration	1,724
Protection	5,348
TOTAL	**21,888 (8% of total area)**

Figure 27

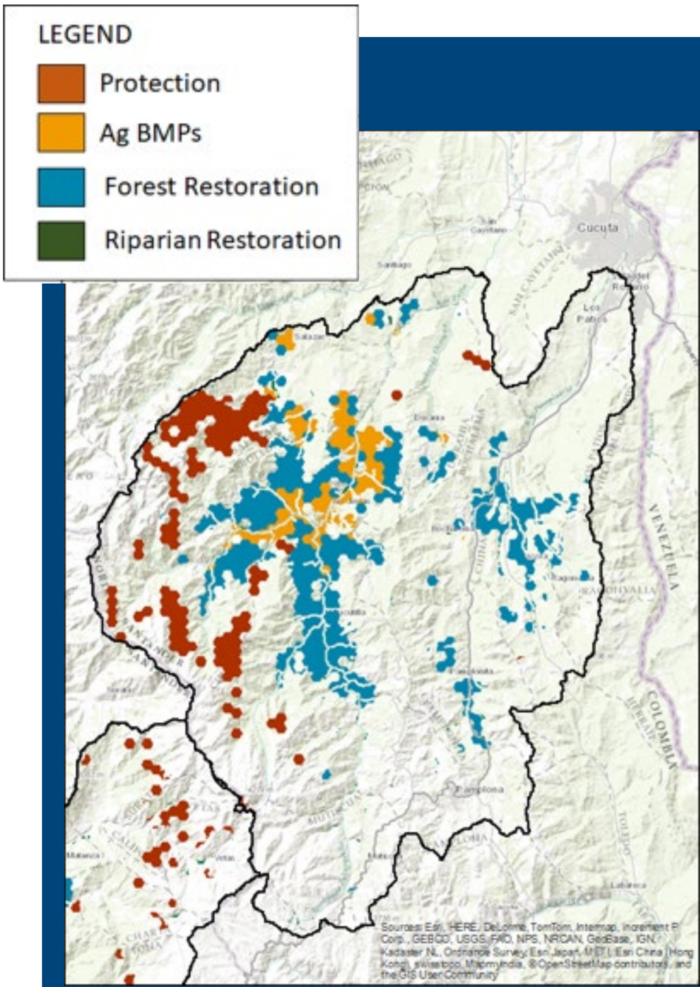


Bucaramanga

Portfolio cost = 24.5 million USD

Activity	Area (ha)
Agricultural Best Management Practices	2,419
Restoration	4,929
Riparian restoration	374
Protection	4,109
TOTAL	**11,831 (16% of total area)**

Figure 28



Cucuta

Portfolio cost = 68.8 million USD

Activity	Area (ha)
Agricultural Best Management Practices	6,257
Restoration	23,308
Riparian restoration	380
Protection	11,697
TOTAL	**41,642 (17% of total area)**

Cost savings

We find that cost savings via multiple benefit optimisation have a range of 13–95% across the six cities and their source watersheds. In other words, in some watersheds, achieving equivalent nutrient, sediment and carbon improvements would cost nearly double if investments were made in achieving those benefits individually. These findings clearly show the cost savings of collective planning and implementation. It is important to note that when implemented individually rather than collaboratively, the portfolios often resulted in even greater overshooting of some targets (meaning that, for example, the realised reduction in sediment was greater than the 10% targeted improvement). While this might be beneficial in some cases, it represents additional inefficiencies in implementation that could be minimised through designing collaborative programmes. In reality, independent efforts to address different benefits — especially water quality and carbon mitigation — would likely be taken via separate policy and planning processes. The inefficiencies of multiple efforts should be considered as additional costs that could be avoided with a more efficient process to target intervention that simultaneously addresses multiple services.

Benefits for base flows

Although seasonal water yield was not optimised in the portfolio analysis, a post-hoc evaluation was undertaken to demonstrate the potential for base flow regulation to improve dry season water availability through implementation of the optimal investment portfolios. Results show increases in potential base flow contribution (in m3/year) ranging 2–11%, with most increases around 3–5% (Table 9).

Table 9: *shows the increases in water flow for each municipality by both volume of water and percent increase in the delivery of this ecosystem service.*

City	**Baseline modelled contribution to baseflow (Qb)** (millions of cubic meters)	**Increase in baseflow (Qb) due to restoration/ protection activities** (millions of cubic meters)	Percent increase
Cartagena	210.6	23	10.9
Medellín	1199.3	26.4	2.2
Cali	108.2	3.8	3.5
Bogotá	905.3	28.2	3.1
Bucara-manga	249.8	11.8	4.7
Cúcuta	906.2	47.4	5.2

While these findings should be considered estimates only, due to the complexities of translating locally-generated infiltration into streamflow available for human use during particular seasons, these results do suggest that additional water could be generated in source watersheds, which could benefit both freshwater species and upstream communities reliant on local streams for their basic needs.

Limitations and conclusions

Field data on sediment, nitrogen loads and carbon stocks were not available for the study areas and selected water intake points. While data are available in some rivers that could enable calibration and model validation, most locations would require use of proxy data and other interpolation methods that were outside the scope of this study. For this reason, targets are expressed in relative terms only. Depending on model performance and parameter calibration, the absolute improvement in services may vary, but we assume that our method adequately captures the relative distribution of marginal values – and therefore the optimal locations for activities and the cost needed to reach targets.

The results for avoided degradation assume that all possible areas are degraded equally. More detailed land cover change modelling would enable us to incorporate risk of conversion into the calculation of degradation; however, such modelling was outside the scope of this study. While we ignore the risk of conversion in our degradation estimates, our approach allows the water funds to target their protection efforts to places where the cost of inaction is highest or where continued degradation and lack of restoration will most negatively impact water sources.

Further, total costs of portfolio implementation should be considered illustrative, as we did not vary ecosystem parameters, costs and targets across the six cities' source watersheds. In reality, landscape restoration and its costs would necessarily incorporate more detailed local and site-based data, and be subject to varying implementation, labour and opportunity costs.

Finally, our results report changes in carbon storage (expressed as mass), not carbon sequestration (typically expressed as a rate over time), which limits the direct comparisons that can be made to Colombia's national climate mitigation commitments. Further work to develop estimates of sequestration rates (in combination with land change modelling over time) would help to clarify this contribution.

Costa Rica

Restoration of coffee and pasture for optimised social, climate and ecological results in Costa Rica

Leander Raes (IUCN), Kelly Meza Prado (Natural Capital Project, University of Minnesota), Peter Hawthorne (Natural Capital Project, University of Minnesota) and Javier León Saborio (CATIE)

In this chapter, a spatially explicit methodology to identify priority areas for landscape restoration is presented for Costa Rica. This study is part of the implementation of the ROAM in Costa Rica, carried out by the Regional Office for Mexico, Central America and the Caribbean of the International Union for Conservation of Nature (IUCN-ORMACC). The restoration assessment was implemented in support of Costa Rica's commitment to the Bonn Challenge of restoring one million hectares of degraded land. IUCN, in collaboration with the Natural Capital Project, performed an optimisation of ecosystem service provision using ROOT. The national-scale optimisation of areas presented is based on the potential impact on sediment export and nutrient retention of a series of restoration actions proposed by the Technical Committee on Restoration of Costa Rica.

Introduction

The Costa Rican national government committed 1 million hectares to the Bonn Challenge in 2012 (Bonn Challenge, 2017). To support Costa Rica in achieving its commitment, IUCN started the implementation of a ROAM assessment in August 2014. As part of this process, a committee of restoration experts was established. To realise the commitment to the Bonn Challenge, this Technical Committee on Restoration made a first proposal, consisting of a series of restoration actions and targets related to those actions (Technical Committee, 2016). This proposal was based on unifying existing programmes in Costa Rica that have a restoration component; namely, Costa Rica's national Payments for Ecosystem Services Program (PPSA for its abbreviation in Spanish), the Nationally Appropriate Mitigation Actions (NAMAs), and the programmes for the implementation of Good Agricultural Practices (GAPs) (see Table 10).

The PPSA was launched in 1997, with the Forest Law (No.7575, 1996) providing its regulatory basis. Costa Rica was the first country to implement a national payments for ecosystem services programme (Pagiola, 2008). The programme is considered to be partially responsible for making Costa Rica a country with a net reforestation (Arriagada et al., 2012; Robalino & Pfaff, 2013). Through the PPSA, landholders receive an annual payment for the conservation of forested lands, and for the establishment and maintenance of timber plantations, areas of natural regeneration and modified forest management. Incentives are also disbursed to landholders for the adoption of agroforestry systems (FONAFIFO, 2014a; Nieters et al., 2016).

In 2007, the Costa Rican government, as part of its National Climate Change Strategy, announced the goal of becoming a carbon-neutral country by 2021 (UNFCCC, 2014). Agriculture is an important contributor to Costa Rica's greenhouse gas emissions, mainly composed of methane emissions from livestock and nitrous oxide emissions from the use of nitrogen fertilizers (World Bank et al., 2014). Thus, the agricultural sector has been identified as a key sector to help Costa Rica reach its carbon neutrality goal – in particular the coffee, banana, livestock, sugarcane, pineapple and rice sectors (MINAE & IMN, 2014). To achieve this goal, a series of agricultural programmes have been developed. NAMAs are seen as one of the key instruments in accomplishing emission reduction targets and achieving low carbon development (Boos et al., 2014; Coetzee & Winkler, 2014). Currently, Costa Rica has implemented NAMAs for the livestock and coffee sectors. Additional emission reductions in several sectors will be achieved through the adoption of GAPs, specifically modifications to fertilizer management (World Bank et al., 2014).

In 2016, the Technical Committee proposed actions to halt deforestation and forest degradation in secondary and mature forests through forest management and conservation. García-Rangel et al. (2017) carried out a spatial analysis to define priority areas for these actions as part of the implementation of the UN-REDD Program in Costa Rica.

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Table 10 *Restoration actions considered for the ROAM assessment in Costa Rica*

Programme	Current Land Use	Restoration action
Livestock NAMA	High altitude pastures (>1000m elevation)	Silvopastoral system with rotation (live hedges)
	Low altitude pastures (pastures <1,000 m elevation classified as apt for agriculture)	Improved pastures with intensification and rotation, and silvopastoral system (live hedges and additional trees inside pastures)
	Low altitude pastures (pastures <1,000 m elevation classified as apt for forestry)	Pasture abandonment and passive regeneration
PPSA	Pastures (outside of Livestock NAMA area)*	Timber plantations
Coffee NAMA	Shade coffee	Fertiliser management, and implementation of agroforestry systems where they do not yet exist
	Sun coffee	
Good Agricultural Practices	Pineapple	Contour planting and crop residue management
	Oil palm	Fertiliser management
	Banana	Fertiliser management
	Banana, oil palm and pineapple	Restoration of riparian forest

Source: Based on proposal of the Technical Committee (2016)
**Pastures considered for the livestock NAMA were identified for Costa Rica's "Strategy for Low Carbon in Livestock" (MAG, 2015)*

The Technical Committee (2016) made a first proposal of the different targets for each restoration action to achieve Costa Rica's commitment to the Bonn Challenge (Table 11).

Table 11 *Proposed targets[11] in hectares to achieve Costa Rica's commitment to the Bonn Challenge*

Current Land Use	Transition	Target[a] (hectares)	Total area[b] (hectares)
High altitude pastures	Silvopastoral system	100,000	310,000
Low altitude pastures	Improved pastures and silvopastoral system	255,000	327,000
Low altitude pastures	Passive regeneration	100,000	134,000
Pastures (outside of NAMA livestock)	Timber plantations	70,000	280,000
Shade coffee	Fertiliser management	25,000	90,000
Sun coffee	Agroforestry system and fertiliser management		
Pineapple	Contouring and crop residue management	6,250	48,000
Oil palm	Fertiliser management	6,250	59,000
Banana	Fertiliser management	6,250	72,000
Pineapple, oil palm and banana	Restoration of riparian forest	6,250	8,000

Source: Technical Committee (2016) andb IUCN

[11] The Technical Committee (2016) also proposed targets for secondary and mature forest management and conservation, totaling 425,000 hectares. García-Rangel et al. (2017) identified almost two million hectares for the implementation of these actions under REDD+.

Although the different programmes and restoration actions presented are part of Costa Rica's carbon neutrality target, additional environmental co-benefits are expected through programme implementation.

Based on the Forestry Law (No. 7575, 1997), the PPSA is expected to support not only the mitigation of greenhouse gases, but also the protection of water and biodiversity, and the provision of scenic beauty (FONAFIFO, 2014b). Likewise, the NAMAs and GAPs consider a series of environmental co-benefits in addition to carbon benefits, such as a decrease in erosion and soil degradation, reduced water pollution through a more efficient application of fertilisers, improved connectivity of landscapes and enriched landscapes for tourism, among others (MAG, 2015; MINAE et al., 2014; Nieters et al., 2016; UNFCCC, 2014).

Although the programmes have established the carbon reduction potential of their different restoration actions, the analysis of the impact on the provision of other ecosystem services and the spatial prioritisation of areas for programme implementation has not yet been carried out. To complement the carbon analyses, and as a part of the ROAM application in Costa Rica, the aim of this study is to estimate the impact of the different restoration actions on water quality and to prioritise areas where the highest benefit of water quality improvement is expected.

Analysis of the impact on ecosystem services provision

The ecosystem services studied are water quality improvement through the retention of sediment and nutrient runoff. These ecosystem services are commonly classified as hydrological ecosystem services (Brauman et al., 2007; de Groot et al., 2010; Terrado et al., 2014). Hydrological ecosystem services refer to the benefits to people produced by the effects of terrestrial ecosystems on freshwater resources (Brauman et al., 2007). They can be important for sustainable development through the supply of clean water, which can benefit human health, and for other uses of water such as irrigation, agriculture and the generation of hydroelectricity (Goldstein et al., 2017). The analysis of sediment runoff evaluated the contributions of the different restoration actions to soil retention, thereby reducing erosion and sediment export into streams and rivers (Fernández-Moya et al., 2014; Goldstein et al., 2017; Guerry et al., 2015; Tscharntke et al., 2011). The nutrient retention analysis evaluated the role of restoration actions in removing a portion of the nitrogen and phosphorus contributed by fertiliser application, as well as the impact of a reduction in the use of fertilisers (Goldstein et al., 2017; Kovacs et al., 2013; Power, 2010; Scherr & McNeely, 2008).

To estimate changes in service provision resulting from the implementation of the various restoration actions, the InVEST tool, model version 3.2, was used (Sharp et al., 2016). InVEST is a spatially explicit tool designed to quantify various ecosystem services and uses biophysical and economic data and relationships to estimate biophysical levels and economic values of ecosystem services (Terrado et al., 2014). InVEST provides information on how changes in landscapes can lead to changes in the flows of ecosystem benefits to people, and can thus be used to inform decisions on the management of natural resources (Sharp et al., 2016). To measure the impacts on the ecosystem services considered, the InVEST sediment model and nutrient model were used.

Sediment export

The objective of the sediment delivery ratio model is to map the generation and delivery of terrestrial sediments to water bodies (Sharp et al., 2016). The model is based on the revised Universal Soil Equation (USLE), which was adapted to represent sediments contributed by sheet-flow erosion (Vogl et al., 2016). The model analyses sediment discharges from the terrestrial area, but, due to model limitations, obviates the formation of uneven terrain that prevents sediments or other sediment sources from passing through (e.g. ravines or landslides). The model calculates how eroded soil is routed down a flow-path, to obtain the proportion of sediments that reaches rivers and streams (Kovacs et al., 2013; Terrado et al., 2014). The model requires spatial data, inputs for the USLE and data on the sediment retention capacity of a given land use or land cover (Sharp et al., 2016).

Nutrient export (NDR Model)

Nutrient export refers to the quantity of nutrients from natural and anthropogenic sources from a given land use that are exported due to the effects of water erosion (Toft et al., 2014). The objective of the NDR model is to map the nutrient sources from the watersheds and their transport to the streams. It was designed for nitrogen and phosphorus nutrients (Sharp et al., 2016). In this study, with a focus on the restoration of agricultural production systems, the main sources of nutrients considered are the application of fertilisers, livestock manure and vegetation (litter and crop residues, among others). The restoration actions modelled will impact both the amounts of additional nutrients, such as a reduction in the application of synthetic fertiliser, and the ability of ecosystems to retain or filter excess nutrients before they reach downstream water bodies (Goldstein et al., 2017; Kovacs et al., 2013; Sharp et al., 2016). Once the nutrients reach a body of water, the model does not assume any additional retention or removal (Kovacs et al., 2013).

To estimate nutrient retention resulting from restoration actions, InVEST used data on expected nitrogen and phosphorous loading and the filtering capacities or retention coefficients for each land use type (Kovacs et al., 2013; Sharp et al., 2016) (see Raes et al., forthcoming).
The InVEST user's guide provides more details on the SDR and NDR models (Sharp et al., 2016).

Impact potential maps

The potential benefits of the different restoration actions to improve water quality were estimated by calculating the difference in sediment and nutrient export to rivers and streams under a 'current' scenario, represented by the current land use/land cover map, and a series of 'restored' scenarios, represented by changing the biophysical data of one of the current land uses with those of its corresponding restoration action. Following Gourevitch et al. (2016), climate and landscape factors, such as slope and hydrologic connectivity, were assumed unchanged between scenarios.

A model simplification for the 'current' scenario was that only one specific production system was considered for each land use category, based on averages of national statistics of, for example, fertiliser application and cattle densities. Additionally, only one restoration action was considered for each specific land use (Table 11). To be able to model the impact for each specific land use, the current land/use land cover map of Costa Rica was modified[12] (see Raes et al., forthcoming).

For pastures, a division was first made between those pastures located within the area designated for programme implementation and those outside (See MAG, 2015). Pastures within the Livestock NAMA were then divided according to altitude, high (>1000m) and low (<1000m) altitude pastures*. The latter area, below 1,000 meters elevation, was then divided again based on whether these pastures were classified as areas appropriate for agriculture or for forestry (as defined by the Costa Rica Tropical Science Centre and the Ministry of Agriculture and Livestock). For the Coffee NAMA, no map was available that allowed for the spatial differentiation between sun and shade coffee plantations. However, data were available on the percentage of each type of production system for seven of Costa Rica's national planning regions. The coffee area was divided according to the seven regions, and biophysical data for the current land use were based on a weighted average of the biophysical data of sun and shade coffee for each region. Finally, to analyse the impact of the restoration of riparian forest, an area of 15 meters along the banks of primary and secondary rivers in banana, oil palm and pineapple plantations was created on the land use map.

To identify priority areas based on the impact of ecosystem service provision of a given restoration action, impact potential maps were calculated. These maps display the expected change in sediment and nutrient export per pixel if the restoration action is implemented. These values are termed 'marginal values' (Natural Capital Project & IUCN, 2017). To obtain the impact potential maps, the SDR and NDR InVEST models were run under the 'current' land use scenario, followed by the different runs under the 'restored' scenarios.[13] The impact potential map of a given restoration action on the export of sediments, nitrogen or phosphorus was calculated as the difference between the spatial outputs of these two scenarios (see Figure 29,31,32) (Natural Capital Project & IUCN, 2017).

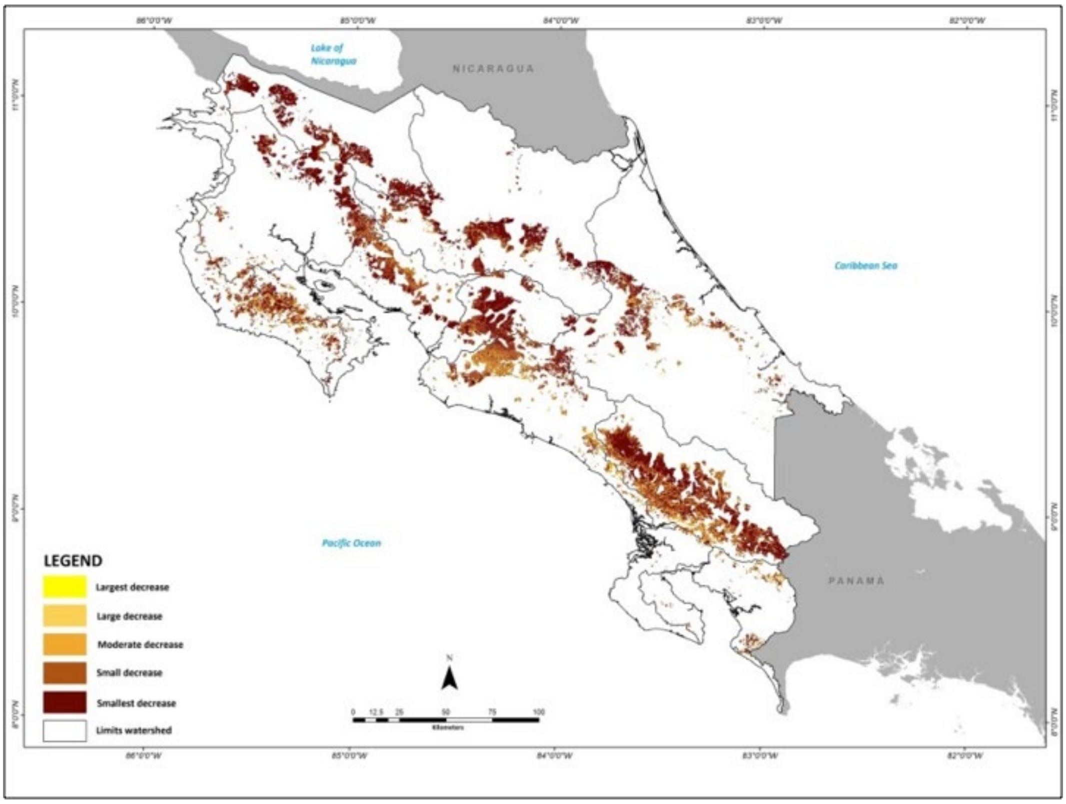


Figure 29: *Impact potential map of reduction in sediment export by implementing a silvopastoral system on pastures used for dairy cattle, Livestock NAMA*

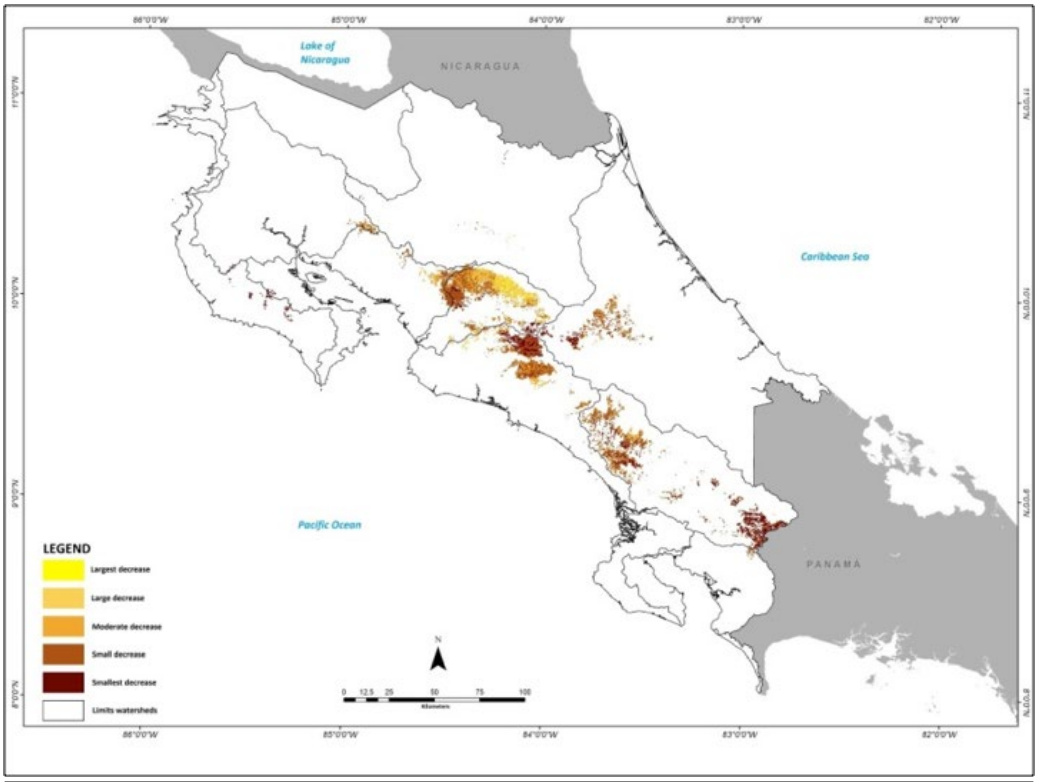
Figure 30 *Calculation of the impact potential map*

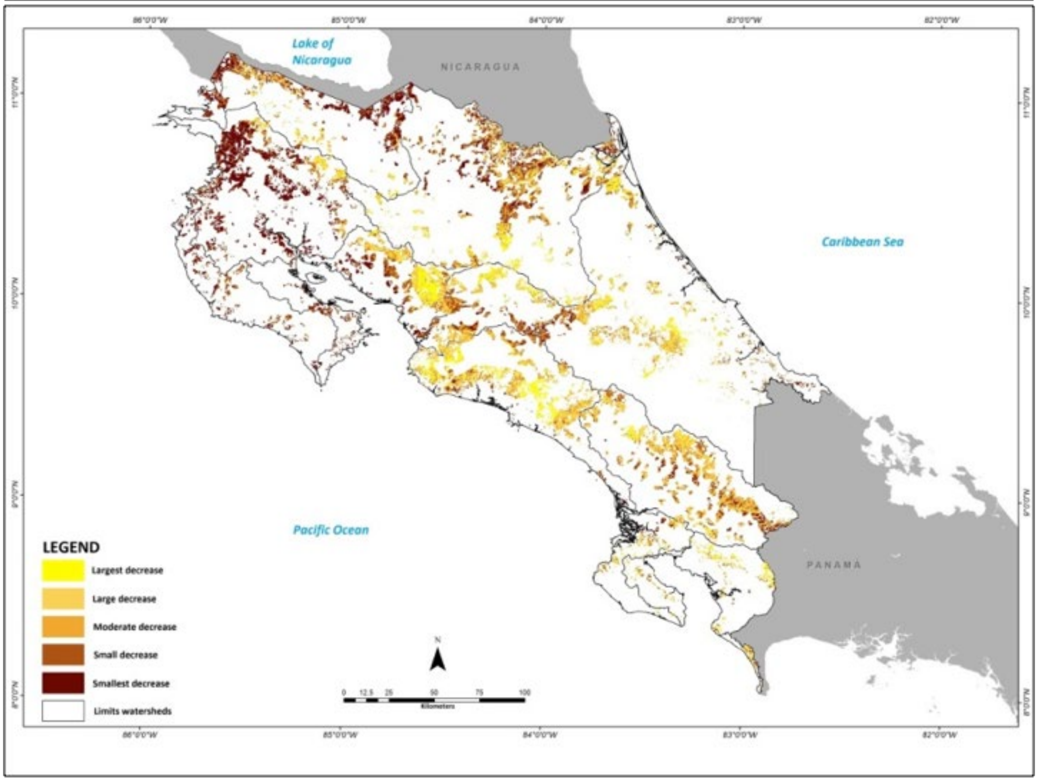
[12] Spatial data were created and modified using ArcGIS and QGIS.
[13] The SDR model was run seven times; the NDR model was run nine times, as the only action considered on banana and oil palm plantations is fertiliser management, which does not have an impact on the current erosion levels.
* High altitude pastures are mainly used for dairy cattle.

InVEST results (impact potential maps)

With the InVEST models, three impact potential maps containing marginal values were generated for each restoration action[14]: (1) change in sediment export, (2) change in the export of nitrogen and (3) change in the export of phosphorus. Figures 28, 29 and 30 show examples of the impact potential maps of implementing several restoration actions.

Figure 31: *Impact potential map of reduction in nitrogen export by implementing agroforestry systems (top) and* ***Figure 32:*** *the use of slow- and controlled release fertilizer, Coffee NAMA (bottom)*





[14] For the actions on banana and oil palm plantations only two impact potential maps were created.

Beneficiaries

The impact potential maps allow the identification of those areas of the country where the strongest reduction[15] in sediment and nutrient export could take place if a specific restoration action is implemented. However, Goldstein et al. (2017) in their restoration prioritisation analysis defined priority areas for hydrological ecosystem services as those areas that provide the highest levels of water quantity and quality benefits to people. The changes modelled with InVEST can result in different kinds of human impacts, such as a decrease in the cost of drinking water purification or an increased reservoir capacity due to reduced siltation (Lele, 2009). Thus, following Fisher et al. (2009) and Jax et al. (2013), who clarified the importance of benefits to define ecosystem services, to prioritise areas for the implementation of restoration actions, not only the ecosystem service impact from restoration actions is modelled with InVEST, but the location of beneficiaries for the potential changes in sediment and nutrient export are identified. In this study, the potential benefits for hydropower production, drinking water quality and reducing the degradation of wetlands are considered.

Hydropower production

Erosion control is an important ecosystem service for the hydropower sector, since higher sediment concentrations in streams decrease electricity production (Goldstein et al., 2017; Vogl et al., 2016). As priority areas for the reduction in sediment export, those parts of sub-watersheds that flow to the water catchment points of the Costa Rican hydroelectricity plants are included in the spatial analysis (Figure 33a). These areas were identified first by locating the hydroelectricity plants that are currently operating or that were under construction when the location map was created. This map shows the location of the hydroelectricity plants, but not where the plants extract their water. As a proxy for the location of the water extraction point, the points located on rivers nearest to each plant were used. The proxy location of water extraction points and the digital elevation model of Costa Rica were then used as input to InVEST's DelineateIT tool to create servicesheds for the production of hydroelectricity.

Wetlands

Another map taken into account for prioritisation is Figure 33b displaying the location of Costa Rica's wetlands (SINAC, 2007). Wetlands provide a range of ecosystem services, such as protection of inland areas from storms, as water reservoirs or as sinks for greenhouse gases (Leibowitz, 2003; Mitra et al., 2005; Russi et al., 2013). Another important ecosystem service provided by wetlands is their function as a filter for pollutants (Knight et al., 2000; Leibowitz, 2003; Mitsch et al., 2000). However, many wetlands, including those in Costa Rica, are degraded and suffer from contamination from pollutants such as phosphorus (Sasa et al., 2015; Tabilo-Valdivieso, 1997; Varnell et al., 2010). The location of wetlands is used as the beneficiary map of the reduction of phosphorus export. The actual beneficiaries are the people who on a local, national or even global level could benefit from an increased provision of the multiple ecosystem services provided by wetlands through a reduction in wetland degradation.

Drinking water

Soil retention and the retention of nutrients can prevent surface water contamination and improve drinking water quality (Goldstein et al., 2017). To create priority areas for improved drinking water quality, two maps were created. One map (Figure 33c) shows the number of people per district of Costa Rica reliant on untreated surface water (INEC, 2011), with those districts with the highest total number of people considered a priority for the improvement of drinking water quality. A second map (Figure 33d) presents the location of surface water sources for drinking water (Direccion General de Aguas, 2016). Both maps together locate beneficiaries not only of increased sediment retention, but also of decreased nutrient export. For drinking water quality, the impact of reduced nitrogen loading is also considered (Guevara & Herrera Murillo, 2014; Lager & Wikström, 2007).

Biological corridors

Improvement in landscape connectivity is considered a co-benefit of the several programmes contemplated in this study (MAG, 2015; MINAE et al., 2014; UNFCCC, 2014). The presence of natural landscape elements, such as forest patches, riparian forests and live fences, can decrease habitat fragmentation by improving ecological connectivity (Fischer et al., 2006; Harvey et al., 2005; Höbinger et al., 2012; Seaman & Schulze, 2010). An additional restoration prioritisation map is thus added as a final input for the identification of priority areas. Figure 33e shows the location of the biological corridors in Costa Rica (SINAC, 2017a). The aim of biological corridors is to connect patches of natural vegetation, to facilitate movement of plants and animals, and to ensure the continued course of ecological processes (Chetkiewicz et al., 2006). In Costa Rica there are 47 official biological corridors, representing 32% of the continental territory (SINAC, 2017b).

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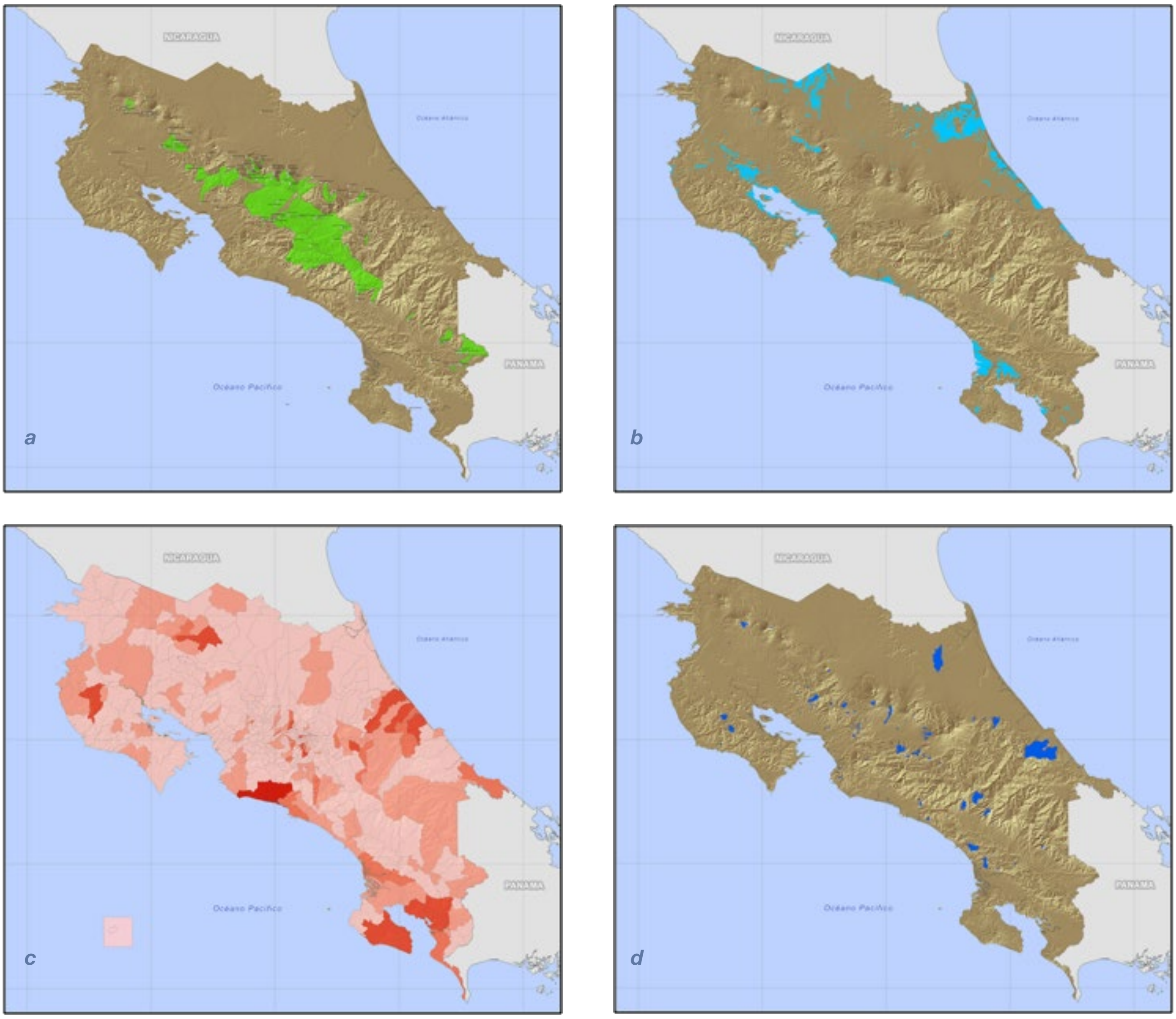
[15] The only exception is the implementation of silvopastoral systems with pasture improvement on pastures for beef and dual-purpose cattle. As this action is accompanied by an increase in the number of heads of cattle on a given area, nitrogen and phosphorus loading is increased. In this case, areas with the smallest increase will be prioritised. Although this restoration action could thus have a negative impact, the proposal of the Technical Committee is that the intensification be implemented jointly with pasture abandonment in other areas, offsetting the impact.

Overview beneficiary maps

Figure 33 (a–e): *These are the beneficiary servicesheds used in the ROOT analysis for Costa Rica. They include* ***a)*** *the location of hydroelectricity production,* ***b)*** *location of major wetlands,* ***c)*** *people without access to potable water (darker colours indication a higher number of people without access to potable water,* ***d)*** *location of major surface water sources for use as drinking water, and* ***e)*** *the location of biological corridors.*



As the main objective of this study is ecosystem provision based prioritisation of areas, the impact potential maps generated with InVEST are expressed in biophysical terms and are spatially related to the beneficiary maps (Keeler et al., 2012; Myers et al., 2013; Ruckelshaus et al., 2015). Monetary valuation would require additional information (Vogl et al., 2016). In addition, by prioritising based on biophysical output and beneficiary maps, double counting, which can potentially occur in monetary valuation, is avoided (Ojea et al., 2012). A higher priority will be given to areas where, for example, a reduction in sediment occurs in a servicesheds that supplies water both for hydroelectricity production and drinking water.

Prioritisation with ROOT

ROOT was used to identify optimal areas for the implementation of each of the restoration actions, considering the impact on ecosystem service provision, the location of potential beneficiaries, and additional priority areas. In this analysis the spatial decision unit map was made up of hexagons of 400 hectares each.

ROOT optimisation

ROOT runs a number of optimisations corresponding with different potential prioritisations of each of the objectives. Prioritisations considered included (1) optimisations based only on the results of the impact potential maps, (2) optimisations including the beneficiary maps and (3) optimisations including the biological corridors map. For this analysis, each individual optimisation, three per restoration action, was run 100 times. In this study, spatial decision units with the highest optimisation scores were summed until they covered the target areas for each restoration action, creating the restoration priority maps.

Results of ROOT

Figures 34-36 show different priority maps, with prioritised areas in green, for implementing timber plantations on pastures not considered for the Livestock NAMA, based on the target of 70,000 hectares (Table 11). Figures 37-39 show the 25,000 hectares prioritised for the Coffee NAMA. The optimisation results presented in Figures 35 and 38 are based solely on the ecosystem service impact potential maps, identifying those areas where the combined reductions in sediment and in nutrient export are largest. Figures 34 and 37 show priority maps for when the beneficiary maps are included in the optimisation in addition to the impact potential maps, i.e. they show where a high supply is met by the highest demand. Finally, Figures 36 and 39 display the results of prioritising areas for the implementation of restoration actions when biological corridors are included in addition to impact potential and beneficiary maps.

Results show how ecosystem services-based prioritisation with ROOT can be used to inform decision makers and programme implementers about those areas that should be considered priorities for programme implementation. Optimisation results that include beneficiary maps are clearly different from results that only maximise a reduction in sediment and nutrient export. This illustrates the importance of including not only the areas where the biophysical impacts of restoration actions are highest, but also those areas where beneficiaries are located, to maximise the benefits to people of implementing restoration actions.

Figure 34: *Prioritisation of timber plantations outside of the Livestock NAMA in areas with strongest reduction in sediment, nitrogen and phosphorus export. Blue indicates optimal areas, red indicates non-optimal areas.*

Figure 35: *Prioritisation of timber plantations outside of the Livestock NAMA in areas with strongest reduction in sediment, nitrogen and phosphorus export including beneficiary maps. Blue indicates optimal areas, red indicates non-optimal areas.*

Figure 36: *Prioritisation of timber plantations outside of the Livestock NAMA in areas with strongest reduction in sediment, nitrogen and phosphorus export including beneficiary maps and biological corridors. Blue indicates optimal areas, red indicates non-optimal areas.*

Figure 37: *Prioritisation of Coffee NAMA in areas with strongest reduction in sediment, nitrogen and phosphorus export. Blue indicates optimal areas, red indicates non-optimal areas.*

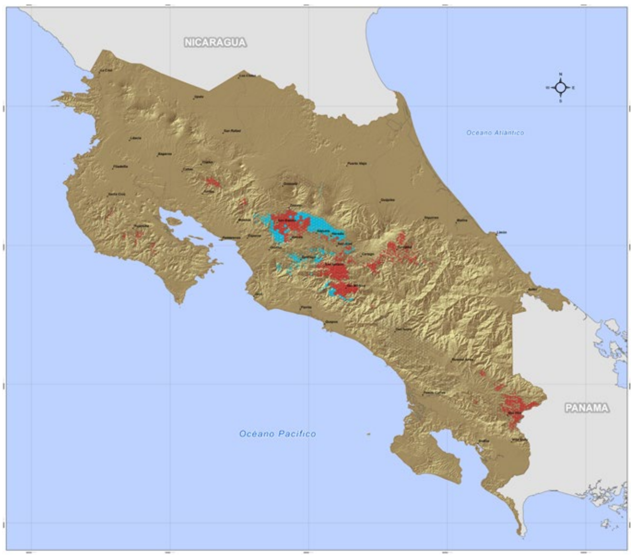


Figure 38: *Prioritisation of Coffee NAMA in areas with strongest reduction in sediment, nitrogen and phosphorus export including beneficiary maps. Blue indicates optimal areas, red indicates non-optimal areas.*

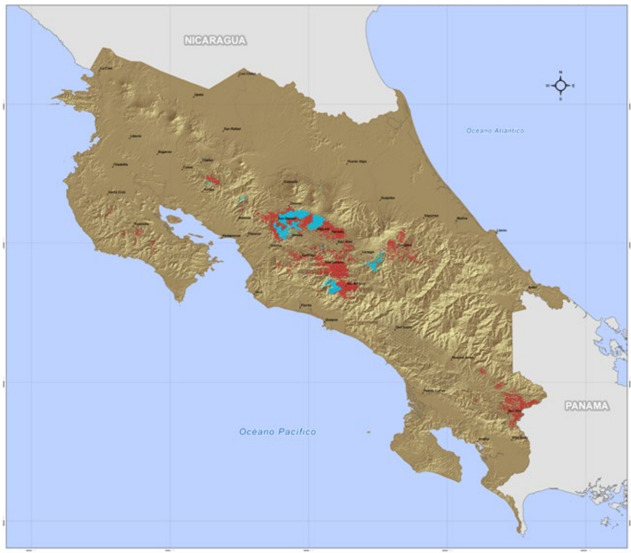
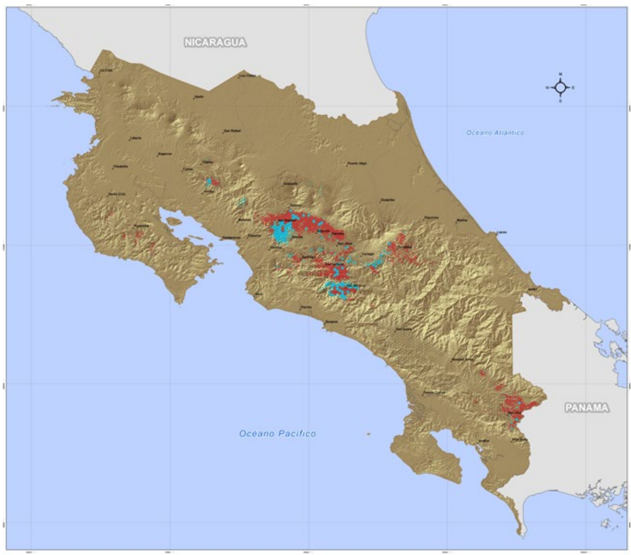


Figure 39: *Prioritisation of Coffee NAMA in areas with strongest reduction in sediment, nitrogen and phosphorus export including beneficiary maps and biological corridors. Blue indicates optimal areas, red indicates non-optimal areas.*



Conclusions

As part of the application of ROAM, InVEST and ROOT provided tools for ecosystem services-based spatial prioritisation of areas for the implementation of a series of restoration actions in Costa Rica. The results provide decision makers and programme implementers with information on where to implement programmes and restoration actions to achieve the highest positive impact on the provision of ecosystem services related to water quality. The use of impact potential and beneficiary maps allowed for relating those areas with the highest potential impact on sediment and nutrient export with those areas with the strongest demand for these changes, maximising the benefits to people of the different restoration actions.

The inclusion of beneficiary maps with the application of ROOT shifted the prioritised areas, illustrating the importance of including beneficiaries to assure restoration actions are implemented where benefits are maximised for people. The inclusion of beneficiary maps potentially also has other advantages. It can create social support for the implementation of restoration actions, and it may facilitate increased funding for restoration actions, for example when restoration decreases costs of hydroelectricity production. Although the results displayed in this chapter show prioritised areas based on the complete target for each restoration action, ROOT results also allow for the identification of smaller areas, such as the first 2,000 hectares that should be prioritised to start programme implementation. An additional strength of ROOT is that including additional prioritisation criteria to respond to the demands of different actors or to a shift in policy orientation is straightforward. Additional prioritisation analysis can be carried out, not only by adding additional layers to the ROOT base model, but by running the model again using the previous optimisations as input. This flexibility is useful in adapting priority areas for FLR to different demands. ■

Synthesis

These case studies demonstrate the many ways that ecosystem service analysis and beneficiaries can be modelled and optimised for conservation and restoration. The first three cases use a scenario approach of changing land use cover to a restored state based on land cover types that produce high ecosystem service benefits (e.g. natural forest) to determine what the ceiling of ecosystem services in these areas might be. This is the simplest approach to scenario generation in ROOT. For examples like Myanmar, where the Forest Department is primarily interested in restoration of the permanent forest estate, these scenarios make a great deal of sense. Similarly, in Espirito Santo, a strong State focus on forest landscape restoration to support restoration of the Atlantic Forest lends itself well to this modelling approach. While Malawi's approach is similar (utilising a conversion of land use to natural forest to determine ecosystem service maximums for restoration opportunity areas), in practice FLR in Malawi will be more nuanced to include interventions that do not necessarily change the land use type, but improve the ecological productivity within land uses. Unfortunately, specifics on the landscape restoration strategy for Malawi had not yet been finalised at the time of this publication.

A hybrid approach can be found in the Colombia case study. This example uses land use conversions based on both landscape restoration and degradation to demonstrate how municipalities can achieve watershed-level ecosystem service targets. In these scenarios land covers are redefined to natural forest or pasture in combination with modifications to ecosystem service model parameters like land cover carbon values and management factors within a land use type. This is also the only example that utilises ecosystem service delivery targets to inform the optimisation. Typically ecosystem services analyses generate a number of scenarios which are then evaluated for their merits. In ROOT, this process is reversed such that the benefits of restoration are the objective and ROOT works to define scenarios in which such objectives can be met.

The Costa Rica case study demonstrates how optimal solutions to achieve an objective can be found without altering the land use type. For each of the ecosystem service scenarios (sediment delivery and nutrient export), ROOT worked on parameter changes within the ecosystem service model inputs, rather than on broad changes in land use. This is more realistic in terms of how forest landscape restoration is implemented in practice, and more in line with the forest landscape restoration approach, which does not suggest broad changes in land use but rather improvement in the ecological productivity of current land use. This process required significant investment in literature review and validation to demonstrate how different attributes of restoration actions within a particular land use (i.e. pastoral systems) were altered by restoration activities (i.e. silvopastoral systems). In this case, the underlying land uses remained the same, but restoration altered the ecological productivity and ecosystem service delivery.

The results of these analyses can be powerful in designing restoration strategies. In particular, they demonstrate that small areas with large ecosystem service potential can have disproportionate and compounding benefits across landscapes. This is especially the case in Myanmar, where only 21,889 hectares of restoration opportunity area may have the potential to place 4 million hectares of land under restoration. The intent here is not to rationalise that small investments will always lead to landscape-scale benefits, but that, if baseline information is collected and restoration activities are effectively monitored and evaluated over the long term, 4 million hectares 'under restoration' through active restoration in 22,000 hectares is not impossible. This is especially the case if the interventions chosen to support restoration are well aligned with degradation drivers and the social and economic objectives of restoration. In the case of Costa Rica, it is certainly the intention that investments in nationally appropriate mitigation actions (NAMAs) will produce large-scale landscape and climate benefits – along with the environmental and social safeguards that the Costa Rican people expect. The ROOT analyses presented here and in more detail in Raes et al. (forthcoming) demonstrate where restoration can support ecosystem service generation for many types of beneficiaries, and will allow Costa Rica to make significant progress on their nationally determined contribution to the Paris Agreement on Climate Change and reduce the costs of implementing these actions. This is achieved both by ensuring that trade-offs in ecosystem services are minimised and that approaches that combine multiple ecosystem services increase the chances of restoration success.

All of these case studies share an assessment of trade-offs and are under consideration to justify large-scale investments in forest landscape restoration. However, what they most notably achieve is a combination of the social and biophysical reasons for restoration that are easily communicated to decision makers. That ROOT was developed out of a demand-driven need by stakeholders in these cases facilitates the mobilisation and direction of funding to FLR actions in optimal areas.

In Espirito Santo, this may mean modification to the payments for ecosystem services scheme to direct payments where they may have the most benefit for people and ecosystem services. Specifically, the ROOT analysis shows that at least half of Espirito Santo's Bonn Challenge commitment of 80,000 hectares can be implemented in areas that are highly optimal for ecosystem service provision and clustered with similar areas. The quantitative approach of ROOT has influenced agenda-setting at the state level, since decision makers recognised all the benefits related to forest landscape restoration and started to incorporate other agendas, such as food security, ecosystem-based adaptation and gender equity, among others, into discursive propositions.

In Malawi, strategies for irrigation and hydropower generation in the Shire River Basin will benefit from the identification of landscapes that are important for restoration interventions. Additionally, the composite national optimisation represents an index of restoration value where, if restored, these areas would contribute the highest ecosystem service values for women, those in extreme poverty and high priority watersheds. From a policy perspective, these optimisations represent geographies where restoration could be most efficiently employed to address the underlying drivers of degradation and support increased ecological productivity for people.

In **Myanmar**, ROOT can demonstrate not only where forest restoration is an opportunity, but also where that restoration could start to support reductions in sediment and increases in livelihood potential. In each of the 100%-optimal watersheds (n=254), less than 10% of the overall watershed area is actual FLR opportunity area. As a result, practitioners may physically restore slightly over 20,000 hectares of degraded land and thereby potentially place nearly 4 million hectares of Myanmar's landscapes 'under restoration'. These areas contribute significantly to sediment retention and offer the most benefits directly to people who would benefit from increases in fuelwood sources or employment opportunities.

The **Colombia** water for cities analysis found that the cost savings through a multiple-service approach range 13–95% across the six cities and their source watersheds. In other words, in some watersheds, achieving equivalent nutrient, sediment and carbon improvements would cost nearly double if investments were made in achieving those benefits individually. The ROOT results provide decision makers with guidance on where to implement water programmes and restoration actions to achieve the highest positive impact on the provision of ecosystem services related to water quality.

Finally, the ROOT analysis for **Costa Rica** provided the government with information on where to best implement their climate change mitigation actions while also supporting forest landscape restoration. This is a case where the multiple benefits of FLR are recognized at a national level and integrated across many sectors and initiatives. Additionally, this is the most technical of the case studies, since the land use type was not altered in the model but modified by different restoration actions. This case also specifically modelled the benefits of these interventions in terms of ecosystem service benefits, social benefits, and an economic analysis (Raes et al., forthcoming). Additionally, the inclusion of beneficiary maps with the application of ROOT (similarly to Myanmar) shifted the prioritised areas, illustrating the importance of including beneficiaries to assure restoration actions are implemented where social benefits are maximised.
ROOT can demonstrate how forest landscape restoration generates multiple benefits beyond just the biophysical realm – it connects those services to people in specific places. This helps translate ecosystem services, which can be a jargon-filled and technical topic, into terms that can be understood by different sectors of society. This was the intent in the development of ROOT: both to provide quantifiable evidence upon which restoration decisions could be made and to ensure that these decisions supported the beneficiaries of most interest in FLR activities.

The continued application of ROOT in contexts similar to these and in other sectors and different scales is an exciting possibility. As a modelling tool that is agnostic to inputs, ROOT is capable of working outside of restoration scenarios to assist in any form of spatial land optimisation scenario. This could include business applications for investments in sustainable resource supply chains, the optimisation of revenue potential for the restoration economy, sustainable land use management, land degradation neutrality, biodiversity conservation, or a plethora of unexplored and interesting applications.

No matter the application, ROOT has the capacity to transport ecosystem services analysis beyond an inventory of services to better include the social, cultural and economic considerations within assessments of functioning landscapes, and to facilitate the implementation of nature-based solutions to the landscape challenges that ail us. ■

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Appendix:

Brazil, Espirito Santo InVEST inputs

Sediment delivery ratio model

"The objective of the InVEST sediment delivery model is to map overland sediment generation and delivery to the stream. In a context of global change, such information can be used to study the service of sediment retention in a catchment. This is of particular interest for reservoir management and instream water quality, both of which may be economically valued."
A full description of the sediment model can be found on the InVEST user website:
http://data.naturalcapitalproject.org/nightly-build/invest-users-guide/html/sdr.html

Water yield: Reservoir hydropower production

"Hydropower accounts for twenty percent of worldwide energy production, most of which is generated by reservoir systems. InVEST estimates the annual average quantity and value of hydropower produced by reservoirs, and identifies how much water yield or value each part of the landscape contributes annually to hydropower production. The model has three components: water yield, water consumption, and hydropower valuation. The first two components use data on average annual precipitation, annual reference evapotranspiration and a correction factor for vegetation type, root restricting layer depth, plant available water content, land use and land cover, root depth, elevation, saturated hydraulic conductivity, and consumptive water use. The valuation model uses data on hydropower market value and production costs, the remaining lifetime of the reservoir, and a discount rate. The biophysical models do not consider surface – ground water interactions or the temporal dimension of water supply. The valuation model assumes that energy pricing is static over time."

A full description of the water yield model can be found on the InVEST user website:
http://data.naturalcapitalproject.org/nightly-build/invest-users-guide/html/reservoirhydropowerproduction.html

Model data sources

Table 12: InVEST Data Sources: Espirito Santo, Brazil.

Components	Models	Data	Source
Soil-Water Component	Water Yield Model	Precipitation	WorldClim http://www.worldclim.org/version1 Hijmans, R.J., S.E. Cameron, J.L. Parra, P.G. Jones and A. Jarvis, 2005. Very high resolution interpolated climate surfaces for global land areas. International Journal of Climatology 25: 1965-1978.
		Average Annual Potential Evapotranspiration	CGIAR http://www.cgiar-csi.org/data/global-aridity-and-pet-database Zomer RJ, Trabucco A, Bossio DA, van Straaten O, Verchot LV, 2008. Climate Change Mitigation: A Spatial Analysis of Global Land Suitability for Clean Development Mechanism Afforestation and Reforestation. Agric. Ecosystems and Envir. 126: 67-80.
		Root restricting layer depth	Harmonized World Soil Database http://webarchive.iiasa.ac.at/Research/LUC/External-World-soil-database/HTML/ FAO/IIASA/ISRIC/ISSCAS/JRC, 2012. Harmonized World Soil Database (version 1.2). FAO, Rome, Italy and IIASA, Laxenburg, Austria.
		Plant Available Water Content	Harmonized World Soil Database http://webarchive.iiasa.ac.at/Research/LUC/External-World-soil-database/HTML/ FAO/IIASA/ISRIC/ISSCAS/JRC, 2012. Harmonized World Soil Database (version 1.2). FAO, Rome, Italy and IIASA, Laxenburg, Austria.
		Land use/land cover	Instituto Jones dos Santos Neves. http://www.ijsn.es.gov.br/ Data not publically available
		Watersheds	IBGE: Institution Brazileiro de Geografica e Estatistica https://www.ibge.gov.br/
		Subwatersheds	IBGE: Institution Brazileiro de Geografica e Estatistica https://www.ibge.gov.br/
		Biophysical Table	See below
	Sediment Delivery Ratio Model	Digital elevation model (DEM)	NASA Jet Propulsion Laboratory (JPL), 2013, NASA Shuttle Radar Topography Mission United States 1 arc second. Version 3. 6oS, 69oW. NASA EOSDIS Land Processes DAAC, USGS Earth Resources Observation and Science (EROS) Center, Sioux Falls, South Dakota (https://lpdaac.usgs.gov at http://dx.doi.org/10.5067/MEaSUREs/SRTM/SRTMUS1.003.
		Rainfall erosivity index (R)	Cecilio, Roberto A., et al. "Assessing rainfall erosivity indices through synthetic precipitation series and artificial neural networks." Anais da Academia Brasileira de Ciências 85.4 (2013): 1523-1535
		Soil erodibility (K)	Harmonized World Soil Database http://webarchive.iiasa.ac.at/Research/LUC/External-World-soil-database/HTML/ FAO/IIASA/ISRIC/ISSCAS/JRC, 2012. Harmonized World Soil Database (version 1.2). FAO, Rome, Italy and IIASA, Laxenburg, Austria.
		Land use/land cover (LULC)	Instituto Jones dos Santos Neves. http://www.ijsn.es.gov.br/ Data not publically available
		Watersheds	IBGE: Institution Brazileiro de Geografica e Estatistica https://www.ibge.gov.br/
		Biophysical table SD	See below
		Threshold flow accumulation	1000
		Borselli IC0 Parameter	0.5
		Borselli k Parameter	2
		SDRmax	0.8

Processing methods

This analysis used version 3.2.0 of the Integrated Valuation of Ecosystem Services Tool (InVEST) and ArcGIS version 10.2.

Spatial data: All data were projected into WGS 1984 UTM Zone 24S prior to any analysis. In several cases, data were received in SIRGAS 2000 UTM Zone 24S. These data were re-projected in the WGS to match with global data layers.

InVEST models require that land use/land cover data be in raster format. The LULC file contained 25 land uses (listed in Table 13), and in order to be used as an input to the models it required conversion from vector format to raster. This was accomplished using the *feature to raster* tool in ArcMap 10.2, using the LULC categories as the primary field. To maintain as much detail as possible during this conversion, raster cell size was set to 10 m.

Table 13: Land use codes and descriptions, Espirito Santo State, Brazil.

LULC Description	Land Use Code
Mata Nativa	1
Brejo	2
Macega	3
Mata Nativa em Estagio Inicial de Regenracao	4
Cultivo Agricola - Cafe	5
Outros	6
Afloraemento Rochoso	7
Pastagem	8
Solo Exposto	9
Massa D'Agua	10
Cultivo Agricola - Outros Cultivos Temporarios	11
Reflorestamento - Euacalypto	12
Extracao Mineracao	13
Cultivo Agricola - Outros Cultivos Permanentes	14
Cultivo Agricola - Coco-Da-Baia	15
Campo Rupestre/Altitude	16
Restinga	17
Cultivo Agricola - Cana-De-Acucar	18
Cultivo Agricola - Mamao	19
Area Edificada	20
Reflorestamento - Seringueira	21
Culitvo Agricola - Abacaxi	22
Mangue	23
Cultivo Agricola - Banana	24
Reflorestamento - Pinus	25

Precipitation data for Espirito Santo was provided by downloading 30 arc-second (1 km) WorldClim precipitation data from Zone 34. These data are available is several formats here: http://www.worldclim.org/tiles.php?Zone=34

Average annual **evapotranspiration data** were not available for Espirito Santo. Substitute data were gathered from Global Potential Evapotranspiration (Global-PET) and Global Aridity Index (Global-Aridity) dataset produced and distributed by the Consultative Group for International Agricultural Research (CGIAR). It provides high-resolution (~1 km) global raster climate data related to evapotranspiration processes and rainfall deficit for potential vegetative growth. In this analysis, mean annual values were used and the global raster was extracted to the Espirito Santo state boundary. Data can be downloaded here: http://www.cgiar-csi.org/data/global-aridity-and-pet-database

The **Digital Elevation Model** for Espirito Santo State was version 3 data at 30 m resolution obtained by the Shuttle Radar Topography Mission (SRTM) from NASA. This data is available via the Earth Explorer portal operated by the US Geological Survey at http://earthexplorer.usgs.gov/. The files used were SRTM3S20W041V2 and the two adjacent DEM tiles collected by the SRTM, stitched together and void-filled. These data were then 'extracted by a mask' of the Espirito Santo state boundary.

Watershed data were provided by IBGE. Primary watershed data used in running the InVEST model were based on the OttoBacias_N4.shp layer provided by Marcelo. OttoBacias_N6.shp served well as the necessary subwatershed layer in these analyses. Each were projected into WGS 1984 UTM Zone 24S prior to analysis. These data are not publicly available.

Data on the **root restricting soil depth, plant-available water content,** and **erodability** were unavailable for Espirito Santo State. Each of these layers was calculated using the data within the Harmonized World Soil Database (version 1.2) produced by the United Nations Food and Agriculture Organisation (FAO). The Harmonized World Soil Database is a 30 arc-second raster database with over 15,000 different soil mapping units that combines existing regional and national updates of soil information worldwide (SOTER, ESD, Soil Map of China, WISE) with the information contained within the 1:5,000,000 scale FAO-UNESCO Soil Map of the World (FAO, 1971-1981). Soil data were extracted for Brazil.

Detailed instructions for creating the root-restricting depth, erodibility and plant-available water content layers from harmonized world soil data can be found here: http://forums.naturalcapitalproject.org/uploads/FileUpload/1b/73867fc6231e8ff8507871f5bd33ae.txt

Erosivity data (used in the sediment delivery ratio model) for Espirito Santo were provided by Cecilio et al., "Assessing rainfall erosivity indices through synthetic precipitation series and artificial neural networks," Anais da Academia Brasileira de Ciências 85.4 (2013): 1523-1535. Data were obtained directly from the researcher, who authorized their use for this study. These data are not publically available.

Biophysical data

Sediment retention

1.usle_c: Cover-management factor for the USLE, a floating point value between 0 and 1.
"C" represents the effects of plants, soil cover, soil biomass and soil-disturbing activities on erosion.
2.usle_p: Support practice factor for the USLE, a floating point value between 0 and 1.
usle_p reflects the impact of support practices and the average annual erosion rate. It is the ratio of soil loss with contouring and/or strip-cropping to that with straight row farming up- and down-slope.

The following is the biophysical table used in the sediment retention model. Within it, LULC classes are assigned proportional values based on their cover management factor (usle_c) and their support practice factor (usle_p). The InVEST user guide contained no useful links or information in tracking down sources for these figures. Regardless, a literature search for "cover management factor" and "support practice factor" returned several useful references:

http://www.iwr.msu.edu/rusle/cfactor.htm

http://www.sciencedirect.com/science/article/pii/S0264837715001611

http://naldc.nal.usda.gov/naldc/download.xhtml?id=CAT10827029&content=PDF

http://www.iwr.msu.edu/rusle/doc/cfactors.pdf (table of c values)

Ultimately, these are difficult values to empirically obtain and their effect on the results of the model are difficult to gauge. Since agricultural land use is not the aim of this modelling effort, where specific values could be obtained for land uses they have been included below. Otherwise, values were estimated based on a qualitative estimate of factor values based on the above literature.

Table 14

LULC_desc	lucode	usle_c	usle_p
Afloraemento Rochoso	7	1	1
Area Edificada	20	0.1242	0.95
Brejo	2	0.0001	1
Campo Rupestre/Altitude	16	1	1
Culitvo Agricola – Abacaxi	22	0.36	1
Cultivo Agricola – Banana	24	0.55	1
Cultivo Agricola – Cafe	5	0.1004	1
Cultivo Agricola – Cana-De-Acucar	18	0.3066	1
Cultivo Agricola – Coco-Da-Baia	15	0.2	1
Cultivo Agricola – Mamao	19	0.36	1
Cultivo Agricola – Outros Cultivos Permanentes	14	0.55	1
Cultivo Agricola - Outros Cultivos Temporarios	11	0.55	1
Extracao Mineracao	13	1	1
Macega	3	0.003	1
Mangue	23	0.012	1
Massa D'Agua	10	0.14	1
Mata Nativa	1	0.012	1
Mata Nativa em Estagio Inicial de Regenracao	4	0.047	1
Outros	6	0.0024	1
Pastagem	8	0.008	1
Reflorestamento – Euacalypto	12	0.219	0.4
Reflorestamento – Pinus	25	0.219	0.4
Reflorestamento – Seringueira	21	0.219	0.4
Restinga	17	0.404	1

Water yield

Root depth for Brazil was extracted as a raster layer from the harmonized world soil database. Within Espirito Santo, all soils were calculated to have maximum root depth of 1,000 mm. Values in the water yield biophysical table therefore attributed depths of 1,000 mm to LULC classes that would permit the growth of roots, and values of 1 mm for those LULC categories that could not support the growth of roots (urban areas, rocky outcrops, water bodies, etc.).

Kc is the plant evapotranspiration coefficient, and it is calculated based on LULC class. These values are relatively easy to find for agricultural land uses, but are based on seasonality and usually exist within a range of values within each crop type or LULC category. For crop types, maximum Kc values were used as a conservative estimate of the evapotranspiration coefficient potential.

Kc values for some of the LULC crop types in the Espirito Santo LULC raster can be found here: http://www.fao.org/docrep/x0490e/x0490e0b.htm. Otherwise, agricultural values were qualitatively estimated based on growth form and size relationships to similar crops. For other LULC category Kc values, estimates were based on descriptions on the Natural Capital Project's InVEST user guide, as well as qualitative estimates based on similar land uses and geographies.

Table 15

LULC_veg	LULC_desc	lucode	Kc	root_depth
0	Afloraemento Rochoso	7	0.01	1
0	Area Edificada	20	0.3	1
1	Brejo	2	1.2	1000
0	Campo Rupestre/Altitude	16	0.01	1000
1	Culitvo Agricola - Abacaxi	22	0.5	1000
1	Cultivo Agricola - Banana	24	1.2	1000
1	Cultivo Agricola - Cafe	5	1.1	1000
1	Cultivo Agricola - Cana-De-Acucar	18	1.25	1000
1	Cultivo Agricola - Coco-Da-Baia	15	1	1000
1	Cultivo Agricola - Mamao	19	0.9	1000
1	Cultivo Agricola - Outros Cultivos Permanentes	14	1	1000
1	Cultivo Agricola - Outros Cultivos Temporarios	11	1	1000
0	Extracao Mineracao	13	0.01	1
1	Macega	3	1	1000
1	Mangue	23	1	1000
0	Massa D'Agua	10	1.05	1
1	Mata Nativa	1	0.5	1000
1	Mata Nativa em Estagio Inicial de Regenracao	4	0.9	1000
1	Outros	6	1	1000
1	Pastagem	8	0.4	1000
1	Reflorestamento - Euacalypto	12	0.7	1000
1	Reflorestamento - Pinus	25	0.7	1000
1	Reflorestamento - Seringueira	21	1	1000
1	Restinga	17	1.2	1000
0	Solo Exposto	9	0.01	1

Malawi InVEST inputs

Land cover

The land cover map used in all the InVEST models was modified from the FAO Land Cover and Land Cover Change of Malawi (1990–2010), 2013. The original land cover data included 44 distinct land cover classes; the classification was simplified by combining similar land cover types together into more general types, as shown in the following table. For land classes that are a combination of 2 land classes (i.e. "Woodland/Rainfed Crops"), we maintained both types in the final classification, and assumed that the first class represents 75% of the area and the second class represents 25% of the area.

Table 16

NEW LULC	OLD LULC ("CLASS_ELEM")
Rainfed crops	RAINFED HERBACEOUS CROP(s) Small (< 2ha)
	RAINFED HERBACEOUS CROP(s) Large to Medium Field(s) (> 2ha)
	RAINFED HERBACEOUS CROP(s) - Small Field(s) (< 2ha) with a layer of Sparse Trees
	RAINFED SHRUB CROP(s) Small Field(s) (< 2ha)
Rainfed crops/Forest	RAINFED HERBACEOUS CROP(s) Small (< 2ha)/Broadleaved Deciduous Trees, Closed > (70-60)%
Rainfed crops/Woodland	RAINFED HERBACEOUS CROP(s) Small (< 2ha)/Woodland Open General (15-65%) with Herbaceous Layer
Rainfed crops/Tree and Shrub Savannah	RAINFED HERBACEOUS CROP(s) Small (< 2ha)/Tree and Shrub Savannah
Rainfed crops/Shrubland	RAINFED HERBACEOUS CROP(s) Small (< 2ha)/Shrubland Closed to Open (Thicket) (100-15%)
Rainfed crops/Built up Urban & Non-Urban	RAINFED HERBACEOUS CROP(s) Small (< 2ha)/Built up Urban Non-Urban
	RAINFED HERBACEOUS CROP(s) - Small Field(s) (< 2ha) with a layer of Sparse Trees/Built up Urban Non-Urban
Rainfed crops/Orchard	RAINFED HERBACEOUS CROP(s) - Small Field(s) (< 2ha) with a layer of Sparse Trees/TREE ORCHARD
Forest	Broadleaved Deciduous Trees, Closed > (70-60)%
Forest Plantation	Forest Plantation
Forest/Rainfed crops	Broadleaved Deciduous Trees, Closed > (70-60)%/RAINFED HERBACEOUS CROP(s) Small (<2ha)
Woodland	Woodland Open General (15-65%) with Herbaceous Layer
Woodland/Rainfed crops	Woodland Open General (15-65%) with Herbaceous Layer/RAINFED HERBACEOUS CROP(s) Small (<2ha)
Woodland/Tree and Shrub Savannah	Woodland Open General (15-65%) with Herbaceous Layer/Tree and Shrub Savannah
Woodland/Bare Rock	Woodland Open General (15-65%) with Herbaceous Layer/Bare Rock And-Or Coarse Fragments
Woodland/Built up Urban & Non-Urban	Woodland Open General (15-65%) with Herbaceous Layer/Built Up Urban Non-Urban
Wetlands	DAMBO Herbaceous Vegetation On Temporarily Flooded Land
	Permanent Marsh
Cultivated DAMBO	CULTIVATED DAMBO
Tree and Shrub Savannah	Tree and Shrub Savannah
Tree and Shrub Savannah/Rainfed crops	Tree and Shrub Savannah/RAINFED HERBACEOUS CROP(s) Small (<2ha)
Tree and Shrub Savannah/Built up Urban & Non-Urban	Tree and Shrub Savannah/Built Up Urban Non-Urban
Shrubland	Shrubland Closed to Open (Thicket) (100-15%)
Rainfed crops/Shrubland	Shrubland Closed to Open (Thicket) (100-15%)/RAINFED HERBACEOUS CROP(s) Small (< 2ha)
Bare Rock And/Or Coarse Fragments	Bare Rock And/Or Coarse Fragments
Built up Urban & Non-Urban	Built Up, Urban / Built Up, Non-Urban
Built up Urban & Non-Urban/Rainfed crops	Built up Urban Non-Urban/RAINFED HERBACEOUS CROP(s) Small (< 2ha)

	Built up Urban Non-Urban/RAINFED HERBACEOUS CROP(s) - Small Field(s) (< 2ha) with a layer of Sparse Trees
Built up Urban & Non-Urban/Woodland	Built up Urban Non-Urban/Woodland Open General (15-65%) with Herbaceous Layer
Built up Urban & Non-Urban/Orchard	Built Up Urban Non-Urban/TREE ORCHARD
Herbaceous vegetation	Herbaceous closed vegetation (15-100%)
Herbaceous vegetation/Woodland	Herbaceous closed vegetation (15-100%)/Woodland Open General (15-65%) with Herbaceous Layer
Waterbodies	Non-Perennial Natural Waterbodies (Flowing)
	Perennial Artificial Waterbodies (Standing)
	Perennial Natural Waterbodies (Standing)
	Perennial Natural Waterbodies (Flowing)
Orchard	TREE ORCHARD
Orchard/Rainfed crops	TREE ORCHARD/RAINFED HERBACEOUS CROP(s) Small (< 2ha)
Tea	TEA PLANTATION
Sugar cane	SUGAR CANE - Irrigated Herbaceous Crop(s) Large to Medium Field(s) (> 2ha)
Rice	RICE FIELDS - Small Sized Field(s) Of Graminoid Crops On Waterlogged Soil (< 2ha)

Sources and definitions of spatial data inputs for the InVEST carbon storage and sequestration, water yield and sediment delivery ratio models

Table 17

Input Layer	Source	Definition
Land use land cover (LULC)	FAO Land Cover and Land Cover Change of Malawi (1990-2010), 2013.	Land use land cover is a GIS raster dataset, with an integer LULC code for each cell. LULC polygons were rasterized from the FAO dataset at 90 m resolution. The original 44 LULC classes were condensed by combining similar types, resulting in 34 final classes.
Root-restricting layer depth	Malawi's national soil data (a vector layer with an attribute table containing soil information). This source does not provide root restricting layer depth; thus, a soil-depth layer was used as a proxy.	Vector layer with attribute table providing Malawi's national data including FAO soil classification, landform description, and soil depth. A soil-depth column was created in the attribute table to assign each of the five FAO soil types a soil depth value. Where soil type was assigned N/A," the landform description was used to infer soil depth. The vector layer was converted to a raster layer using the new soil depth as a the "value field."
Precipitation	Clipped from WorldClim Global Climate Data (http://www.worldclim.org/version1)	Average annual precipitation in mm representing long term average 1960–1990 (30 arc-seconds, ~1 km resolution)
Plant-available water content	Clipped from global PAWC data layer –The Natural Capital Project	See methods used to create PAWC layer here: https://drive.google.com/open?id=0B0C_OkQ0E8OgNFZNMjU0T2NDc0xlWjNmSl9lbjVRU05US2JZ
Average annual reference evapotranspiration	Clipped from CGIARCSI Global Aridity and PET Database (http://www.cgiar-csi.org/data/global-aridity-and-pet-database)	Annual average PET in mm representing long term average 1960–1990 (modelled using WorldClim data)
Watersheds	HydroSHEDS http://hydrosheds.org/	Annual average PET in mm representing long term average 1960–1990 (modelled using WorldClim data)
Subwatersheds	Clipped from Hydrosheds database (http://www.hydrosheds.org/)	Global watershed boundaries and sub-basin delineations derived from HydroSHEDS data at 15-second resolution

Digital elevation model (raster)	Jarvis, A., H.I., Reuter, A., Nelson, E., Guevara, 2008, Hole-filled SRTM for the globe Version 4, available from the CGIAR-CSI SRTM 90m Database (http://srtm.csi.cgiar.org).	90 m digital elevation model from NASA SRTM
Rainfall erosivity index (raster)	Global Rainfall Erosivity https://esdac.jrc.ec.europa.eu/content/global-rainfall-erosivity	Panagos P., Borrelli P., Meusburger K., Yu B., Klik A., Lim K.J., Yang J.E, Ni J., Miao C., Chattopadhyay N., Sadeghi S.H., Hazbavi Z., Zabihi M., Larionov G.A., Krasnov S.F., Garobets A., Levi Y., Erpul G., Birkel C., Hoyos N., Naipal V., Oliveira P.T.S., Bonilla C.A., Meddi M., Nel W., Dashti H., Boni M., Diodato N., Van Oost K., Nearing M.A., Ballabio C., 2017. Global rainfall erosivity assessment based on high-temporal resolution rainfall records. Scientific Reports 7: 4175. DOI: 10.1038/s41598-017-04282-8.
Erodibility layer (raster)	Clip from Global Soil Data (HWSD) by Justin Johnson (NaturalCapital Project).	To calculate erodibility, we used parameter values from Wischmeier, Johnson and Cross (1971), as reported in Roose (1996). In this work, rules for calculating erodibility were defined based on location within a soil texture pyramid where soil texture for each soil unit was defined using the USDA NRCS soil texture classes. Additionally, we applied the adjustments reported in Roose that adjusted erodibility values based on where organic matter content was greater than or less than 2%. We used data from ISRIC on soil text and organic matter content to calculate this globally with a 1 km resolution. See methodology document for full description of this data.
Drainage layer	Using the LULC layer, only the class of 'waterbodies' got a value of 1 and everything else 0. The resulting layer was used as the drainage layer input.	The drainages layer gets combined with the DEM streams to determine where sediment flows to, then stops. It stops at streams, and stops where Drainages are set to 1.

Note 1: While the drainage layer is an optional layer for SDR, it is necessary for Malawi's SDR model. Without the drainage layer, no streams are defined in the small areas around the major lakes (because they are too small to be defined by anything except a very small threshold flow accumulation). Thus, without somewhere for the sediment to flow to, the model cannot do subsequent SDR-related calculations and assigns these areas a value of NoData. This problem is addressed by adding a drainage layer.

Note 2: A 1 km buffered layer of Malawi, obtained from the Harmonized World Soil Database (HWSD), was utilised to clip out raster layers from other global databases.

Biophysical parameters used in the InVEST carbon storage and sequestration, water yield and sediment delivery ratio models

All values are literature estimates averaged or adjusted to reflect local conditions, crop type, management and climate.

^Rainfed crops were assumed to be primarily maize, based on http://www.fao.org/docrep/005/y4632e/y4632e0n.htm, which states that 60% of the cultivable land in the country is maize.

*For land classes that are a combination of 2 land classes (i.e. "Woodland/Rainfed Crops"), the parameter values are a 75–25 weighted average of the first and second classes' values, respectively.

**Cultivated dambo is assumed to be a combination of maize and rice, so parameter values reflect an average of those two classes

Table 18

Land Use Code	Land Use Description	LULC_ Veg	Root Depth	Kc (Crop Coef.)	C above	C below	C soil	C dead	usle_c	usle_p
100	Rainfed crops^	1	1175	0.83	3.3	0.9	123.3	0.1	0.3277	1
102	Rainfed crops/Forest*	1	1631.25	0.76	57.95	14.225	121.675	2.8	0.2512	1
103	Rainfed crops/Woodland*	1	1631.25	0.7125	16.6	5.4	118.65	1.475	0.2512	1
111	Rainfed crops/Tree and Shrub Savanna*	1	1525	0.6975	9.625	2.95	121.525	0.825	0.302	1
112	Rainfed crops/Shrubland*	1	1418.75	0.695	18.2	5.625	118.675	2.475	0.275	1
117	Rainfed crops/Built up Urban & Non-Urban*	1	881.25	0.71	2.475	0.675	120	0.075	0.4933	1
130	Rainfed crops/Orchard*	1	1218.75	0.79125	24.825	6.15	120.8	1.175	0.2533	1
200	Forest or Forest Plantation	1	3000	0.55	221.9	54.2	116.8	10.9	0.0215	1
201	Forest/Rainfed crops*	1	2543.75	0.62	167.25	40.875	118.425	8.2	0.0981	1
300	Woodland	1	3000	0.36	56.5	18.9	104.7	5.6	0.0215	1
301	Woodland/Rainfed crops*	1	2543.75	0.4775	43.2	14.4	109.35	4.225	0.0981	1
311	Woodland/Tree and Shrub Savanna*	1	2893.75	0.345	49.525	16.45	107.575	4.95	0.0724	1
315	Woodland/Bare Rock*	1	2250	0.395	42.875	14.175	102.525	4.35	0.0211	1
317	Woodland/Built up Urban & Non-Urban*	1	2250	0.3575	42.375	14.175	106.05	4.2	0.2636	1
400	Wetlands	0	NA	1.1	23.5	43.5	683	0	0.001	1
1001	Cultivated DAMBO**	1	962.5	0.9775	3.15	0.85	115.6	0.1	0.2389	1
1100	Tree and Shrub Savanna	1	2575	0.3	28.6	9.1	116.2	3	0.225	1
1101	Tree and Shrub Savanna/Rainfed crops*	1	2225	0.4325	22.275	7.05	117.975	2.275	0.2507	1
1117	Tree and Shrub Savanna/Built up Urban & Non-Urban*	1	1931.25	0.3125	21.45	6.825	114.675	2.25	0.4163	1
1200	Shrubland	1	2150	0.29	62.9	19.8	104.8	9.6	0.1167	1
1201	Shrubland/Rainfed crops*	1	1906.25	0.425	48	15.075	109.425	7.225	0.1695	1
1500	Bare Rock And/Or Coarse Fragments	0	NA	0.5	2	0	96	0.6	0.02	1
1700	Built up Urban & Non-Urban	0	NA	0.35	0	0	110.1	0	0.99	1
1701	Built up Urban & Non-Urban/Rainfed crops*	1	293.75	0.47	0.825	0.225	113.4	0.025	0.8244	1
1703	Built up Urban & Non-Urban/Woodland*	1	750	0.3525	14.125	4.725	108.75	1.4	0.7479	1
1730	Built up Urban & Non-Urban/Orchard*	1	337.5	0.43125	22.35	5.475	110.9	1.1	0.75	1
2100	Herbaceous vegetation	1	1070	0.925	17.9	26	108.4	0.3	0.0566	1
2103	Herbaceous vegetation/Woodland*	1	1552.5	0.78375	27.55	24.225	107.475	1.625	0.0478	1
2300	Waterbodies	0	NA	1.05	0	0	90.2	0	0.023	1
3000	Orchard	1	1350	0.675	89.4	21.9	113.3	4.4	0.03	1
3001	Orchard/Rainfed crops*	1	1306.25	0.71375	67.875	16.65	115.8	3.325	0.1044	1
3300	Tea	1	1200	1.075	35.1	9.3	115.5	1.2	0.02	1
3400	Sugar cane	1	1600	1.05	46.3	12.4	161.9	1.6	0.4448	1
3500	Rice	1	750	1.125	3	0.8	107.9	0.1	0.15	1

Explanations and references used to generate parameter estimates

Root depth

The root depths for each land cover type were based on the depth at which 95% of root biomass occurs for each vegetation type. The root depth values for all natural land cover types were based on Schenk and Jackson 2002 and the values for agricultural crop cover types were based on Allen et al 1998. For all land cover classes that were a weighted ratio of two individual land cover classes, the root depth value was calculated using the same weighted ratio.

Allen R. G., L. S. Pereira, D. Raes, and M. Smith. 1998. Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56. FAO, Rome 300:6541.

Schenk H. J., R. B. Jackson. 2002. Rooting depths, lateral root spreads and below-ground/above-ground allometries of plants in water-limited ecosystems. Journal of Ecology 90:480-494.

Kc (crop- or vegetation-specific evapotranspiration coefficient)

The plant evapotranspiration coefficient, Kc, is based on physiological characteristics of the dominant plants of each land cover class and is used to modify the reference evapotranspiration and calculate the potential evapotranspiration for each land cover class. The reference evapotranspiration is based on alfalfa. As a plant grows, its Kc value changes. Allen et al. (1998) provides Kc values for various crops at different stages in the growing process. However, InVEST requires an annual average Kc value for the water yield model. In order to convert the values from Allen et al. into an annual average Kc value, we used a weighted average of Kc values for each growth period, weighted by the average number of days per year in each period. These average values were taken from a table created by The Natural Capital Project for use in this model. For crops not in the table, we used the mid value from the tables in Allen et al.
For non-cropland vegetation land cover classes, we estimated Kc using Leaf Area Index (LAI) relationships. Allen et al. (1998) outline a typical LAI relationship as follows:

$$K_c = \begin{cases} \frac{LAI}{3}, & if\ LAI \leq 3 \\ 1, & otherwise \end{cases}$$

We used remotely sensed LAI data from Ribeiro et al. (2008) for our calculations.
Allen, R.G., Pereira, L.S., Raes, D. and Smith, M. (1998). *Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56*. FAO, Rome 300:6541.
Ribeiro, N.S., Saatchi, S.S., Shugart, H.H. and Washington-Allen, R.A. (2008), *Aboveground biomass and leaf area index (LAI) mapping for Niassa Reserve, northern Mozambique*, J. Geophys. Res., 113, G02S02, doi:10.1029/2007JG000550.
Carbon Pools
The carbon pool values are the average carbon stocks for each land cover class in aboveground, belowground, soil and dead biomass. The values used in this analysis are based on Wilcock et al. (2012).
Willcock, S., Phillips, O.L., Platts, P.J., Balmford, A., Burgess, N.D., et al. (2012) *Towards Regional, Error-Bounded Landscape Carbon Storage Estimates for Data-Deficient Areas of the World*. PLoS ONE 7(9): e44795. doi:10.1371/journal.pone.0044795

USLE-C and USLE-P

USLE-C parameter is the crop management factor used in the USLE model to calculate erosion losses from the landscape, and represents the effect of land use, vegetation cover and roughness on soil erosion. These parameters were derived from a database of published studies that report USLE-C values for different land cover types (NatCap 2015). The database was filtered to include only entries from the African continent within the temperate or tropical Köppen climate zones (excluding dry and continental). USLE-C values were taken as the average of all reported values for different land cover types (ranging from n=1 for rangeland to n=44 for crops). Some land cover types (wetlands, urban, water bodies) had no entries in Africa, so averages were taken from studies in all regions, within the temperate or tropical Köppen climate zones.

USLE-P is the support practice factor used in the USLE model, and reflects any management practices that act to reduce soil erosion, such as strip cropping, contouring and terracing. P is the ratio of soil loss with a support factor to that with straight row farming parallel to the slope. Because no information was available on current erosion control practices in Malawi, all land covers were set to USLE-P = 1.

The Natural Capital Project. (2015) *Sediment model parameter database*. Available from: http://www.naturalcapitalproject.org/invest/. Accessed 20 Aug 2016. Link to database.

Z-Parameter calculation

Calculated using the User Guide equation:
*Z = ((w - 1.25)*P) / AWC*
where AWC = Available water content
P = Annual precipitation
1. Parameter w is estimated as having a value of 3.1 from the graphic in Fig 3a in

Local and global factors controlling water-energy balances within the Budyko framework (Xianli Xu, Wen Liu, Bridget R. Scanlon, Lu Zhang & Ming Pan). GEOPHYSICAL RESEARCH LETTERS, VOL. 40, 6123–6129, doi:10.1002/2013GL058324, 2013

2. Parameter P is the mean value of annual precipitation across Malawi

3. Parameter AWC is the mean value of AWC across Malawi, where AWC is first calculated as
*AWC = Min(soil depth, root depth) * PAWC*
Where PAWC = Plant available water content
Mean AWC = 124.3
Mean P = 1091
w = 3.1
So: Z = (((3.1 - 1.25) * 1091) / 124.3) = 16.24 (which is within the range of 1-30 noted in the User Guide.)

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