

# Who loses? Tracking ecosystem service redistribution from road development and mitigation in the Peruvian Amazon

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Development projects must increasingly include mitigation actions to offset their negative environmental and social impacts. However, current mitigation approaches can exacerbate social inequality by ignoring how the spatial location of offsets affects the benefits local people receive from ecosystem services (ES). Here, we present a method for tracking changes in ES benefits resulting from development and mitigation actions. To demonstrate this approach, we use as an example a proposed road through the Peruvian Amazon. We assessed the road's ES impacts and prioritized offsets in a socially equitable way. We found that the road is likely to have a disproportionate negative effect on drinking-water quality for nearby indigenous communities, and that offsets cannot fully compensate for these impacts. Equity was improved by including ES in spatial prioritization of mitigation. Including ES information in a "serviceshed"-based approach reduced average remaining, unmitigated impacts to drinking-water quality more than fourfold for sediment, 16-fold for nitrogen, and 38-fold for phosphorus loads, as compared with the impacts seen when offsets were sited based on methods relying on ecological processes alone.

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The environmental costs of development have been well documented, and, as a result, governments and financial institutions often require assessment and mitigation of these environmental impacts (Madsen *et al.* 2011). In cases where negative environmental impacts cannot be avoided or reduced by means of changes in development design or location, activities to offset the impacts may be mandated. The most recent survey of such compensatory mitigation programs listed 45 currently in operation worldwide, with a further 27 in development (Madsen *et al.* 2011). The standard approach is to design offsets based on area, habitat quality, or ecological processes affected (Quétier and Lavorel 2011; Robertson *et al.* 2014), with particular attention paid to biodiversity and ecosystem functions.

However, because siting of offset areas does not consider the locations of affected people, these mitigation programs can benefit the environment but exacerbate inequities in environmental quality experienced by marginalized human communities. Studies of wetland mitigation programs in the US have found that such programs routinely relocate wetlands – and their associated benefits – away from urban areas with high population densities toward rural areas with low population densities, often resulting in a loss of the ES provided by wetlands for poor and minority communities (King and Herbert 1997; Ruhl and Salzman 2006; BenDor *et al.* 2007). The environmental justice implications of development and miti-

gation have rarely been examined in developing countries (Reed and George 2011), but the limited number of studies that do exist suggest that disproportionate impacts to already disadvantaged communities are commonplace (O'Rourke and Connolly 2003; MA 2005).

To address this shortcoming, we present an analytical framework and assessment process that tracks how people are affected by environmental degradation. We combine an ecosystem services (ES) modeling framework with data on where people live and how they rely on benefits from the environment and use the information to design a more equitable mitigation strategy than would be created by simply focusing on habitat type or ecosystem processes. We illustrate this approach using the example of a proposed road in the Peruvian Amazon connecting Pucallpa, Peru, to Cruzeiro do Sul, Brazil.

This study is, to our knowledge, the first to use ES to design a mitigation strategy that accounts for impacts to humans. Many assessments have mapped ES (eg Naidoo *et al.* 2008) and have demonstrated how development may affect ES (Nelson *et al.* 2009), but ES mapping and quantification approaches have yet to be combined into one synthetic assessment that tracks the distributional effects of development and intentionally promotes equitable mitigation of the resulting impacts through ES offsets. We use this approach to address two questions regarding offsetting ES losses as a result of road development: (1) do current methods for choosing mitigation sites based on ecosystem processes lead to equitable ES offsets?, and (2) does intentional prioritization of ES in offset selection resolve the inequality problem, successfully offsetting impacts to the communities affected by

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**Figure 1.** Roads affect the surrounding environment and the provision of ecosystem services not only through the direct effects of their construction and operation, but also by improving access to the adjacent landscape. This access often spurs conversion of natural vegetation around roads (eg for logging, mining, and agriculture), such as seen here in the Brazilian Amazon.

the road development? In asking these questions, we focused on four ES: three associated with the water quality of surface drinking-water supplies (sediment retention, nitrogen [N] regulation, and phosphorus [P] regulation) and one associated with climate regulation (carbon [C] storage); groundwater supplies were not considered in this assessment. We chose these four particular services because they are likely to be unaccounted for in classic impact assessment, are of importance to local stakeholders, and are likely to be affected by the proposed road.

Roads represent one of the most pervasive forms of infrastructure project in the developing world (Figure 1; Dobbs *et al.* 2013). Between 2000 and 2010, the global paved road network increased by 12 million lane-kilometers, with three-quarters of the growth occurring in non-OECD (Organisation for Economic Co-operation and Development) countries. Global road infrastructure is projected to increase a further 60% by 2050 (Dulac 2013). Although roads may provide substantial economic and development benefits to human societies, their negative impacts on the environment and local communities have been well documented (eg Tsunokawa and Hoban 1997).

As with many development projects, road construction in developing nations risks disproportionately affecting indigenous groups, which traditionally lack political power and access to decision-making processes. Allocating mitigation activities to address ES losses as a result of road building is critical for effective and equitable development.

We used the “serviceshed” – that is, the area that provides a particular ES to a particular beneficiary (individual or group of people; Tallis *et al.* 2012) – concept to determine the likely location and degree of mitigation

needed to offset ES losses to those people who would be negatively affected by the Peruvian portion of the proposed Pucallpa–Cruzeiro do Sul road. We integrated serviceshed-based analysis of ES impacts from development with information on the biophysical suitability and practical feasibility of potential mitigation sites. This approach creates a mitigation strategy designed to offset ES losses for local residents whose services will be affected by road construction, and transparently assesses the equity of environmental costs and benefits resulting from development and mitigation.

## Methods

### Services and servicesheds

We assessed four ES – sediment retention, N regulation, and P regulation (for surface drinking-water quality) as well as C storage (for climate regulation) – with the software tool InVEST 2.4.4 (Tallis *et al.* 2011; see WebPanel 1 for details). InVEST includes spatially explicit, ecological production-function-based ES models and has been used previously to estimate ES changes under future scenarios (Geneletti 2013; Bhagabati *et al.* 2014).

Ecological processes become ES when they provide benefits to people. Servicesheds are defined by delineating where services are produced relative to the people who receive the flow of these benefits. For the three water-quality-related services, each population center’s serviceshed is the upstream catchment area that delivers water to the river or stream nearest the settlement. For C storage, each population center’s serviceshed is the entire globe because the atmosphere is well mixed, so that settlements are affected by changes in C sequestration anywhere in the world and, conversely, the population of the entire planet is affected by changes in C storage as a consequence of road development. Using InVEST, we summed the changes in each ES across scenarios of development and mitigation within servicesheds in order to link changes in land use to changes in benefits to people.

### Study site

The proposed road would connect Pucallpa, Peru, with Cruzeiro do Sul, Brazil. Given that the watershed-based servicesheds for water-quality services are the smallest serviceshed unit in this study, we identified populations likely to be affected by road impacts as those who had some part of their upstream catchment falling within 5 km of the Peruvian portion of the proposed road (Figure 2a). In this way, we identified 107 population centers,

home to nearly 250 000 people, including more than 15 000 members of indigenous Amazonian communities. Indigenous households – especially those in remote communities – have lower income levels, fewer assets, and higher rates of poverty than non-indigenous households in the region (Porro *et al.* 2015). Catchments in the study area were dominated by upland Amazonian moist forests, transitioning to Andean moist forests in the west, and also including Amazonian white-water floodplain forests in the lowlands (Josse *et al.* 2007).

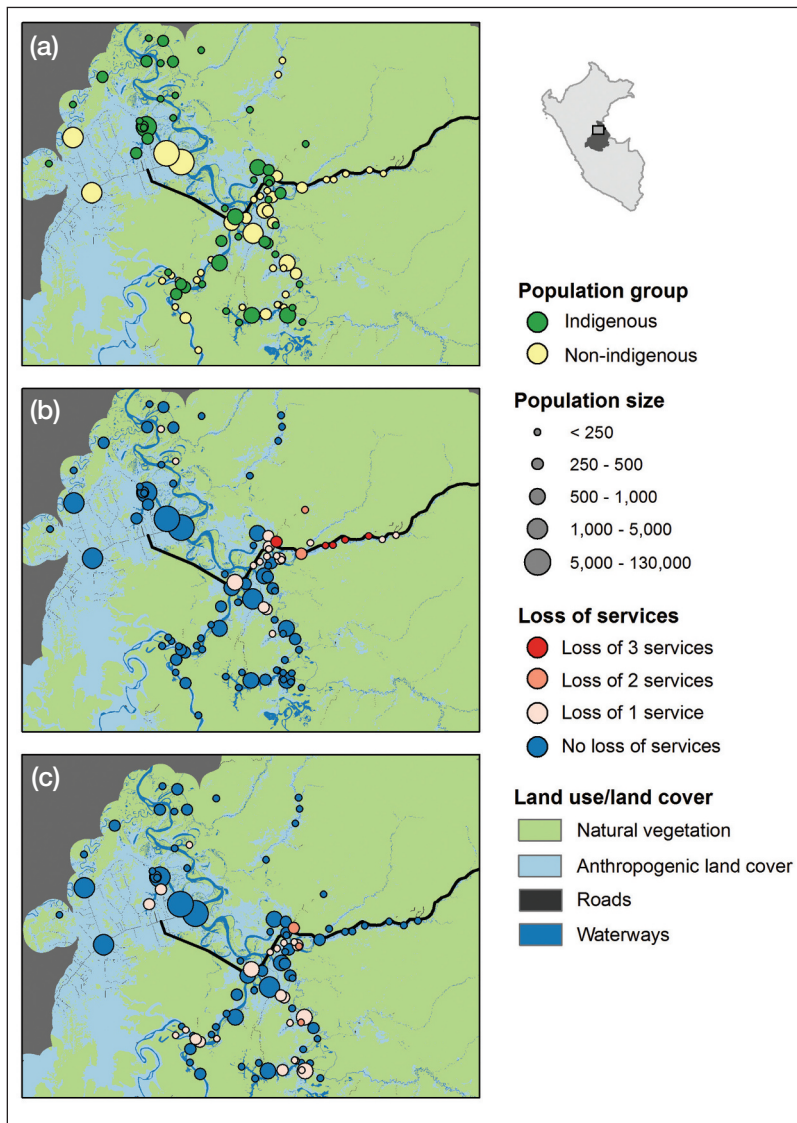
### Quantifying impacts

The effects of road construction on ES generally include both the direct impacts of the road itself and the indirect impacts of increased deforestation in the surrounding landscape resulting from improved access to those areas. We used the most likely of the currently proposed routes for the Pucallpa–Cruzeiro do Sul road and calculated the total combined effects of the road and road-associated deforestation on ES (“total impacts”). See WebPanel 1 for further details.

### Selecting offsets for mitigation

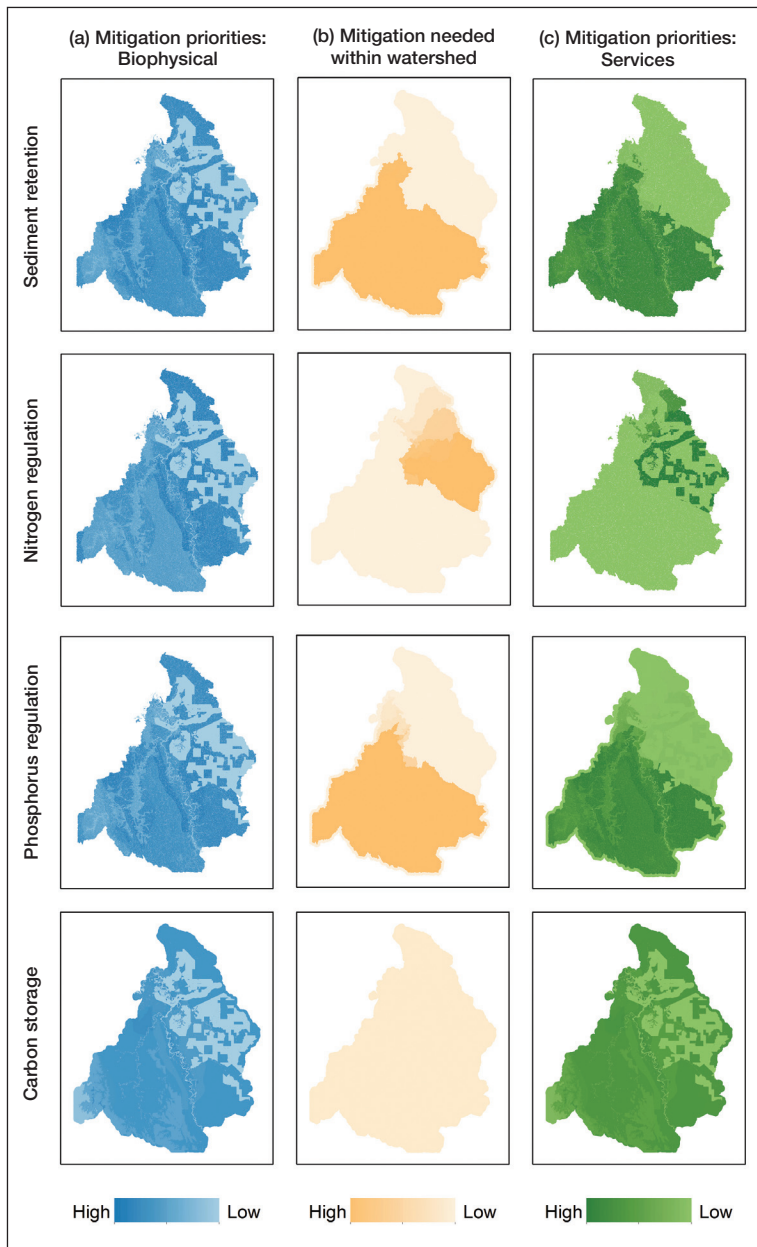
For mitigation to be successful, it must be technically, economically, and politically feasible. We included two forms of mitigation activities: protection of natural vegetation (avoided deforestation) and restoration of natural vegetation (WebFigure 1). We considered protection to be plausible in natural areas outside of designated protected areas but not in areas containing forestry and mining concessions already slated for extractive management. We considered restoration possible in human-modified areas (primarily pasture) excluding urban areas, roads, existing mines, and land within 5 km of the proposed road, where the high value of agriculture is likely to make the opportunity cost of mitigation too high (LA Gonzalez, pers comm).

We compared two approaches for selecting offset areas. In the first approach, we selected sites using ranking models (Vogl *et al.* 2013) that prioritize the most effective locations for protection and restoration based on biophysical and ecological characteristics (such as slope, distance from rivers, and vegetation type) of the site under current and potential future conditions (eg restored vegetation or averted deforestation). This approach to selection considered *only* ecosystem functions, or the *potential* provision of ES, and is similar to existing mitigation



**Figure 2.** Maps of the study area depicting (a) the location of indigenous and non-indigenous communities as well as ecosystem service (ES) losses to these communities with (b) biophysical mitigation priorities and (c) ES-based mitigation priorities. The proposed Pucallpa–Cruzeiro do Sul road is represented by the thick black line running east–west.

approaches that focus on measures of ecosystem or habitat quality (Maron *et al.* 2012). In the second approach, we incorporated servicesheds and beneficiaries into the ranking models to account for the different capacity for sites to return ES to those people affected by the road development. Under this approach, we selected sites based on not only their ecosystem functions but also the number of downstream beneficiaries and the amount of downstream mitigation required. This latter approach prioritizes sites that are important for providing ES back to the same people who are projected to lose them due to road development and associated deforestation. In both cases, we selected the same area – 15% of the total – for mitigation. Additional mitigation beyond this amount did not substantially increase ES provision in the second approach. See WebPanel 1 for more details.



**Figure 3.** Maps of the study area showing (a) the mitigation value of offset sites (biophysically based); (b) the demand for mitigation based on ES impacts (biophysical amount of service required downstream multiplied by the number of people); and (c) the mitigation value of offset sites (service based). Locations that are not feasible for mitigation in (a) and (c) received the lowest ranking. The areas with high biophysical potential to supply mitigation benefits (a) differ from the areas that can provide ES benefits for people affected by development (b). When service flows to people are considered, the location of high priority offset sites changes substantially (c). See WebFigure 2 for details of the biophysical value of protection versus restoration activities across the landscape.

To determine whether full mitigation of development impacts was achieved, we compared projected ES benefits from mitigation to projected total impacts for each population center. When the amount of services provided by mitigation equaled or exceeded the total impact, “no net loss” was deemed to have been met

within that serviceshed. When this balance was not met, we calculated the remaining, unmitigated amount of impact on ES (“residual losses”). We also estimated the number of people affected across the study area as a whole, and divided these into indigenous and non-indigenous populations, allowing us to identify who would lose ES, even under different scenarios of mitigation.

## Results and discussion

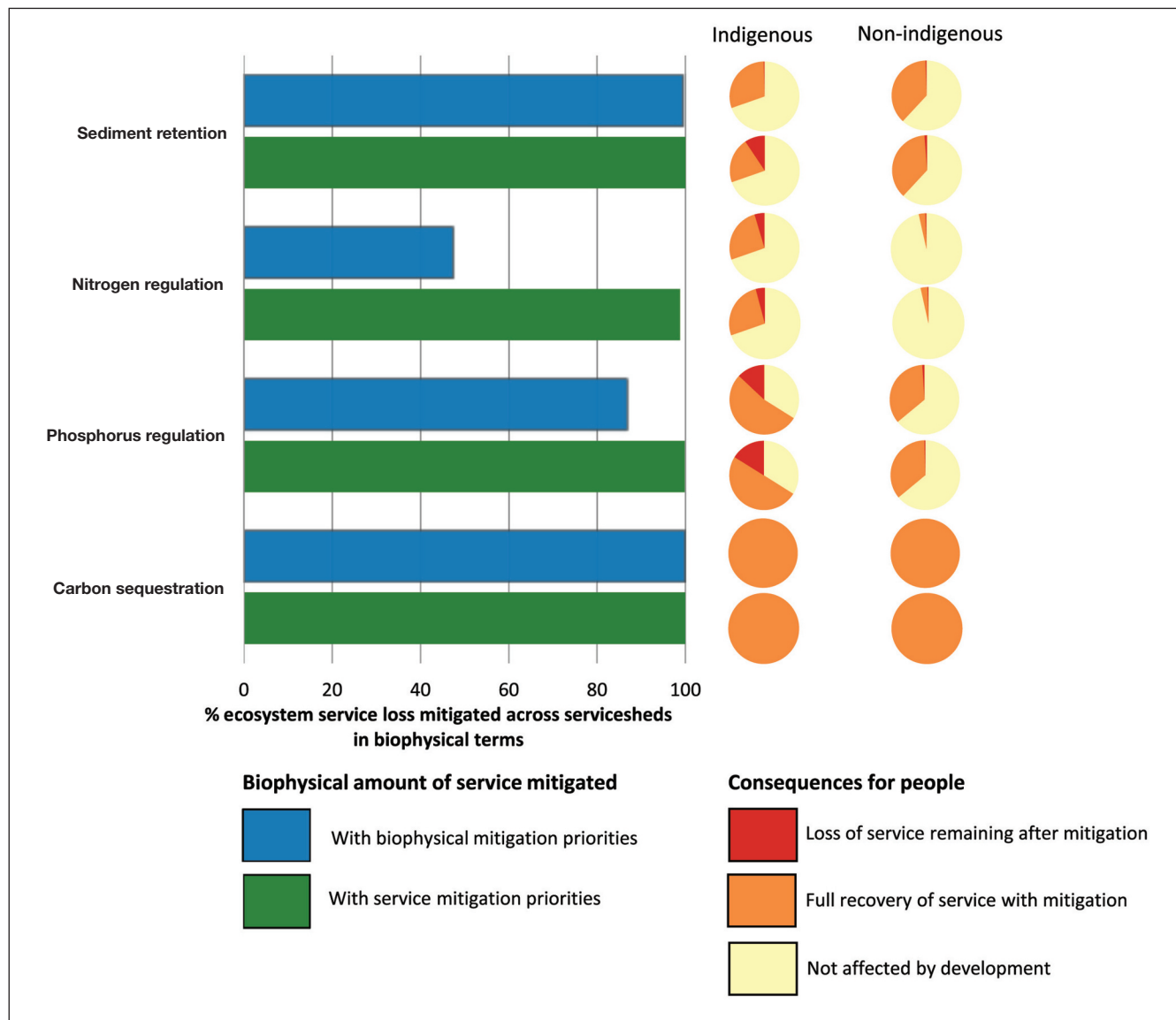
### *Do current methods for choosing mitigation sites lead to equitable ES offsets?*

Choosing mitigation sites based on ecosystem function did not lead to equitable mitigation of ES losses. Within areas where restoration or avoided deforestation were considered feasible, the ecosystem function approach prioritized mitigation where these activities would most increase C storage and most reduce the amount of sediment, N, and P from reaching watercourses (Figure 3a). For C, this method prioritized the protection of, or restoration to, tropical forests, particularly the high-C Amazon forest types found in the western portion of the study area. For the three ES related to drinking-water quality, this method prioritized protection or restoration of forests along streams, especially those growing on deep and highly erodible soils.

In biophysical terms, mitigation offset 100% of C and 99.5% of sediment retention losses but only 86.9% of P control and 47.5% of N control losses (Figure 4, blue bars). Twenty-six population centers, including 13% of the area’s indigenous population and 1% of the non-indigenous population, experienced residual losses of P regulation services (pie charts in Figure 4). Eleven population centers each experienced residual N and sediment retention losses, affecting 5% and 0.4%, respectively, of the area’s indigenous population and affecting 0.5% of the area’s non-indigenous population for both services. A total of 30 population centers experienced residual losses of at least one service, whereas eight population centers – all non-indigenous communities – experienced residual losses of all three drinking-water-quality regulation services (Figure 2b).

### *Does intentional prioritization of ES in offset selection using servicesheds reduce inequality?*

Factoring in ES by including servicesheds increased benefits returned from mitigation and improved the equity of their distribution but did not entirely resolve the inequal-



**Figure 4.** Bar charts show the proportion of offset met in relative biophysical terms (tons sediment, kilograms N and P, megagrams C) across the study area. Pie charts depict the proportion of the indigenous and non-indigenous population with complete recovery of services (orange), without complete recovery (red), and unaffected by development (yellow). Selection of offset sites based on ecosystems' biophysical properties alone (blue bars and adjacent pie charts) results in lower overall mitigation of ES losses because offsets are not necessarily located in places that restore benefits to people affected by road development. When offsets are selected based on the ecosystems' biophysical properties and the flow of services from ecosystems to people (green bars and adjacent pie charts), the same amount of offset area can mitigate a greater amount of ES losses to more people.

ity problem. Mitigation that directly targeted the loss of ES shifted mitigation priorities on the landscape as compared to the approach that considered ecosystem function alone (Figure 3, c versus a). With an ES approach, areas must both score high in terms of ecosystem functions and be located where those functions benefit people affected by development (Figure 3c). Spatial correlation in biophysical suitability of sites to provide ES was high across services (Figure 3a), meaning that many places have the *potential* to provide all of the four ES assessed. Based on biophysical suitability alone, 0.05% of the landscape fell within the top 10% of scores for all four services (as compared to an expected 0.01% with no correlation among

services). However, the areas that are capable of mitigating ES losses to affected people differed across the four services (Figure 3b). When the mitigation requirements of beneficiaries were included, no locations were in the top 10% of scores for all four services. This finding indicates that the sites with the highest levels of ecosystem function across the entire landscape under analysis are not the sites most valuable for the provision of ES to people affected by road development. This also suggests that selecting offsets based on a single service may not provide effective mitigation for all other services, even when the ecosystem functions underlying those services are well correlated across the landscape.

Mitigation that takes servicesheds into account returned a greater amount of benefits to more people, even though the area of land committed to mitigation was the same (Figure 4). Using a serviceshed-based approach reduced the per-person average residual losses of drinking-water-quality regulation more than fourfold for sediment, 16-fold for N, and 38-fold for P, with 15% of the land area in mitigation, as compared to the ecosystem-function-based approach. No population centers experienced losses of more than two services, although 27 population centers experienced residual losses of at least one service (Figure 2c).

Together, these results emphasize that the current practice of selecting mitigation sites based on biophysical functions alone is an inefficient way to restore ES. Climate regulation via C sequestration was an exception to this finding. Because everyone shares the same global climate regulation serviceshed, mitigation anywhere on the landscape provides benefits to everyone, so considering only biophysical suitability alongside economic and political feasibility is sufficient where C sequestration for climate regulation is the final ES goal. However, accounting for servicesheds – so that benefits can be returned to those who lose services due to development – is likely to be critical for any locally provided services (eg bushmeat provision, crop pollination, recreational or subsistence fishing, flood regulation).

With the serviceshed-based approach, 13 population centers experienced residual P regulation losses, including 16% of the indigenous population and 0.5% of the non-indigenous population. Six population centers had residual N regulation losses, affecting 4% of the indigenous population and 1% of the non-indigenous population. Residual losses of sediment retention services remained for 17 population centers, composed of 9% and 1% of the indigenous and non-indigenous population, respectively. The greater impact on indigenous populations – even after mitigation – suggests the road will likely affect social equity.

While the serviceshed-based approach reduces residual ES losses, it does not lead to a complete offsetting of losses for more of the population (pie charts in Figure 4). We were able to offset ES losses from road development and associated deforestation to 74.5% of the indigenous population and 98.7% of the non-indigenous population, as compared to 82.5% and 98.9%, respectively, when considering only ecosystem function. This is because service provision is a combination of biophysical change and the number of people affected. The level of impact is not equal across all affected populations. In the case of sediment retention and P regulation, more people experienced residual losses with serviceshed-based mitigation. Yet these people experienced much lower levels of residual service losses than with biophysical-only mitigation, resulting in greater total service offsets (see WebFigure 3).

By increasing the area devoted to mitigation and refining our prioritization algorithms, we would possibly increase the amount of offset benefit achieved for fewer

hectares of land. It is not possible, however, to offset all ES losses to all people because of limits to suitable mitigation options in some servicesheds. This appears to be the case particularly for indigenous communities. For example, all of the area available for mitigation of water-related services was selected in the upstream catchments of several indigenous communities through the serviceshed-based approach, but this was not enough to offset the ES losses to those communities.

The data needed to delineate servicesheds and assess potential mitigation options for more localized ES, such as the harvest of non-timber forest products, were not available within the study region. Nevertheless, we expect that for such services, as compared with climate and water-quality regulation services, development impacts are likely to be more concentrated around areas of land-use change but that mitigation options would also be more constrained across the landscape. In instances where local data and expert knowledge are available, our approach is applicable to designing equitable offset strategies to address local services as readily as it is for the regional and global services considered in this study. The relevance of servicesheds across a broad range of ES types, along with the variation in priority mitigation areas by service (Figure 3c), indicates that the location of landscape-level mitigation priorities will vary depending on which services are included, underscoring the value of considering a suite of the most relevant services to achieve comprehensive mitigation.

## ■ Conclusions

Our novel approach to tracking the effects of development and mitigation on ES and prioritizing locations for offsets improves the efficiency of mitigation for ES benefits. It also makes apparent how the impacts and benefits of these activities are distributed across the landscape and different segments of society, showing how mitigation choices can create inequality.

To avoid exacerbating inequities in the case of the Pucallpa–Cruzeiro do Sul road, we argue that either additional compensation is needed for groups where mitigation is not complete or the road's route and mitigation activities should be reconsidered, particularly to reduce impacts on indigenous groups. Our serviceshed-based approach provides a mechanism to explore other development and mitigation options that could diminish the disparity among affected populations; for example, these methods could be used to evaluate alternative routes for the proposed road, or to determine whether additional mitigation activities (such as improved agricultural management practices to reduce nutrient and sediment runoff) might lead to more equitable outcomes.

This approach could also be extended to evaluate the consequences of other forms of development, such as mining or agricultural expansion, or for land-use planning more generally. Beyond the Peruvian Amazon, exist-

ing global and local datasets make it feasible to apply this method to other locations around the world. Provisioning of ES can be evaluated separately for other groups of interest (eg by poverty levels, gender, or age). If desired, mitigation activities could be prioritized to distribute benefits equitably, or to preferentially secure benefits for those groups who are most vulnerable to losses of ES. In addition, the method could be expanded to more explicitly consider trade-offs among services, taking into account not only the preferences of beneficiaries but also service provision thresholds and beneficiaries' ability to absorb or adapt to different levels of service loss. In general, our approach provides greater transparency regarding the consequences of development and mitigation activities by accounting for the ES benefits that people receive across the landscape and throughout society.

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