

Working Paper:

“Servicesheds” Enable Mitigation of Development Impacts on Ecosystem Services

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Abstract:

While many countries require offset programs to balance the environmental degradation caused by development, these programs do not explicitly mitigate the impacts to people. To overcome this shortfall, we present an ecosystem services framework for mitigation programs that uses “servicesheds”, the areas that provide specific ecosystem services to specific beneficiaries. We applied this approach to ecosystem service (erosion control and nitrogen retention for drinking water quality) impact assessment and mitigation for potential mining operations in Colombia. Using the simple InVEST models, we found that, depending on the number and location of mines, mitigation through native habitat protection and restoration could fully compensate anywhere from 24% to 99% of the impacted population without redistributing ecosystem service benefits. This serviceshed approach makes clear what can and cannot be mitigated from the perspective of people and is a promising foundation for future mitigation policy implementation that places a premium on human well-being.

Introduction

Permits for development and associated environmental impact assessments are required in 191 countries of the world [1]. Currently, 64 of those countries have existing or developing programs that also require compensation or mitigation for the environmental impacts of approved development projects [2]. The underlying philosophy of these regulations is that while activities, such as the creation of new mines, oil and gas platforms, transportation corridors, or dams, are needed for economic development under growing human populations [3] and resource demands [4,5], environmental harm should be avoided as much as possible. Further, if harm does occur it should be compensated for by restoration or conservation investments elsewhere.

It is an explicit intent of most of this legislation to avoid the negative impacts of environmental degradation *on people*. Language in legal documents establishing environmental impact assessments and mitigation requirements calls out the specific intent of these laws to protect several components of human wellbeing including; quality of life, generational equity, long term access to natural resources (e.g. fisheries, timber, water, etc) or recreational opportunities and health (Table 1). Beyond the public sector, as of 2012, the International Finance Corporation calls for the consideration of human wellbeing through ecosystem service impact assessment and mitigation in its performance standards [6].

However, all existing, documented offset and mitigation programs are limited because they do not explicitly account for whether or not the people affected are compensated (Table 1). Current implementation of mitigation laws requires impact calculation (environmental impact assessments) and assessment of mitigation investments based on environmental measures, but

does not account for impacts on society [7]. The unintended social effects of this approach have been documented in the United States where the implementation of the Clean Water Act has led to the redistribution of wetland-derived ecosystem services (such as fish production, flood mitigation, recreation opportunities, etc) away from the urban poor [7,8].

We develop a new analytical approach using “servicesheds” that builds on the widely adopted mitigation hierarchy [9-11] and expands it to include impacts on ecosystem services and the people who benefit from those services. While others have reviewed the needs for, and possible steps towards a way to include ecosystem services in certain kinds of impact assessments [12], none have provided a practical framework for implementing such an approach. Our framework can be applied to any permit assessment process for any sector (e.g., mining, oil and gas, transportation, timber) to inform whether a permit should be issued, how activities can be adjusted to avoid, or minimize impacts and where mitigation payments for offsets should be directed to most efficiently meet requirements and maintain social equity.

A serviceshed is defined as the area that provides a specific ecosystem service to a specific beneficiary (individual or group of people). This unit in space does not describe how much demand exists for a service (as do ‘service providing units’ and ‘ecosystem service providers’ [13]), but rather the location and identify of beneficiaries and the associated regions providing them with benefits. Servicesheds are characterized by three components; 1) ecosystem service supply, 2) institutions (formal or informal legal access), and 3) physical access. The configuration of servicesheds and the importance of these three factors vary by service and beneficiary. For some services, such as climate regulation through carbon sequestration, the

serviceshed is the entire planet because the atmosphere is well mixed and there are no laws or infrastructure that limit a person's ability to benefit from carbon sequestration. Other services are more locally produced and delivered. The serviceshed for crop pollination is the area around farm fields of interest within the flight range of native pollinators. For water-related services (e.g., drinking water supply, hydropower supply, water purification, flood mitigation, erosion control), the serviceshed is the catchment area that delivers water to a population or beneficiary of interest that has legal and physical access to the source.

We demonstrate the first use of servicesheds and multiple ecosystem service models (erosion control and nitrogen retention for drinking water quality) for mitigation assessments using two scenarios of proposed coal mining activities in northern Colombia (Fig. 1). The use of servicesheds in this context ensures that mitigation considered for offsetting impacts on ecosystem services *does not* unintentionally redistribute benefits around the landscape and create social inequity.

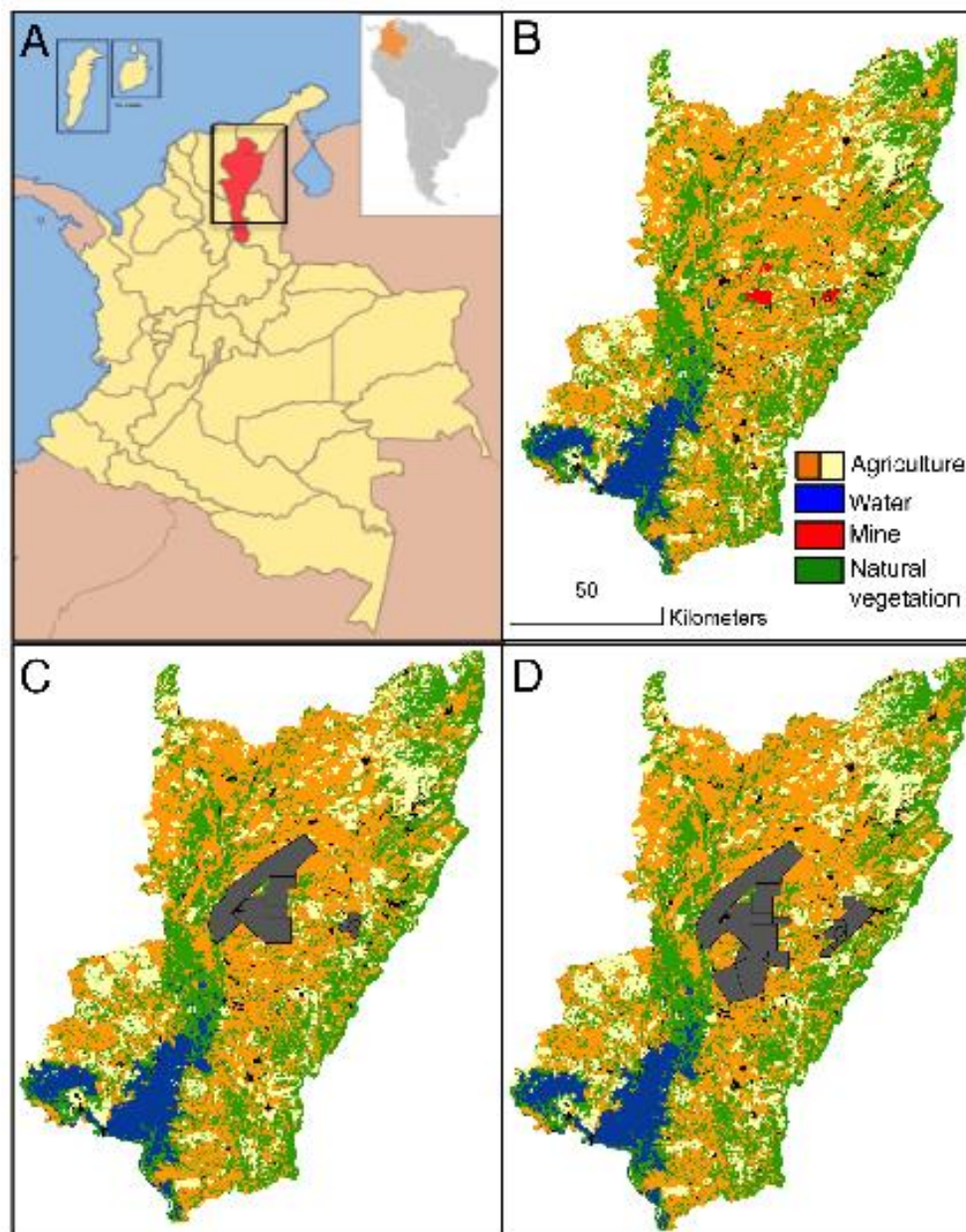


Figure 1. Cesar Department, Colombia, and proposed coal mine expansion. The Cesar Department is a state in the northern part of the country (A). The inset in (A) is the watershed of the Cesar River, the area used for the case study (B). The river flows from north to south with forested mountains on the eastern part of the watershed. The central valley is a major production region for crops and cattle, and the Cesar River flows into the Zapatos wetland (large water body at south of watershed) before joining the Magdalena River. Full development of all currently granted coal mining permits (moderate scenario, C) and full development of all permits that have been proposed (full exploitation scenario, D) are shown in grey.

Results and Discussion

If impacts on people are to be part of a mitigation assessment, the first questions to answer are how much impact will likely occur and which people will be impacted? We answered these questions by using annual average models of nutrient retention (total nitrogen) and sediment retention (InVEST models, [14-17]) to estimate the change in services expected under the two mining expansion scenarios relative to current conditions. Total nitrogen (TN) retention was reduced in all servicesheds under both the moderate (3 - 46% reduction serviceshed⁻¹) and full exploitation (1 - 46% reduction serviceshed⁻¹) scenarios (Fig. S1C, D). Erosion control was also reduced under both scenarios (moderate, 7 – 1020% reduction serviceshed⁻¹; full exploitation, 5 – 1038% reduction serviceshed⁻¹) (Fig. S1A, B). Overall, people living in the city of Potrerillo (Fig. 2) will receive the highest proportional loss of nitrogen retention and sediment retention for drinking water quality (Fig. S1) because the majority of their serviceshed falls within proposed mine areas in both scenarios (Fig. 1, 2).

Once the amount of impact is assessed, the first step in the mitigation hierarchy is to avoid as much of that impact as possible through the selection of permits. To inform avoidance considerations, we need to understand which mine permits are likely to cause the largest total impact. Our results of a ranking that combined ecosystem service impact estimates with population data show mines with higher or lower population level impacts (Fig. 3). Larger mines, and those on the eastern part of the region are estimated to have higher total impacts. The eastern region has steep mountains and some of the little remaining native vegetation in the area, so loss of this vegetation leads to larger marginal losses of ecosystem services (Fig. S1). In this

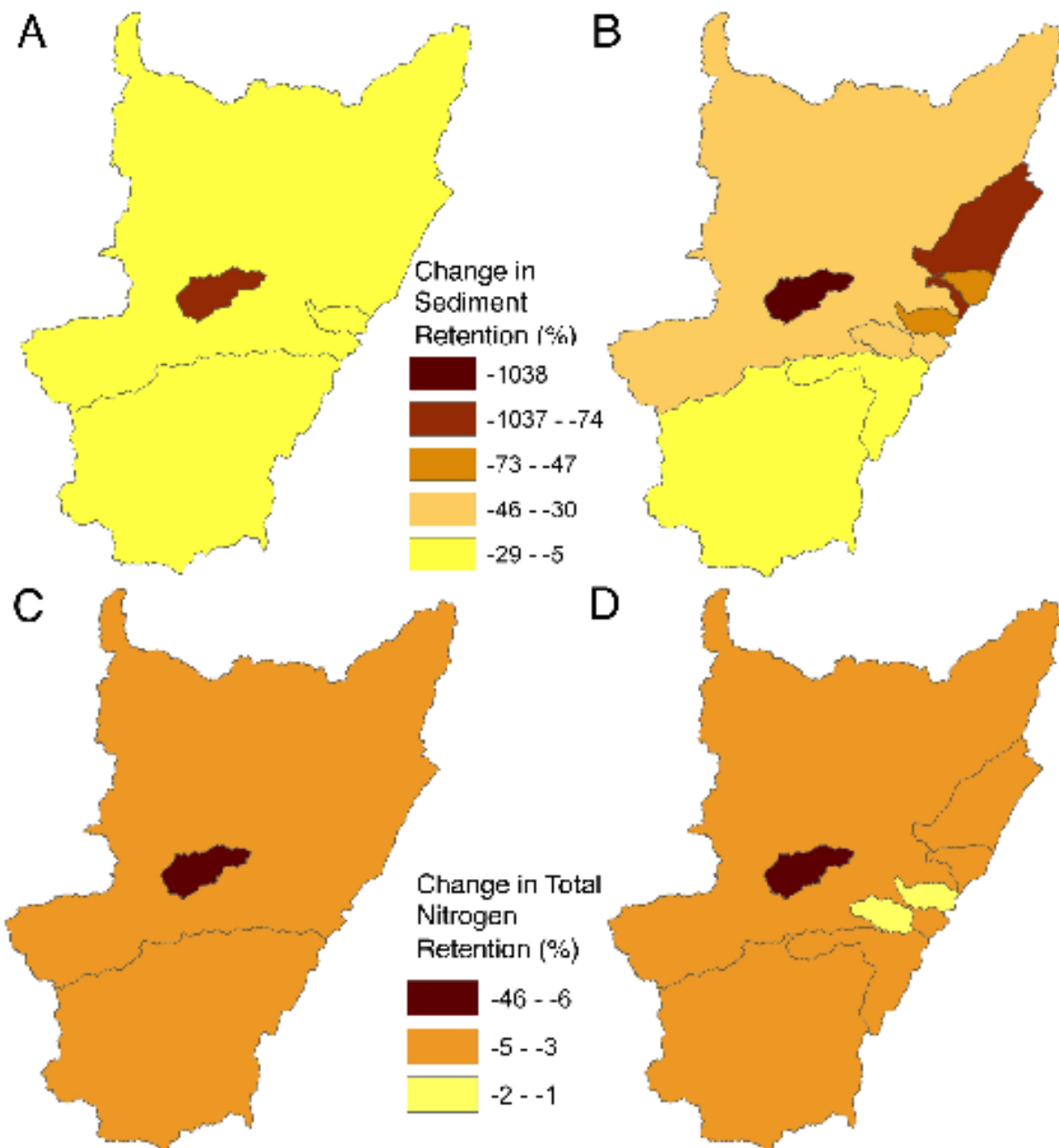


Figure S1. Relative ecosystem service losses by serviceshed. All servicesheds experience losses of sediment and total nitrogen retention in the moderate (A, C) and full exploitation (B, D) scenarios. Impacts to the central serviceshed for the city of Potrerillo would receive the largest proportional impact on both services in both scenarios because a large part of the serviceshed falls within proposed mine areas in both scenarios. Sediment retention losses were estimated to be much higher overall than nutrient retention losses.

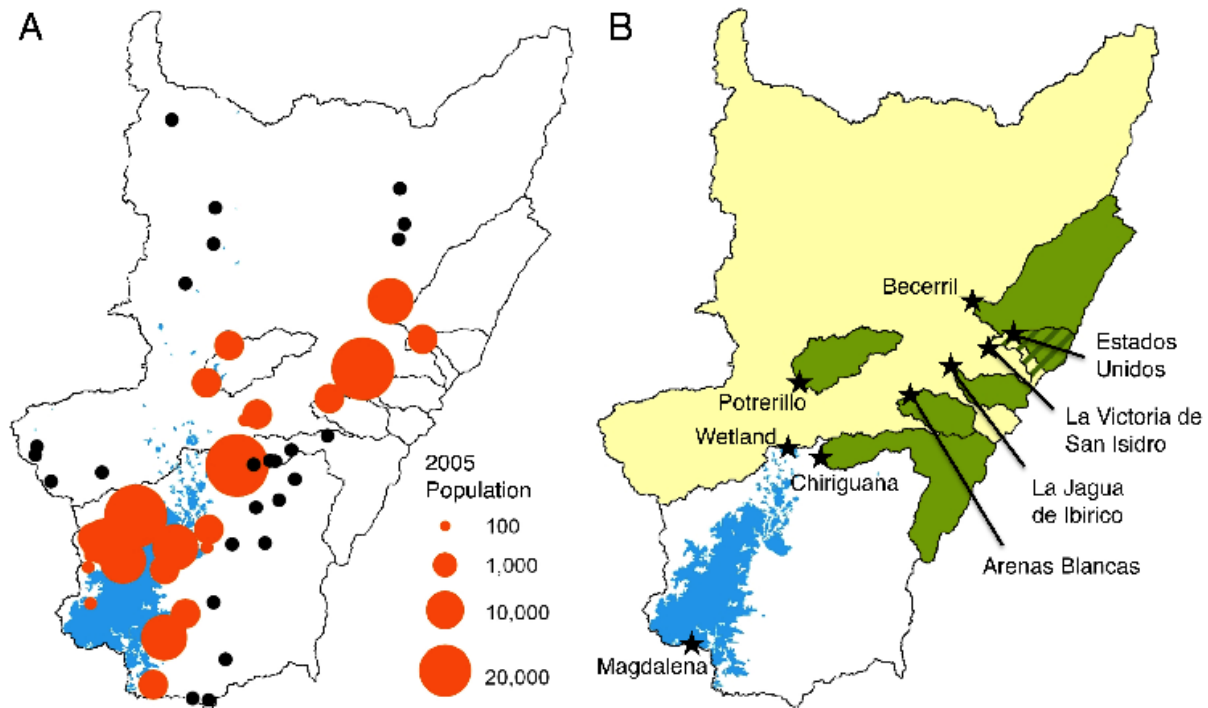


Figure 2. Cesar Department beneficiaries of nitrogen retention and erosion control for drinking water quality, and associated servicesheds. Beneficiaries were defined as cities (all dots in A). Those likely to be impacted by at least one proposed mining scenario are shown in orange (A) and servicesheds were defined as the watershed area upstream of each potentially impacted beneficiary. Only cities with potential for mitigation within their serviceshed were analyzed (B, stars). Most serviceshed areas are shown in green. All cities bordering the wetland are considered as one beneficiary (B, yellow serviceshed), and all cities downstream of the Cesar river watershed on the Magdalena River are represented by the point named Magdalena (B), with the entire Cesar River watershed as their serviceshed.

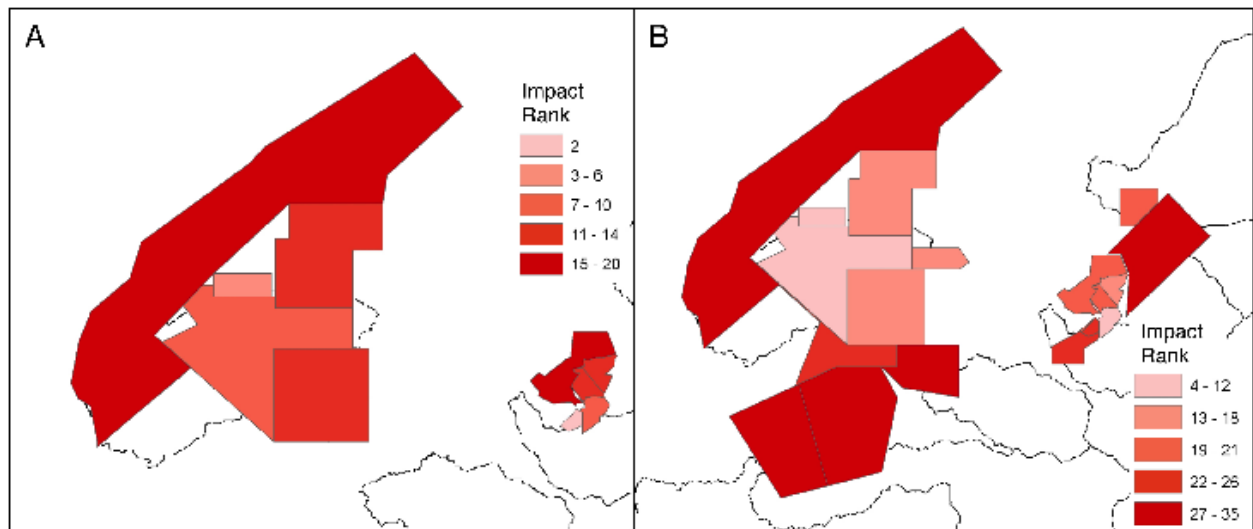


Figure 3. Impact ranks per mine permit. Ranked impacts of proposed mining areas on nutrient retention and erosion control scaled to downstream beneficiary population size for the moderate (A) and full exploitation (B) scenarios. Mine permits with the largest estimated population-level impacts on both nitrogen retention and erosion received the highest ranks.

ranking exercise, we considered the two services to be equally important based on local stakeholder information, but unequal weights could be applied among services in other contexts.

The next two steps of the mitigation hierarchy are to minimize and reduce impacts through best management practices over the lifetime of the development project. Addressing these steps was beyond the scope of this work and we turn to the final step in the hierarchy, mitigation. For impacts that cannot be avoided, minimized or reduced, mitigation activities are often required to offset- or replace- impacts. Habitat protection (Fig. S2) and restoration (Fig. S3) focused in priority conservation areas outside the proposed mining areas but within each serviceshed could offset both nitrogen pollution and erosion impacts in 3 out of 4 servicesheds impacted under the

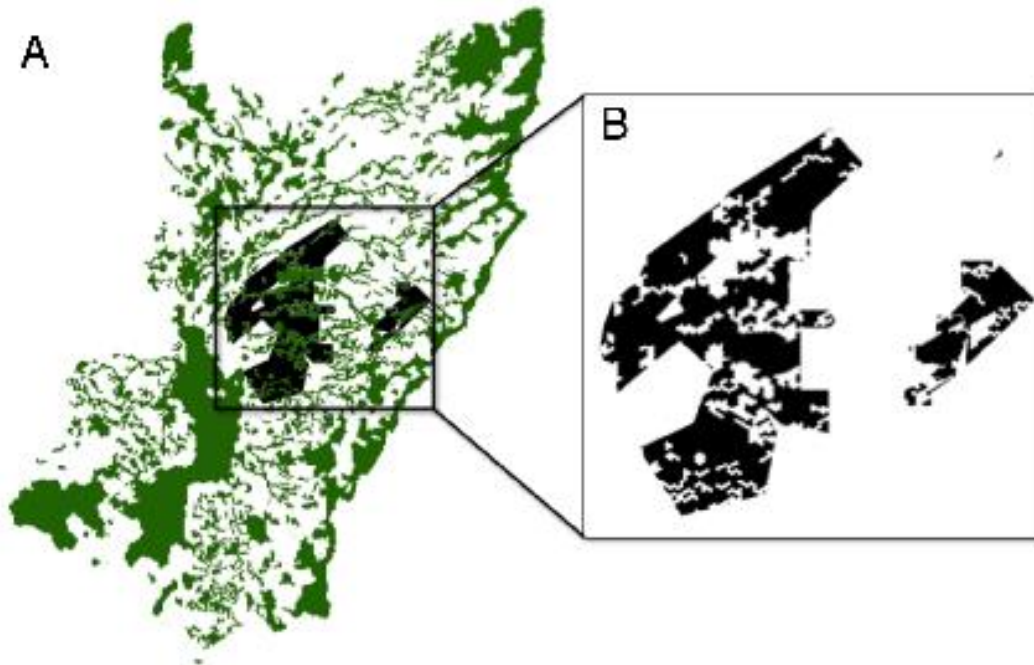


Figure S2. Mine portfolio adjustment for required avoidance of biodiversity priority areas.

The Nature Conservancy and the Humboldt Institute have identified priority biodiversity protection areas for the Cesar Department (A). Development activities must avoid these areas by law when possible, so they were removed from the proposed mine permit areas before ecosystem service impacts were assessed (B). This figure represents the altered full exploitation scenario, but the same process was followed for the moderate scenario.

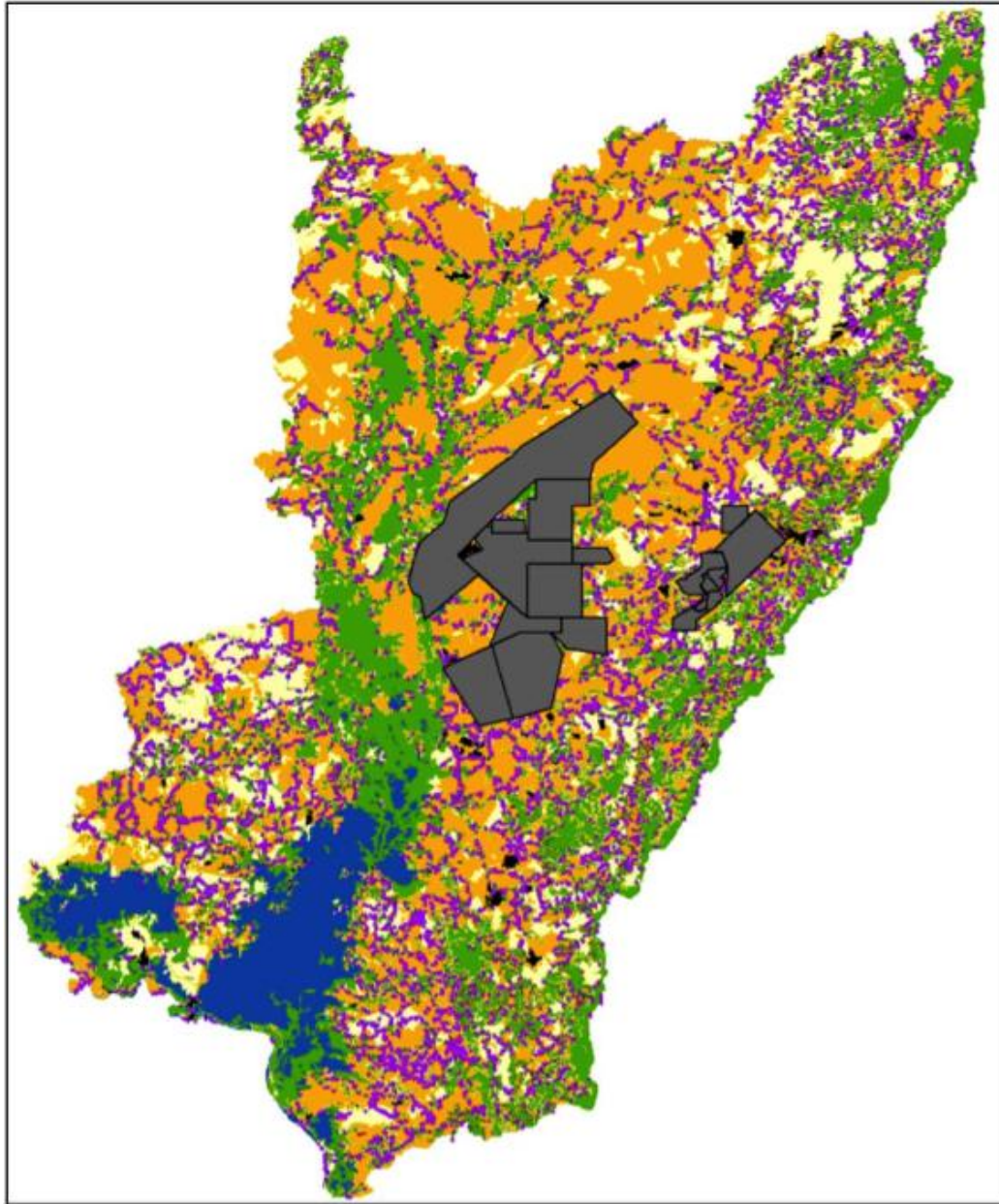


Figure S3. Restoration priority areas. Areas in purple have been identified as priority corridor areas to target for restoration. All other coloring is as in Figure 1. Potential ecosystem service benefits from restoration were assessed assuming all priority corridor areas outside of proposed mine permit areas (dark grey) could be converted to native vegetation. Those areas are shown here for the full exploitation scenario, and the same approach was used for the moderate scenario.

moderate mining scenario (Fig. 4A, C; Fig. S4), representing full mitigation (with a 1:1 mitigation ratio) for 98% of the impacted population.

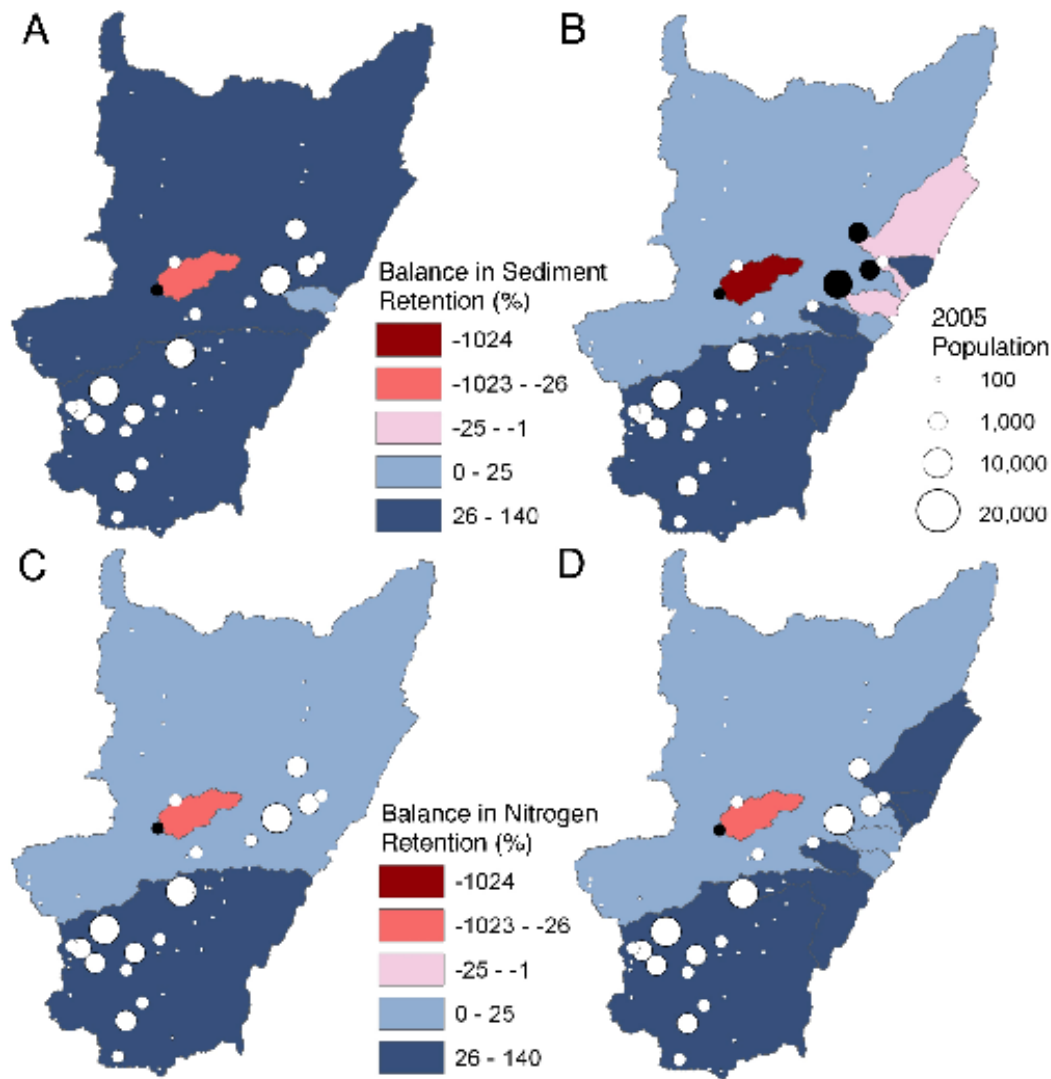


Figure 4. Mitigation balance after protection and restoration of native habitat. Protection and restoration in The Nature Conservancy’s priority areas provides enough recovery of sediment retention and nitrogen retention for drinking water quality to offset impacts (neutral or positive balance) for all but one relatively small city in the moderate mining scenario (A, C). The same is true for the nitrogen retention balance under the full exploitation scenario (D), but more beneficiaries in the eastern mountains will lose sediment retention benefits for drinking water quality even after mitigation (B). Cities impacted after mitigation are shown by black symbols. Fully mitigated cities are shown by white symbols.

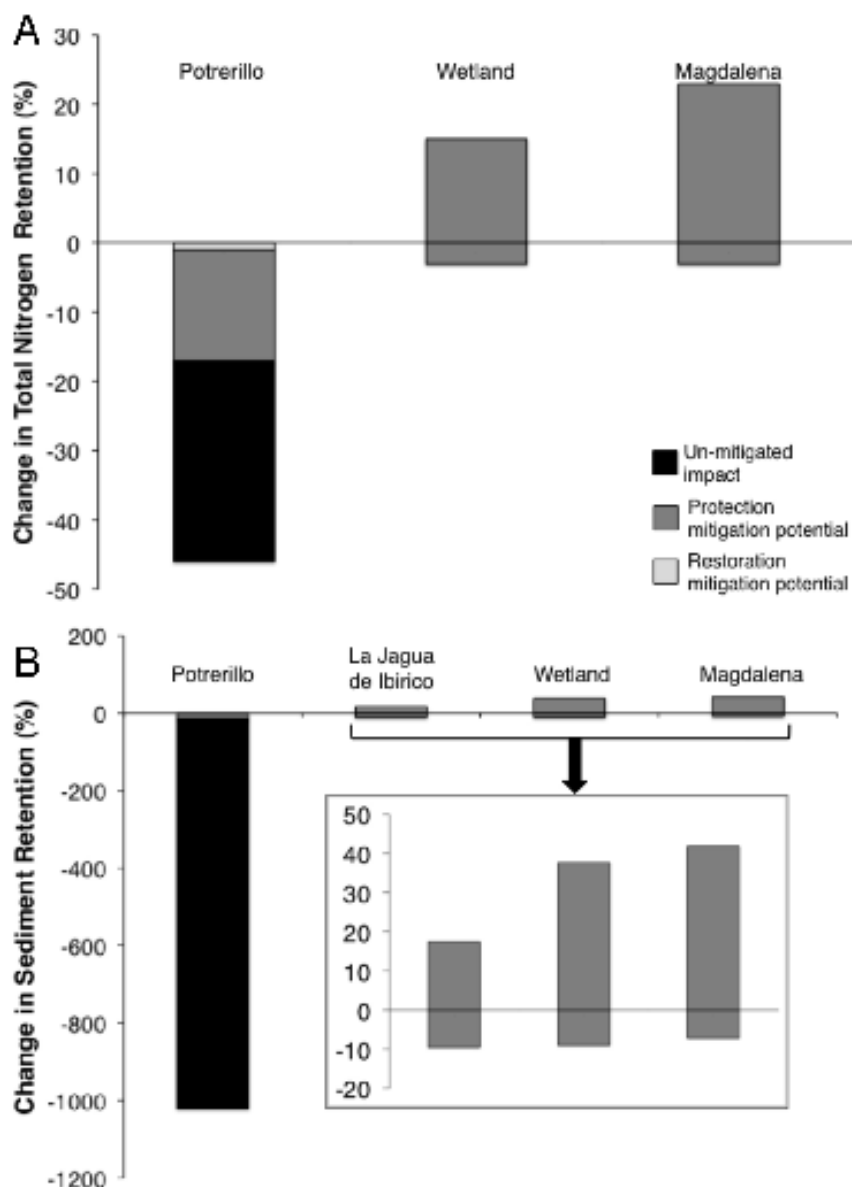


Figure S4. Contribution of protection and restoration to offsetting moderate mine development impacts. Total nitrogen retention (A) and sediment retention (B) losses cannot be offset to the city of Potrerillo in the moderate scenario. Restoration (light grey) contributes much less to mitigation than protection (dark grey) does for Potrerillo. Restoration was not considered for the other cities as their impacts can be fully mitigated by protection alone. For those cities with a positive mitigation balance, the dark grey bars in the negative space show the original impact that can be fully offset by protection. The dark grey bars extending into the positive space show the additional mitigation, or surplus mitigation, that is possible through full protection of the conservation portfolio analyzed.

In the full exploitation scenario, the same actions could offset nitrogen pollution for 8 out of 9 impacted servicesheds (Fig. 4D; Fig. S5A), representing 99% of the population, but erosion impacts could be offset for only 5 out of 9 impacted servicesheds (Fig. 4B; Fig. S5B), representing only 24% of the impacted population. In this case, the landscape holds much greater potential for offsetting nitrogen pollution impacts than erosion impacts, and under the full exploitation scenario there is no possibility of full mitigation for the impacted population.

The scenarios we analyzed were a small subset of the full suite of serviceshed analyses the Colombian Ministry of Environment could consider for permit granting. For example, explorations of lower impact scenarios could include options for splitting permit blocks to avoid high impact areas, greater investment in on-site treatments that lessen the need for landscape-based mitigation, and avoidance of a subset of proposed permits. The change analyses conducted could be used to inform the consideration of each of these options, providing flexibility and transparency in the decision making process.

The application of simple ecosystem services models to servicesheds illustrated here is relevant throughout the world. Development touches a huge swath of the earth's surface and will only continue to grow in scope as the human population expands and consumption increases [3-5]. Undesirable indirect social and environmental outcomes of this development can be reduced by many policies that are already in place [18]. Meeting the intent of existing legislation that has the maintenance of human well-being at its core will require moving beyond current approaches that track habitat acres, biodiversity scores or similar metrics to one that explicitly includes people. The serviceshed approach provides a step in that direction.

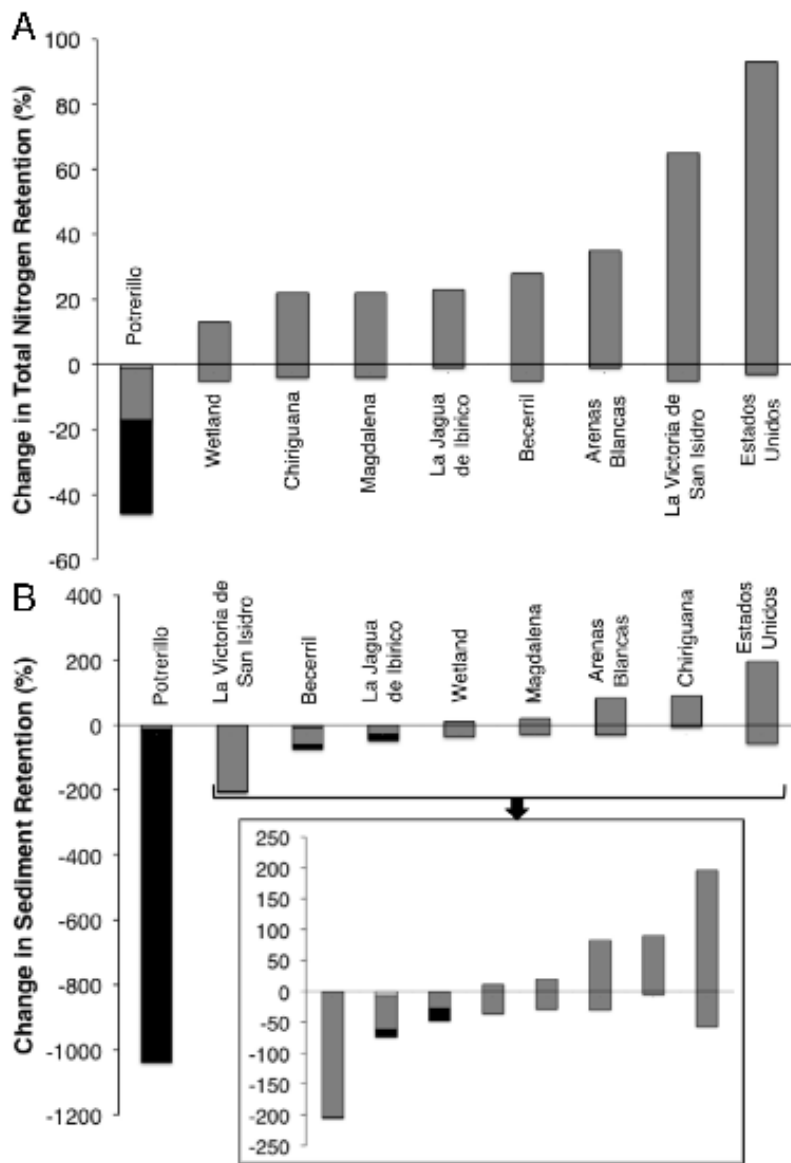


Figure S5. Contribution of protection and restoration to offsetting estimated full exploitation scenario mine development impacts. Total nitrogen retention (A) cannot be offset to the city of Potrerillo in the full exploitation scenario. Four cities have un-mitigatable sediment retention losses (B) even after protection (dark grey) and restoration (light grey) offsets. Color coding is as in Figure S4.

Materials and Methods

Site Description

Our study area was the Cesar Department in the northern part of Colombia (Fig. 1). The Cesar Department boundary closely follows the watershed of the Cesar River, which flows from northeast to southwest and drains into the Zapatosá wetland, before joining the Magdalena River, one of the principal large river basins in the country. Remaining native habitats include the mountainous northern Sierra Nevada de Santa Marta Ecoregion with altitudes from 200 to 5,775 meters above level, rich in tropical Andean species and the source of eight rivers that irrigate the Cesar Valley and drain into the Zapatosá wetland. In the west the Perijá Range extends to the border with Venezuela and is primarily covered by forest of very high biodiversity value. The central and southern areas of the department are occupied by the Cesar Valley Ecoregion with fertile soils where important productive activities take place including cattle ranching, agriculture and mining. The Zapatosá wetlands are a source of food security (protein from fish) and flood control. The Magdalena River Ecoregion connects the central valley and the wetlands and has highly productive soils that support the most important agricultural activities in the Department.

Mining Scenarios

We analyzed the impacts of two possible mine expansion scenarios developed by the Colombian Ministry of Environment and The Nature Conservancy [19]. These scenarios represent realistic options for mine expansion in the near future. The moderate mine expansion scenario represented full development of currently permitted mines with no new mines (Fig. 1C), whereas the full exploitation scenario represented full development of all currently permitted and proposed future mines (Fig. 1D).

Ecosystem Service Selection

The removal of vegetation and topsoil in the creation of open pit mines likely leads to the loss of carbon sequestration [20], erosion control [21] (that impacts drinking water quality and the lifetime of downstream infrastructure), surface water flow (for drinking, irrigation, recreation, etc.), flood regulation, and groundwater recharge (for drinking), among others. The provision of clean drinking water is of primary interest in the Cesar region. Most population centers in the watershed get their drinking water from groundwater wells. However, observed and further expected drawdown of groundwater from mine-related pumping will make groundwater use impractical and shift reliance to surface water. While many countries regulate direct pollution from mines, they do not account for the lost water quality regulation provided by vegetation and soils that are removed in the mining process. Given the importance of drinking water in the region, the complexity of groundwater-surface water interactions, the lack of available information on aquifer boundaries, and the likelihood that local water sources will switch from groundwater to surface water in the near future, we focused on two components of surface water quality; total nitrogen retention and sediment retention (or erosion control).

Delineating Servicesheds

Towns and cities were identified as the major beneficiaries of interest in the region. As we focused on two water-related ecosystem services, we used watershed boundaries to define servicesheds (Fig. 2B). We considered towns at risk of impact if they fell directly within the boundaries of a proposed mine, or if a proposed mine fell upstream of the town in the same watershed. There are 24 towns or cities that could be impacted (49% of cities in the region) (Fig.

2A), with a total population of 69,308. These are the populations that will lose water quality regulation benefits unless ecosystem service mitigation is implemented. There are two servicesheds that reflected benefits to more than one population center. We used the inlet of the Zapatos wetland to represent the towns surrounding it, including Antequera, Belen, Candelaria, Chimichagua, El Trebol, Hojanca, La Mata, Saloa, San Jose, Sempegua, Soledad and Zapatos. Here, the assumption is that the wetland is relatively well mixed and that the impacts of higher nitrogen and sediment loads entering the wetland as a result of mining will be felt equally by all cities and towns bordering the wetland. Similarly, we considered the outflow of the wetland as indicative of impacts to all cities downstream on the Magdalena River.

Assessing Impact to Beneficiaries

Colombian law currently requires the avoidance of impacts on biodiversity, with subsequent mitigation of any allowed impacts, following the mitigation hierarchy. Given this legal requirement, priority biodiversity areas are avoided when possible inside proposed permit areas. To reflect this reality, we excluded the priority biodiversity areas, identified by the Humboldt Institute and The Nature Conservancy [22] through a biodiversity prioritization process (Fig. S2A), from the proposed coal mining permit areas (Fig. S2B). We then assessed the likely impact of converting the remaining proposed permit areas to open pit coal mines.

To estimate impacts, we used InVEST, a freely available software package that models ecosystem service change (<http://naturalcapitalproject.org/InVEST.html>; 14-17). We used the water purification model to assess impacts on total nitrogen regulation for drinking water quality and the avoided sedimentation model to assess impacts on sediment retention for drinking water

quality. These models were developed to use the simplest possible approach to modeling complex processes as a way to provide sound scientific estimates while requiring minimal data, time and resources to apply.

The water purification model is a routed model that estimates the annual average amount of nitrogen or phosphorus pollution and retention based on a simple annual average water balance, export coefficients and downslope retention of nutrients by vegetation. Export coefficients, developed by Reckhow and others [23], are annual averages of pollutant fluxes derived from various field studies that measure export from parcels. Since these coefficients are average fluxes, we include a hydrological sensitivity score that accounts for differences in condition across the analysis region. Total nitrogen exported to the stream (TN) from each pixel x was calculated as:

$$TN_x = EXP_x \cdot HSS_x \left(\prod_{j=x+1}^{SN} 1 - RN_j \right) \quad (1)$$

where EXP_x is the export coefficient at pixel x , RN_j is the proportional downstream nitrogen retention efficiency on pixel j , and the product follows the flow directions from the pixel immediately downstream of the originating pixel x (denoted “ $x+1$ ”) to the stream network (SN). HSS_x , the hydrologic sensitivity score of pixel x , estimates the variation in export coefficients of different pixels within the landscape, and is calculated as:

$$HSS_x = \frac{\ln \left(\sum_{i \in I(x)} Y_i \right)}{\frac{1}{n} \sum_{j \in W} \left(\ln \sum_{i \in I(j)} Y_i \right)} \quad (2)$$

The HSS_x term uses the annual average water yield (Y) output from the simple water balance model summed over the upstream catchment area $I(x)$ (including water yield on pixel x), normalized across the watershed W .

The annual average water yield on pixel x is calculated based on the Budyko curve as follows:

$$Y_x = P_x \left(1 - \frac{AET_j}{P_x} \right) \quad (3)$$

where AET_x is the annual actual evapotranspiration and P_x is the annual average precipitation.

The ratio of evapotranspiration to precipitation is calculated as:

$$\frac{AET_x}{P_x} = \frac{1 + \omega_x E_x}{1 + \omega_x E_x + \frac{1}{E_x}} \quad (4)$$

where E_x adjusts the potential evapotranspiration to precipitation ratio for vegetation type:

$$E_x = \frac{kc_x \cdot ETo_x}{P_x} \quad (5)$$

with ETo_x as potential reference evapotranspiration and kc_x as the vegetation coefficient

and where ω_x accounts for weather seasonality and soil characteristics as:

$$\omega_x = Z \frac{s_x AWC_x}{P_x} \quad (6)$$

where Z is a seasonality factor, s_x is the minimum effective soil depth, and AWC_x is the soil available water content. We used a value of 4 for Z , appropriate for representing the two annual rainy seasons in the region. Further descriptions of the bases and assumptions of these equations are available elsewhere [14, 16, 17].

In this analysis, we used data on digital elevation model [24], annual average precipitation [25], potential evapotranspiration (modified Hargreaves method [26] applied to 20 years of station data from Instituto de Hidrologia, Meteorologia y Estudios Ambientales), land use and land cover (current landscape created from multiple satellite images from 2000 to 2008 [27]; Moderate scenario as full exploitation of the extent of existing mine permits embedded in the current LULC map; Full exploitation scenario as full exploitation of all mine permits currently granted by the Ministry of Mines and Energy but awaiting environmental license embedded in the current LULC map), root depth (derived from a global literature review of observed root depths per dominant vegetation type or species), export coefficients (derived from global literature review of observed total nitrogen export rates), uptake efficiency (the relative ability of plants and soils to take up, absorb and cycle nitrogen, derived for each LULC class from global literature review of observed nitrogen retention experiments and mass balance studies) and soil characteristics (plant available water content and effective soil depth; 28-30). We applied the model for total nitrogen fluxes.

The avoided reservoir sedimentation model predicts annual average export via sheetwash erosion (SE) based on a fully-distributed variant of the widely used Universal Soil Loss Equation (USLE) as follows on each pixel x :

$$SE_x = (R_x \cdot K_x \cdot LS_x \cdot C_x \cdot P_x) \left(\prod_{j=x+1}^{SN} (1 - RS_j) \right) \quad (7)$$

where R_x is rainfall erosivity, K_x is soil erodibility, LS_x is the slope length factor, C_x is the vegetation factor, P_x is the management practice factor, RS_j is the proportional sediment retention efficiency of downstream pixel j . The equation is applied to all pixels downstream of pixel x until a stream channel is reached (SN). The first half of the equation represents the standard

USLE form and the second half represents routing downslope with land use land cover-based retention of sediment along the flowpath.

The land use land cover and digital elevation data sources used were the same as those noted above. In addition, we used data on rainfall erosivity [25], soil erodability (derived from 28-30), factors that represent the effects of vegetation type and management practices on soil erosion processes (crop factor and management factor per LULC category derived from global literature review), and retention efficiency (the relative ability of plants and soils to retain sediment eroded from upstream areas, derived from global literature review).

InVEST also has the capacity to give estimates of the retention of nutrient and sediment fluxes as well as the economic value of these and other ecosystems services (hydropower production, carbon sequestration, timber production, crop pollination, fisheries, aquaculture, recreation). However, we focused on biophysical estimates of ecosystem service change because economic data were not consistently available for the region.

To estimate ecosystem service impact, we used each model to calculate fluxes from the current landscape and each of the two proposed mining scenarios. We calculated likely mining impact in each serviceshed as the percent difference between nutrient (total nitrogen) export ($\text{kg TN pixel}^{-1} \text{ yr}^{-1}$) or sediment export ($\text{tons pixel}^{-1} \text{ yr}^{-1}$) in each scenario and the current landscape. We also summarized these changes within each serviceshed to estimate impact to each beneficiary.

There are many limitations to both the nutrient and sediment models. For example, the nutrient model does not account for in-stream processes and so may over-estimate the contribution of landscape nutrient inputs to downstream nutrient concentrations. The sediment model only represents sheetwash, leaving out the key processes associated with gully and bank erosion, and neglecting in-stream depositional and erosive processes. Given the many limitations of these models and our inability to calibrate the models to the region given limited observed data on key fluxes, their outputs can best be interpreted as showing relative patterns across a landscape. As such, we do not discuss the absolute outputs of the models in any way and only reflect on relative changes and equivalencies.

Ranking Mine Permits

We ranked mine permit blocks by their total population level impact for each service. To calculate population level impact, we first summarized the change in each service within each individual proposed mine permit. We then multiplied the total impact per service by the number of people in the largest downstream population. Some mine blocks intersect more than one serviceshed, and in these cases, we used the largest downstream beneficiary, providing a conservative underestimate since some portion of the impacts will flow to additional beneficiaries that are not accounted for in this estimation. We then ranked each proposed permit based on the population level impact, and then added the rankings for the two services. This approach weights the two services equally, which we deemed appropriate in this region based on stakeholder input. Alternative weightings could be applied to services to represent stakeholder preferences as desired. In the absence of economic data, the use of population data in the ranking approach allowed us to represent the reality that a large environmental impact on a small town

could translate into less ecosystem service loss for society than a small environmental impact to a large town.

Mitigation Potential

Colombia does not have an additionality policy and habitat conversion is still progressing at relatively high rates. Given these conditions, protection is the preferred activity for mitigation offsets. We asked how much ecosystem service mitigation is possible from protection of existing native habitat by using the same InVEST models to estimate how much nitrogen retention and erosion control could be provided by protecting the biodiversity conservation portfolio created by TNC and the Humboldt Institute [23] (Fig. S2A). We estimated the benefit of protection as the inverse of the loss of services expected with the loss of native habitat. In this region, native habitat is predominantly converted to pasture. To represent this likely change without protection, we created new scenarios for each mine expansion option that converted all native habitat within the biodiversity conservation portfolio areas to pasture. We then used the InVEST models to estimate total nitrogen and sediment export under each new scenario. We estimated the marginal benefit of protecting native habitat as the difference in export between the converted and unconverted habitat scenarios. These marginal changes represent the mitigation potential from protection. We summarized these changes within each serviceshed and compared the percent improvement to the summarized percent impacts from mine expansion to identify which towns have the potential to receive offset impacts through protection.

It is also possible to achieve mitigation through restoration activities, so we asked how much recovery of ecosystem services is possible through those activities. We created restoration

scenarios by converting all areas within TNC corridor priority areas (Fig. S3) to the most proximal native habitat type. We did this in each mine scenario to represent the restoration potential outside mine permit areas in each case. These are very optimistic restoration scenarios as they assume the ability to cause restoration in all corridor priority areas and the ability to achieve full recovery to native habitat. Restoration for compensation (offsetting) currently supported by the government generally consists of planting native and non-native fruit trees, a much less ambitious restoration approach than the one we modeled.

We again used the InVEST models to estimate total nitrogen and sediment export in these two new scenarios. Marginal benefits were calculated as the difference between export of TN or sediment in the mine scenarios and the restored habitat scenarios. We again summarized these changes within each serviceshed and compared the percent restoration mitigation potential to residual percent mine impacts (after accounting for mitigation potential through protection). The net balances between impacts and mitigation through both protection and restoration in each serviceshed were mapped.

In our calculations of whether or not mitigation through protection and restoration could fully offset the impacts incurred in each mining scenario, we assumed a requirement of a 1:1 mitigation ratio. Higher mitigation ratios are commonly used in biodiversity mitigation to account for time lags and risks associated with mitigation activities. No framework has been developed for establishing ecosystem service mitigation ratios so we assumed a ratio of 1:1, which means that each lost ton of sediment retention must be replaced by one ton of sediment retention and each lost kg of total nitrogen retention must be replaced by one kg of retention. The

use of this ratio established the minimum possible mitigation requirement and it is likely that higher ratios should be applied in practice.

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Table 1. Examples of legislation establishing mitigation requirements with at least partial intent to provide benefits to people. Text included is paraphrased from official language of legislation. Countries included are a subset of all nations with such legislation. None of the countries with this kind of legislation include people in the calculation or placement of mitigation offsets.

Country/ Region	Legislation	Language Regarding Human Wellbeing	Offsets Account for People
Argentina	Environmental Framework Law (no. 25,675)	- provide quality of life for present and future generations, as a priority - promote the rational and sustainable use of natural resources - enable ecological sustainability, economic and social development	No
Australia	National Strategy for Ecologically Sustainable Development	-enable development that improves the total quality of life, both now and in the future, in a way that maintains the ecological processes on which life depends. - enhance individual and community well-being and welfare by following a path of economic development that safeguards the welfare of future generations	No
Brazil	National Biodiversity Policy (Decree 4339)	- everyone in present and future generations is entitled to an ecologically balanced environment and the common human use essential to a healthy quality of life	No
Canada	Policy for the Management of Fish Habitat	-maintain or increase the natural productive capacity of habitats for the nation's fisheries resources, to produce fish suitable for human consumption and to benefit present and future generations	No
China	Forestry Law of the People's Republic of China	- protecting, cultivating and rationally exploiting forest resources, and making use of forests in water storage and soil conservation, climate regulation, environmental improvement and supply of forest products to sustain people's livelihoods	No
Colombia	Decree 2820	-avoid serious deterioration of renewable natural resources or the environment -provide compensation to communities, regions, towns and the natural environment for negative impacts generated by projects	No

Table 1 (cont'd).

European Union	Directive on Environmental Liability (2004/35/CE)	-address concern over contaminated sites posing significant health risks, and the loss of biodiversity - avoid land damage that creates a significant risk of adverse human health effects	No
Mexico	General Law of Ecological Balance and Environmental Protection	- promote sustainable development -establish the basis for guaranteeing the right of everyone to live in an environment adequate for their development, health and wellbeing	No
South Africa	National Environmental Management Act (Act No. 107)	-everyone has the right to have the environment protected, for the benefit of present and future generations - environmental management must place people and their needs at the forefront of its concern, and serve their physical, psychological, developmental, cultural and social interests equitably	No
United States	Clean Water Act	-maintain water quality which provides for the protection and propagation of fish, shellfish, and wildlife and provides for recreation in and on the water -management programs shall conserve such waters for the protection and propagation of fish and aquatic life and wildlife, recreational purposes, and the withdrawal of such waters for public water supply, agricultural, industrial and other purposes	No