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For services rendered? Modeling hydrology and livelihoods in Andean payments for environmental services schemes

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Abstract

In the Andes, demand for water is growing and upland land-use changes are increasing. Water quality, quantity and seasonal flow have thus also become environmental services with potential monetary value. Yet, currently the region's pioneer PES schemes are not paying for measured environmental services, but for proxy land uses thought to provide the(se) service(s). Hydrological modeling makes explicit the tacit causal relationships and tests underlying assumptions. Ideally, when combined with an economic analysis of land-use alternatives, this could inform decision makers on how much to pay for different interventions in different spatial locations. This paper focuses on two Andean watersheds: Moyobamba (Peru) and Pimampiro (Ecuador). In the first case, a municipal water company is preparing a payment for environmental services (PES) scheme to reduce upstream sediment loads. In the second, a similar conservation-oriented municipal PES scheme has operated since 2000, but the hydrological linkages have never been tested. Applying the Soil & Water Assessment Tool (SWAT), we identify in both watersheds biophysically critical areas for service delivery, and compare services for current land uses with change scenarios: deforestation, reforestation, live barriers, and agroforestry. We then use the ECOSAUT optimization model to predict net economic benefits for service providers. In Moyobamba, switching to shade-grown coffee would halve sediment yields, and increase significantly farmers' economic benefits. This requires high up-front investment, but the willingness to pay of water users in Moyobamba town may suffice to cover the upfront costs. In Pimampiro, resumed deforestation would increase sediments by >50% and reduce dry-season flow by 0.5%, thus reinforcing the rationale of the existing PES scheme, focused on conserving native forests and grasslands.

Keywords: Watershed protection, natural resource management, payments for environmental services, Andes.

1. Introduction

World population and commodity demand is growing rapidly, placing increasing pressure on ecosystem functions, including watershed services such us sediment retention and streamflow regulation (Kremen, 2005). One alternative is ecosystem conservation or restoration through payments for environmental services (PES) , including watershed protection (Asquith & Wunder, 2008). In Latin America, PES schemes are popular, though few possess all stylized ‘ideal’ PES criteria of conditionality, voluntariness, transactions between at least one buyer and one seller, and an adequate definition of the services being paid for (Wunder, 2005). This article will deal with the last assumption: hydrological services being traded in watershed PES systems are normally inadequately defined and quantified, yet widely accepted in a pragmatic way (Quintero and Estrada, 2006). Much work exists on ecosystem services threats and valuation (e.g. Daily, 1997), but the relation between incremental area conserved or restored and marginal ecosystem service gains has received much less attention (Dasgupta et al. 2000). Hence, it is difficult to know how much, and where in the landscape, land should be protected or land uses be changed, in order to deliver ecosystem services.

Desired watershed services in the Andes are mostly enhanced dry-season streamflow and sediment retention (Celleri, 2009). Biophysical complexity across watersheds is high, with large altitude variations (1000–5000 m.a.s.l) within small distances, generating a mosaic of soils, precipitation, vegetation types, and land uses. Hence, management interventions have highly variable impacts across the landscape. When PES resources are scarce, spatial prioritization becomes essential (Wünscher et al

2008). Yet, when services are neither spatially determined nor quantified, more informed economic analysis is precluded.

The concept of a "service-providing unit" in watersheds refers to relatively homogenous spatial entities determining e.g. seasonal water yield, sediments, etc. (Kremen 2005; Houlahan and Findlay 2004). Once critical service-providing units have been determined, one can establish which are needed to safeguard a target level of ecosystem service provision. Combining such biophysical data with socioeconomic analysis can then help estimating landowners' opportunity costs of introducing desired land uses in these "service-providing units".

Lumped hydrological models use basin-wide averages, assuming uniformity across the basin in estimating total basin streamflow (HEC 2000; Johnson 1997; Shah 1996). Lumped models consider a catchment as one complete unit, characterized by a relative small number of parameters and variables (Refsgaard 1997). In contrast, hydrological distributed models establish specific parameters values for the different spatial subunits of a watershed (Beven, 1985). Thus, they can identify "service-providing units" and also distinguish complex physical functions determining watershed services (Jakajrisnhan et al.2005), and are thus arguably more suitable under conditions of high spatial heterogeneity within watershed. However, lack of data often hinders the applicability of distributed models. In response, the Soil and Water Assessment Tool (SWAT) is a model with less complexity, and yet powerful in data generation (Arnold et al. 1999; Huevelmans, et al. 2005). SWAT is a continuous-time model where modeled catchments are subdivided into sub-basins and hydrologic response units (HRU), which are spatially explicitly parameterized to capture the impacts from different topography, soils, and land covers (Eckhardt et al, 2005; Diluzio et al. 2005). HRUs contribute to the subwatershed with specific streamflow and sediment yields (Haverkamp et al. 2005). Thus SWAT spatially identifies units that are crucial for delivering watershed services (retention of sediments and production of water). This may also provide strategic spatial information to PES scheme designers.

We will present two small-scale municipal case studies to illustrate how SWAT, combined with an economic optimization model, can spatially predict effects on dry season flows, sediment yields, and socioeconomic impacts from different land-use alternatives. Our approach may serve as a relatively low-cost predictive tool for the spatial allocation of PES interventions.

The article is structured as follows. Section 2 will briefly describe study areas and methods applied to quantify the environmental services and the analysis of opportunity costs. Sections 3 and 4 will describe and compare the results for both sites. Section 5 summarizes conclusions and recommendations.

2. Methods

2.1. Study areas

The Pimampiro PES scheme, Ecuador Pimampiro, a town of 13,000 people, is located in Imbabura Province (northern Ecuador), in the eastern Andes (2150 m.a.s.l.). It relies on surface sources for drinking water and irrigation. The Palahurco micro-watershed, a main source, is part of the Pisque watershed and extends over 13.17 km^2, at 2900-3900 m.a.s.l., with mean annual precipitation of 965 mm and mean annual temperature of 11.8°C. The principal native vegetation there is cloud forest and *páramo* (alpine Andean grasslands), and the topography is rugged.

The Palahurco River originates in the relatively well-protected Cayambe-Coca Ecological Reserve, but the vegetation in the middle part of the watershed, immediately upstream of Pimampiro's water intake of an estimated average 60 $\mathrm{l\ s^{-1}}$, was during the 1990s affected by progressive agricultural land colonization. Indigenous farmers had founded the Nueva América cooperative on the Palahurco River's right bank, 32 km upstream from Pimampiro. They gradually expanded pastures and crops (predominantly potatoes), at the expense of native forest and páramo; it is estimated that each household at its peak deforested around 0.5 ha $\mathrm{year^{-1}}$ (Wunder and Albán 2008).

These upstream land-use changes alarmed the municipality of Pimampiro, due to perceived risks for water quality from increased sediments, and for less dry-season flows through reduced water retention on converted soils (Echavarría et al. 2004). After a prolonged drought and alarming water shortages in 1999, Pimampiro was ready for action to address the emerging environmental threats, mainly to protect forests and *páramos* from the advancing agricultural frontier. Yet, the expected positive environmental impacts were never measured or analyzed. The rationale was of the precautionary principle type: if upstream native forests and páramos so far had secured clean and stable water flows, then a radical disturbance with unpredictable impacts should be avoided (Wunder and Albán 2008).

In 1999, a Quito-based non-governmental organization, financed by a foreign donor grant, set up a PES scheme that started operation in 2000 (CEDERENA 2002). The Municipality charged its 1350 water-using households a 20% surcharge, which is directly channeled to a water fund. No previous willingness-to-pay study was carried out, but water prices had at US$0.05/m^3 (residential use) to US$0.11/m^3 (industrial use) been highly subsidized (Echavarría et al. 2004: 23). The surcharge by now fully finances the recurrent PES transfers to upstream 'service providers'. The latter hold 550 ha under PES contracts, corresponding to 87 % of the land in Nueva América. 19 families have contractually committed not to convert forest and *páramo*, nor to extract trees (other than for minor domestic uses), and to leave some degraded areas to natural regeneration. The scheme is probably the main reason why the land-conversion process in Nueva América was reverted, from 198 ha (31%) under crops pasture in 2000 to just 88 ha in 2005 (Wunder and Albán 2008: 690). Correspondingly, a 2003 survey among urban water consumers found that out of 36 randomly selected households, 35 agreed that upstream watershed protection was important, and 30 were satisfied with the current water services (Echavarría et al. 2004: 23).

The payment each upstream family receives varies according to vegetation type and conservation state of the forest or *páramo* being protected from US$6 to US$12 year^{-1} ha^{-1} (Echavarría et al., 2004: 27). These fixed amounts were negotiated, without any prior hydrological or opportunity -cost analysis. Our *ex-post* analysis will evaluate to what extent conserving native vegetation produces watershed services (sediments, streamflow) for water users and net socioeconomic benefits for Nueva América farmers.

The Moyobamba PES proposal, Peru

The Rumiyacu and Mishquiyacu micro-watersheds, located in the Altomayo transitional zone between the Peruvian Andes and the Amazon (1022-1539 m.a.s.l), encompass 7.3 km^2, and have an average annual precipitation of 1408 mm. They supply drinking water to the town of Moyobamba, benefiting about 40,000 inhabitants. The Mishquiyacu River is the regular source of water supply, while during shortages water is also taken from the Rumiyacu.

The two micro-watersheds are mostly covered by natural forest (61%); the remainder is under a mosaic of slash-and-burn systems, coffee, and permanent pastures. However, deforestation in the Altomayo region is at a staggering 4.2% annual rate (PEAM, 2004), due to farm establishment by immigrants who make up more than half of Moyobamba Province's population (PEAM, 2004). Their land is untitled; most migrants have taken possession through deforestation. Slash-and-burn systems include subsistence crops (mainly maize), which are succeeded by pastures when soil productivity decreases. 42% of farmers cultivate coffee, but under currently low productivity.

The replacement of native vegetation by other land uses has caused high sediment loads, thus from 2003 increasing the drinking-water treatment costs of Moyobamba's water and sanitation company (EPS -- a public entity but operating under private law) by about 20%, (Quintero et al., 2005, F. Aspajo, pers.comm., 2005). Hence, the Municipality of Moyobamba declared the watersheds as Municipal Conservation Area, with the purpose of conserving remaining forests and to promote sustainable land uses in already disturbed areas. EPS also explored options to reduce upstream sediments and simultaneously improve livelihoods.

The Municipality and EPS jointly formed a PES committee, which created a fund. As in Pimampiro, the idea was to levy a surcharge on Moyabamba's water consumers, and correspondingly subsidize upstream farmers willing to change towards less sedimentprone land uses (Aspajo, 2006). Our below analysis was an integrated part of land-use planning, identifying critical sediment areas and land-use alternatives with opportunity costs that could be compensated through PES. The water surcharge has recently been approved, meaning that PES could soon be implemented, either as recurrent payments or subsidized conditional credits (Section 3).

2.2. Hydrological analysis

The SWAT model (version 99.1) was used in both case studies. Through the ArcView-SWAT interface, information about topography (digital elevation model), soils (soil map and survey), weather (climatic stations and its coordinates) and land use (most recent land-use map -- see Table 1) were combined for simulation. Incorporated soil properties were depth, bulk density, available water capacity, saturated hydraulic conductivity, clay, sand, silt and organic matter content (Table 2). The climatic information for simulating the water balance of the HRUs consisted in daily rainfall, maximum and minimum temperatures, and monthly radiation., Rainfall data was available for 1991-2000 in Palahurco and for 1999-2005 in Rumiyacu–Mishquiyacu.

[Insert Table 1 here]

[Insert Table 2 here]

For the simulation, the watersheds were delineated using a digital elevation model. Sub-watersheds and HRUs with unique soil and land use characteristics were defined. For each HRU, SWAT calculated the soil loss through water erosion and the water yield, thus featuring the two main hydrological services of interest. For this, the water balance per HRU was calculated taking into account three storage volumes: soil profile, shallow and deep aquifer. The soil profile was subdivided into multiple layers, according to the number of horizons identified in soil-profile descriptions. The soil-water processes modeled with SWAT included infiltration, evaporation, plant uptake, lateral flow and percolation to lower layers. Thus, we calculated water yields (total amount of water leaving the HRU and entering the main channel) and sediment yields (amount of sediment contributed by the HRU to the stream) (Neitsch et al. 1999), and routed them through drainage to the watershed outlet. The model was calibrated to reduce parameter uncertainty and increase robustness of the results, i.e. some parameters were marginally adjusted until the best possible correspondence between observed and simulated streamflow at the basin outlet was obtained. For Palahurco, simulated streamflow was compared to the mean minimum streamflow reported ($60\ l\ s^{-1}$) through the cumulative frequency ("flow duration") curves, showing the average percentage of time that specific daily flows are equaled or exceeded. In Rumiyacu–Mishquiyacu, simulated flows were compared to daily observed flows during November 2004–May 2005. In both cases, the streamflow data available for calibration was thus rather limited. For Rumiyacu-Mishquiyacu, the observed and simulated daily series were compared using the Nash-Sutcliffe criterion, indicating simulation efficiency (Nash and Sutcliffe, 1970).

During calibration, the runoff curve number, the saturated hydraulic conductivity, and the USLE (Universal Soil Loss Equation) C and P factors were varied. Runoff parameters, water-holding capacity and saturated hydraulic conductivity have shown high sensitivity in other studies (i.e. Lenhart et al. 2002, Jakajrisnhan et al. 2005, Govender and Everson, 2005, Heuvelmans et al. 2005). Once calibrated, different land-use scenarios were model-evaluated for their effects on water and sediment yields (Jakajrisnhan et al. 2005)

For Rumiyacu–Mishquiyacu, the scenario assessment was conducted in selected HRUs with high sediment yields, this being the primarily targeted service there. The scenarios screened sedimentation from current and potential land uses and practices: (1) current slash-and-burn agriculture, (2) shade-grown coffee, (3) reforestation, and (4) live barriers for crops. In Palahurco, we selected HRUs that due to their proximity to the agricultural frontier are likely under the greatest pressure. .Here we assessed the impact of resumed conversion of natural forest to annual crops and pastures, which corresponds to a likely scenario without the PES scheme.

2.3. Economic analysis of opportunity costs

The ECOSAUT model uses linear programming to optimize net income from different land-use systems, taking into account social, economic, and environmental criteria (Quintero et al. 2006). It was employed to evaluate the socioeconomic impacts of PES-promoted land use systems. The purposes slightly differed in the two cases:

(1) For Palahurco, we evaluated how current PES amounts compared to farmers' estimated conservation opportunity costs;

(2) For Mishquiyacu-Rumiyacu, we assessed the socioeconomic viability of the modeled environmentally benign land-use alternatives.

For Palahurco, the typical production system of farmers participating in the existing PES scheme was under a "without PES" counterfactual assumed to be incrementally enlarged into areas now being conserved. Hence, economic returns to this expansive production system can be used as a baseline to assess farmer opportunity cost for conserving *páramos* and native forests. We assumed a hypothetical linear projection of pre-PES deforestation and farmland extensification rates of 0.5 ha year^{-1} per farm (Wunder and Albán 2008). The net present values of the baseline were compared with those of the current PES scenario.

Information about these production systems drew on earlier research (Echavarría et al. 2004; Wunder and Albán 2008), supplemented by two site visits in 2006/07 to detail information about land uses, farm areas, labor costs, crop productivity, animal stocking rates, production and transportation costs. Wherever farming-system parameters could not be clarified *in situ*, we extrapolated parameters from similar Andean sites, especially regarding pasture protein and energy contents, dry-matter content, and labor requirements (Rubiano et al. 2006). We also used cattle and potato farm-gate prices, and potato productivity levels from Ecuador's Information Service and Agricultural Census (SICA) (http://www.sica.gov.ec/), and corroborated this information in the field. With this information in hand (see Table 3), we then defined a farm prototype and projected its net income cropping and livestock returns over ten years.

For Rumiyacu–Mishquiyacu, we collected secondary data for those HRUs and production systems that currently produce the highest sediments. A field visit in June 2005 helped verifying this, including vis-à-vis local slash-and-burn cropping cycles. We used this system as our baseline scenario, assuming it will continue if farmers do not receive incentives to change to more benign land uses. In addition, we gathered information about three alternative land-use scenarios: (1) shade-grown coffee, (2) reforestation, and (3) live barriers. These scenarios were selected considering both erosion control and livelihood benefit criteria. As in Palahurco, we extracted data on production and livelihoods systems from previous studies (EPS, 2004) and used these for a socioeconomic assessment of land-use alternatives (Table 3)

[Insert Table 3 here]

Finally, for both cases the spatially specific results of sediment and water production from the SWAT simulations were entered into the ECOSAUT model. This allowed us to assess the environmental benefits from these land-use alternatives, together with their respective socioeconomic returns, in an integrated manner.

3. Results

3.1. Palahurco

Hydrological analysis

We defined eight sub-watersheds, encompassing 31 HRUs. The obtained flow-duration curve indicates that our simulated streamflow compares well with the reported data. Streamflow exceeding 75 l s^{-1} occurs in the watershed with a probability of 95%, which is comparable to the average streamflow reported of 60 l s^{-1} (Figure 1). For both sedimentation and infiltration, some HRUs have a disproportionate impact. The HRUs under potato-based systems contributed most to sedimentation, especially those located in sub-watersheds 4 and 7, with soil types classified as Snr-Df, Snr-C and Df (MAG-ORSTOM, 1981), and with high slopes (Table 4). Six critical HRU, making up 8.65% of the watershed's land area, contributed two thirds of projected sediments. The other land-cover types (primary and secondary forests, pastures, and *páramo*) presented only low quantities of sediments.

[Insert Figure 1 here]

[Insert Table 4 here]

With regard to annual water production (m^3 s^{-1}), the HRUs producing most water are those under agriculture. However, this is correlated (81%) with high runoff water and sediment production, indicating that most water from agricultural areas is lost by surface runoff. This is corroborated by a negative correlation (69%) between sediment production (t/ha) and water that infiltrates the soil (lateral flow and groundwater). For comparison, HRUs under forest and páramo produce slightly less total annual water, but more water infiltrates than in agriculture, thus also feeding more lateral flow and aquifers that are essential dry-season flow.

With regard to the benefits of conserving natural land cover through PES, unfortunately we lacked geo-referenced data for land under PES. Thus, we simulated the effect of converting to agriculture all forest in HRUs found near the current agricultural frontier (replicating in proportion the currently prevalent pasture-crop mix) (Figure 2). This corresponds to the clearance of 92 ha of forests (i.e. 23 PES-enrolled families who would counterfactually have deforested 0.5 ha/yr^{-1} over the 8 years of scheme implementation since 2000). Much is sloped marginal agricultural land, thus also increasing dramatically the erosion risks. We found that average annual sediments would over the projected decade increase by 53%, from the current levels of 4,699 t/yr to 7,227 t/yr, raising also average annual sediment yields from 3.6 t/ha to 5.4 t/ha. This is a highly conservative estimate, since the PES scheme likely also triggered farmers to abandon 110 ha of agricultural land (Wunder and Albán 2008:690), but we were unable to estimate the hydrological conservation effect of the heterogeneous secondary vegetation replacing it.

The sedimentation avoided through PES corresponds over the projected decade to 25,283 t. The water that infiltrates (lateral flow and contribution to groundwater) would also have decreased, but by a more moderate 0.5% in 10 years (Table 5). PES-induced conservation impacts thus seem to be relatively stronger for the subservice of sedimentation retention than for that of maintaining high dry-season flows. If we project deforestation further to reach an accumulated 400 ha, then sedimentation almost triplicates, as gradually more sloped and marginal areas are taken into agricultural production (scenario not shown in Table 5)

[Insert Figure 2 here]

[Insert Table 5 here]

Economic analysis

To estimate farmers' opportunity cost of conserving *páramo* and native forest, based on our field assessment of production systems we defined a 32 ha prototype farm with 12.8 ha undisturbed forest, 6.2 ha disturbed forest, 2.7 ha undisturbed *páramo*, 3.6 ha under potato-based systems, and 7.3 ha disturbed *páramo* used for extensive livestock production. We then compared the net present values (NPV), i.e. the time-discounted future farm incomes over 10 years, for a PES-cum-conservation system with one that receives no PES and has progressive annual deforestation of 0.5 ha of *páramo* or forest. The results show that deforesting generates higher NPVs than receiving PES, but the difference is small at high discount rates (e.g. 20%): US$20,424 with payments for forest conservation vs. US$24,471 for continued land clearing (Table 6, and discussion below).

[Insert Table 6 here]

3.2. Rumiyacu–Mishquiyacu

Hydrological analysis

We determined 7 subwatersheds and 22 HRUs for the Mishquiyacu watershed, and 6 subwatersheds and 28 HRUs for Rumiyacu. For the modeled period, 1999–2005, in those dry months when some potable water was drawn from the Rumiyacu River for consumption in Moyobamba, the latter did not increment sediments to total flow. This indicates that most sediment in the water treated by EPS come from the Mishquiyacu watershed (Quintero et al., 2005).

With respect to the performance of the simulation, we obtained a Nash-Sutcliffe coefficient of only 0.03: comparison of observed and simulated time series demonstrates that during days of high rainfall (>100 ml), observed streamflow is systematically underestimated; regressing the latter on the former yields an R^2 of 93.75%. . This is probably explained by limitations in the local measurement technique and frequency (e.g. stream stage), resulting in underestimated observed data. Yet, the minimum and intermediate streamflows are better predicted: R^2 is 96.5 and 97% in the two cases, without systematic biases. . In general, , the simulated time series fits quite well with the observed one, which is important for determining the HRU with higher sediment yields.

The sedimentation analysis was thus focused on Mishquiyacu, where 8 HRUs showed particularly high sediments per hectare. They contained slash-and-burn systems or abandoned areas occupy 23.1 ha, and currently account for 27% of total sediments in the watershed (Table 7).

[Insert Table 7 here]

For these HRUs, SWAT simulations showed that the establishment of live barriers, forest plantations, and shade-grown coffee each would about halve sediments, compared to "business as usual". In terms of total streamflow (although this is not the main externality of interest for Moyobamba and results are only shown as additional information), shade-grown coffee would reduce quantities by 11% and forest plantations by 14%, while live barriers would not have any impact (Table 8).

[Insert Table 8 here]

Economic analysis

Like for Palahurco, we used ECOSAUT to calculate the NPV (discount rate of 15%, 10 years) for the different land-use alternatives. Introducing shade-grown coffee would require significant initial investments, but still increase NPV by 91%, compared to the traditional slash-and-burn system. In contrast, forest plantations would reduce NPV by 62% and live barriers by 11%, if no compensations are being paid to farmers.

Finally, we calculated the cost of reducing one ton of sediments, using the marginal NPV and including labor costs (Table 9). The results show that the live barriers alternative is cheapest to install (US\$0.36 t^{-1}). The higher cost of reducing sedimentation with shade coffee and forest plantations (US\$1.16 and 1.10 t^{-1}, respectively) is due to their higher investment costs. However, live barriers had negative income effects, so farmers are unlikely to adopt them unless they receive compensation. Instead, shade-coffee systems seem to provide the best trade-off between environmental, since they both increase environmental services and medium-term incomes. Yet, high initial investment costs may mean that farmers may only be willing to change if they receive PES in the form of significant transitory payments or subsidized, contingent credits.

[Insert Table 9 here]

4. Discussion

4.1. Palahurco

From a hydrological viewpoint, our results show that PES-compensated forest and páramo conservation is preventing much sediment production that would significantly affect water quality under the baseline of continued conversion to crops and pastures (Table 5). Conservation reduces total water yield, but this still slightly favors infiltration that feeds lateral flow and groundwater, thus marginally increasing seasonal flows. Similar effects have been obtained using instead the RAINRUN model by van der Weert (1994, cited in Bruijnzeel, 2004) where the replacement of forest for agriculture gradually increased surface runoff, yet reduced baseflow and subsurface flows. It is noteworthy that the differences in annual and seasonal water yields are generally small across land-use scenarios, compared to what is found in some other studies (e.g. Edwards, 1979; Lal, 1989 cited in Bruijnzeel 2004). This small water-yield effect of forest clearing probably relates to the low evapotranspiration of cloud forests in Palahurco, and its ability to capture fog (Bruijnzeel, 2004). On the contrary, avoided sedimentation is a highly significant and the clearly dominating hydrological subservice. Our modeling exercise identified HRUs currently not included in the PES scheme, which continue producing disproportionate amounts of sediments. Future conservation efforts by the Municipality and its service users should focus on these areas: enrolling another 115 ha of targeted

HRUs under PES would cut current sedimentation loads by two thirds (Table 4). Conversely, abandoning the PES scheme and allowing for incremental reconversion to agriculture would cause a tripling of current erosion over 25 years, while increasing it by 53% (25,283) over the eight-year lifetime of the PES scheme (Table 5). Over the same period, the PES scheme cost US$77,800 -- US$37,500 startup costs plus US$5037.50 average annual running costs over 8 yr (Wunder and Albán 2008:689). Thus, the implicit price of PES-avoided sedimentation has been US$3.1/ton of sediment. The Municipality received the start-up costs from a foreign donor, so it only paid US$40,300, i.e. US$1.6/ton, which can be considered a worthwhile investment.

Our socioeconomic evaluation showed that continued deforestation yields higher farming income than conservation with PES; i.e. current payments seem to under-compensate farmers' opportunity costs from conserving native forests and *páramo*. Several factors could explain this apparent paradox. First, usury interest rates in informal money markets indicate a high preference for current income, thus diminishing the NPV gap (Table 6). Second, current clearing pressures may be less than the historic 0.5 ha yr^{-1} per household, due to structural changes in Ecuadorean meat and dairy markets that have reduce return to clearing (Wunder & Albán 2008) and possibly diminishing returns to scale when more marginal lands are incorporated. If the baseline rate is 0.3 ha yr^{-1} instead, the NPV values break even in the 15-20% interest-rate range. Third, landowners reside downstream, so receiving a stable, risk-free payment may be more attractive than contracting labor to expand farming in remote upper parts of the watershed, at only a marginal premium. Finally, formally the watershed also holds (weakly enforced) legal protection status, so recently enhanced threats about stricter future enforcement could disincentivize farmers' conversion further. In conclusion, the existing PES in Pimampiro clearly contributes to avoided sediments and enhanced water infiltration, by paying Palahurco farmers probably just enough to make them desist from land conversion.

4.2. Mishquiyacu

Our hydrological results are in line with what the literature reports: there is little doubt that both annual water yields and particularly surface erosion from forests are lower than for non-forested tropical areas (Bruijnzeel et al. 2004). Converting the 23.1 ha of critical slash-and-burn areas to shade-grown coffee would provide a 'win-win' of both significantly more sediment retention and higher farmer incomes. However, probably due to liquidity shortages, as the main obstacle, low-return slash-and-burn systems still dominate the watershed. The initial capital investment needed to establish shade-grown coffee is US\$176 ha^{-1} In contrast, the traditional burning-maize-pastures system requires only \$9 ha^{-1} in capital costs for seeds. The lack of financial infrastructure (and possibly of technical assistance) may thus constrain the adoption of shade-grown coffee systems.

The favored strategy of EPS and the Municipality is to buy environmental services while also improving the socioeconomic conditions of upstream farmers. For setting up live barriers on land dedicated to maize and pastures, the marginal cost of reducing erosion is US\$0.36 t^{-1}, i.e. \$16.6 ha^{-1} $year^{-1}$ -- to be paid every year, since the barriers need yearly maintenance. In comparison, to encourage farmers to establish shade-grown coffee would seemingly require only a two-year transitory subsidy ofUS\$269 ha^{-1} $year^{-1}$; in the following years, profits from shade-grown coffee exceed those from annual cropping. Taking into account that priority areas only cover 23.1 ha, and that changing their use could potentially cut sediments by 18%, this is the preferred alternative for stakeholders in Moyobamba. Subsidized loans for shade–coffee aoption are thus now discussed, which would seemingly be cheaper than a permanent PES scheme. The resources could probably be collected directly from the Moyobamba water users whose stated willingness to pay is US\$1.3 family^{-1} month^{-1} (Nowick, 2005). With 7136 paying water users, the necessary resources for promoting a change in the land use might be collected in just two months.

Perpetual versus transitory performance payments

In Pimampiro, a PES scheme for natural forest and páramo conservation was applied, using the rationale of the precautionary principle: since the targeted watershed so far had provided clean and seasonally stable water flows, paying for preserving its status quo, and for reverting incipient threats, was seen as desirable, even without *ex-ante* technical evaluations of expected quantitative impacts on environmental services and livelihoods. Our ex-post analysis proved the strategy adequate in avoiding higher sediment loads and marginal decreases in dry-season flows. Considering the scheme's costs and benefits, Pimampiro's PES system has been cost-effective, since it is avoiding the reduction of water quantity and quality at a low cost (US\$12 ha^{-1} year^{-1} payments, plus the PES startup and recurrent transaction costs).

However, in already heavily disturbed areas, with higher population density and multifaceted land-use mixes, more complex solutions may be required. In Moyobamba, paying upstream farmers to abandon or set aside cropped areas in favor of forest regrowth would have been an economically and politically less feasible solution. On the one hand, high immigration and lack of land titles undermine the potential use of PES to avoid new deforestation. On the other, watershed services there need not only protection, but also active restoration through reconversion of intervened areas to more benign land uses. Win-win alternatives that require an initial PES-like conditional incentive for adoption, but then allegedly can be self-sustained, have functioned elsewhere (e.g. Pagiola et al. 2004), and could thus be more attractive than perpetual compensations (e.g. for live barriers), as long as the former can be sustainably adopted in practice.

The second aspect that complicates the design of PES in Moyabamba, compared to Pimampiro, is the existence of more heterogeneous land uses and farmers. In this case, hydrological modeling has a higher potential for clarifying the biophysical and socio-economic trade-offs, and to determine the contribution of the different land uses to hydrological services in order to target interventions.

The validity of SWAT results

Hydrological models are commonly calibrated modifying sensitive variables in a ±10% range to optimize model fit.

However, the efficiency of SWAT simulations in the Andes will depend highly on the watershed area. In watersheds bigger than 10.000 ha, with more climatic stations measuring conditions, the response time it takes for rainfall to reach a stream is high, so that one daily streamflow measurement will still provide a good approximation of hydrologic fluctuations. . However, in smaller watersheds with complex conditions (e.g. high slopes and rainfall intensities; short dry season), and few rainfall measurements available, SWAT calibration will be challenging. Here, the use of simpler models with less data requirements --including non-distributed, lumped models-- may be preferable, although their accuracy and the capacity to determine service providing units will also be compromised.

Pros and cons of our methodological approach

The SWAT model is generally quite time- and cost-efficient in analyzing watershed management and decision-making (Jayakrishnan et al. 2005). A main advantage of SWAT is that watersheds without monitoring data (e.g. stream-gage data) can be modeled and that the effect of changed input data (e.g. in management practices, climate, vegetation) on results (e.g. water quality, streamflow) can be quantified (Neisch et al. 1999).

In principle, SWAT is universally applicable, because its physical equations can be used for any climatic zone or land-use type (Heulvelmans et al. 2005). Some SWAT empirical equations (e.g. curve number technique and Modified Universal Soil Loss Equation -MUSLE) were based on field experiments in USA, and during calibration modified for local conditions, as recommended by SWAT developers proper. SWAT is able to manage the heterogeneity of biophysical conditions typical in the Andes (soils, topography, weather, and land uses). Yet, detailed input data such as streamflow, rainfall and soil data will definitely improve SWAT's simulation in Andean contexts; in particular, detailed soil data are hard to find. Analogous observations have been made for

SWAT applications in Africa (e.g. Jayakrishnan et al. 2005). Even when insufficient input data imply that the absolute quantitative predictions of 'services rendered' can be improved, SWAT will still be very useful for spatially identifying critical HRUs where watershed management can make a significant difference. Other factors could be added, such as the special contribution of cloud forest to flows that was not considered in the analysis for Pimampiro. Cost-wise, SWAT software can freely be downloaded, while the analysis cost between US$8,000 and US$60,000, depending mostly on watershed size (from 1300 to 22,000,000 ha).

For the economic analysis (ECOSAUT), optimization models depend on quality data about benefits and costs of production systems. Past deforestation and other land-use change data, including their fluctuations over time in response to changed commodity prices or other external shocks, could critically affect incomes, as shown for Pimampiro. Hence, refined information in this field might change the results.

Finally, the Pimampiro and Moyobamba examples illustrated that different settings call for different levels of pre-analysis, in terms of quantifying environmental services, estimating opportunity costs and identifying critical service-providing units. The PES scheme in Pimampiro could operate almost a decade without previous studies, but the level of conservation investment was low – accumulated start-up and running costs combined for 2000-05 were US$62,987 (Wunder and Albán 2008: 689) – the PES-protected area had few and relatively homogenous landowners with a large portion of intact native vegetation, and there was a high consensus among service users that upstream protection was needed. In Moyobamba, potential payments are higher, service restoration is needed in a more intervened landscape, and the upstream land-use alternatives are more complex. Hence, the rationale for hydrological and socioeconomic *ex-ante* analysis was much more obvious.

5. Conclusions and recommendations

In Pimampiro (Ecuador), our hydrological modeling confirmed that protecting natural forest and páramo cover in the upstream Palahurco watershed from gradual conversion to pastures and crops has cost-effectively prevented a projected dramatic tripling in sedimentation (thus safeguarding water quality), and, to a minor extent, protected lateral/ groundwater flows (thus stabilizing dry-season water quantities) from decreasing by 0.5% over a decade. However, the SWAT analysis clearly revealed that some high-erosion areas remain, and additional erosion protection on 115 ha of currently cropped land could cut about two thirds of currently remaining sediments. Sedimentation avoided through PES corresponds over the projected decade to 25,283 t, at an attractive price of only US$3.1/ton (including high PES start-up costs). These model quantifications remain conservative approximations, due to limitations in input data, but the spatially critical areas can be assumed to have been fairly exactly identified.

For the Peruvian watersheds, hydrological modeling showed that most sediments come from the Mishquiyacu watershed, and that shade-grown coffee might provide the best combination of farm yields and reduced sediment; yet it requires high initial labor and capital inputs that upstream farmers currently are unwilling or unable to provide. Since the critical areas causing highest amounts of sediments are small (23.1 ha), and Moyobamba's water users have confirmed willingness to pay for water-quality protection, it will probably be possible to provide PES-like incentives (conditional low-cost credits or transitory subsidies) that could ensure adoption of shade-grown coffee and a 18% sediment reduction.

Methodologically, the combination of a hydrological distributed model such us SWAT and a socioeconomic optimization model such as ECOSAUT to assess the income effects of land-use scenarios, enables the discrimination in space of watershed services and the livelihood consequences for land users from changed land uses – such as in Moyobamba. It also permits screening projected impacts from PES schemes -- such as the quantification of conservation opportunity cost in Pimampiro, although the lack of vital input data will inevitably trigger error margins in quantitative predictions.

When services come from heterogeneous landscapes, such as the two Andean watersheds analyzed here, service provision often differs dramatically across the landscape, with variations in soils, slopes, rainfall and baseline land uses. Identifying these critical areas and outlining alternatives for their best management, is perhaps the most powerful policy application of these types of models. With this information in hand, policymakers can thus also better spatially target PES and other landscape interventions, making sure that genuinely critical areas are always included, and perhaps offering higher change incentives to their landowners. In turn, the socioeconomic modeling can help quantifying these incentives, thus ensuring that upstream livelihoods are also improved.

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Tables

Table 1. Basic data used for hydrological modeling

Type	Palahurco watershed	Mishciyacu-Rumiyacu watersheds
Topography	*SRTM Digital Elevation Data* model[a]	*SRTM Digital Elevation Data* model[a]
Land use	Current land-use map[b]	Landsat 2002 image[c]
Soil	Digital soil map and soil-unit description[bd]	Digital soil map and soil-unit description[bd]
Rainfall	Daily precipitation data, 1991-2000[e]	Daily precipitation data, 1990-2005[f]
Temperature and radiation	Mean monthly temperature (for maximum, mean, and minimum) and radiation[g]	Maximum and minimum (daily and monthly) temperature and radiation[g]

[a] At 90m resolution

[b] At 100m resolution

[c] Data verified in the field

[d] Soil characteristics were organic matter content, horizon depths, granulometry, water retention curves, and bulk density. Hydraulic conductivity was determined with a soil-texture triangle used for estimating soil-water characteristics (Saxton et al., 1986). Values were adjusted according to those found in Andean soils with similar high organic matter content.

[e] From San Francisco de Sigsipamba weather station

[f] January 1999 to May 2005, at the Moyobamba weather station; November 2004 to May 2005, daily precipitation measured in each micro-watershed

[g] Through the MarkSim® model (Jones, 2006), generating climatic parameters at 1 km resolution

Table 2. Soil characteristics parameters used in SWAT modeling

Soil unit	Profile code	Hydrological group	(K factor) USLE	Depth (cm)	Bulk density (g/cm³)	Available water content (mm/mm)	Saturated hydraulic conductivity (mm/mm)	% Carbon	% Clay	% Silt	% Sand
Palahurco watershed											
Dm	E825	B		0-40	0.87	0.24	38.4	6.0	5	85	10
			0.60	40-100	1.06	0.12	104.8	3.4	10	8	82
Db	E742	B		0-15	0.68	0.24	38.4	2.3	5	85	10
				15-40	0.53	0.24	38.4	2.3	5	85	10
			0.60	40-50	1.06	0.13	12.8	1.4	10	8	82
Df	E902	B		0-70	0.86	0.24	38.4	2.3	5	85	10
			0.60	70-100	1.25	0.12	102.8	1.2	10	8	82
Snr		C		0-10	1.28	0.05	16.9	1.6	25	33	41
				10-20	1.37	0.04	1.5	1.0	25	33	41
			0.60	20-40	1.50	0.03	0.7	0.07	25	33	41
Snr - C		B	0.79	0-70	0.86	0.24	38.4	2.3	5	85	10
			0.75	70-100	1.25	0.12	102.8	1.2	10	8	82
Snr + Df		B	0.79	0-70	0.86	0.24	38.4	2.3	5	85	10
			0.69	70-100	1.25	0.12	102.8	1.2	10	8	82
Df + R		B	0.79	0-70	0.86	0.24	38.4	2.3	5	85	10
			0.75	70-100	1.25	0.12	102.8	1.2	10	8	88
Rumiyacu-Mishciyacu watershed											
Ni	AC	C		0-10	1.15	0.11	0.50	2.5	80	8	12
			0.01	10-40	1.23	0.15	0.20	0.8	50	32	18
CA	ABCR	C		0-15	1.25	0.13	0.16	1.97	51	20	29
				15-40	1.22	0.13	0.18	1.39	55	23	22
				40-70	1.25	0.14	0.19	1.04	48	29	23
			0.04	70-110	1.22	0.12	0.16	1.04	61	13	26

Table 3

Productive-system parameters used for assessing land-use and management alternatives

	Palahurco watershed		**Mishciyacu watershed**				
Variable	**Potato**	**Cattle**	**Maize**	**Live barriers**	**Cattle**	**Shade-grown coffee**	**Tree plantation**
Annual average of labor used (# workdays/ha)	99	5	42	3	16.5	42.3	39.4
Annual average production cost (excl. of labor) (US$/ha)	913	63	12.5	4	2	49.6	47.5
Annual average productivity (t/ha)	16	6	2.6		15	0.8	12
Average sale price (US$/t)	170	.	150		.	800	30
Meat sale price (US$/t)		1000			1000		
Animal weight (kg)		530			580		
Annual health costs (US$/animal)		10			30		
Annual cattle nutritional requirements (per animal)							
Energy (megacalories x 1000/yr)		3.05			2.4		
Protein (t/yr)		0.03			0.04		
Nutritional composition of pastures							
Energy (megacalories/kg)		2			1.8		
Protein (kg of protein/kg dry matter)		0.2			0.1		
Dry matter (%)		20			20		

Note: Blank cells indicate “not applicable”.

Table 4

Prioritized hydrologic response units under current land use in Palahurco watershed, Ecuador

HRU code #	Area size (ha)	Sediments over 10 years		% contribution to total sediments produced in micro watershed
		(t ha^{-1})	(t)	
11	12	398	4777	10.1
12	18	421	7588	16.1
18	20.6	187	3857	8.2
19	14.3	186	2673	5.6
20	31.3	188	5912	12.5
29	18	425	7655	16.2
All critical HRU	**114.2**	**301.4**	**32462**	**69.1**
Non-critical HRU	1202.8	17.2	14523	30.9
Entire watershed	1317	35.6	46985	100

Table 5

Comparing land-use scenarios for sediments and streamflow impacts in prioritized hydrologic response units of the Palahurco watershed, Ecuador[a]

Scenario	Infiltrated water (m^3)[b]	Total water yield (m^3)	Sediment production (t)
With-PES (current conservation scenario)	96,898,020	102,903,333	46,989
Without-PES (hypothetical land-clearing scenario)	96,374,597	102,988,083	72,272
Marginal absolute change (on 92 ha) (in t)	-523,423	84,750	25,283
Relative change (6% of watershed area) (in %)	-0.5%	0.08%	53%
of which critical HRUs (20.6 ha) absolute	-120,206	16,796	8587
of which critical HRUs (1.6% of area), %	23%	20%	34%
of which critical HRUs (10.4 ha) absolute	-60,686	8,480	4332
of which critical HRUs (0.9% of area) %	12%	10%	17%
of which critical HRUs (28.6) absolute	-165,923	24,340	5282
of which critical HRUs (2.1% of area) %	32%	29%	21%
of which critical HRUs (26.9) absolute	-156,060	22,894	5018
of which critical HRUs (2.0% of area) %	30%	27%	20%
of which other HRUs (4.9 ha) absolute	-20,548	12,242	2061
of which other HRUs (0.3% of area) %	4%	14%	8%

[a] The results correspond to the accumulated results for a simulation period of 10 years.

[b] Runoff water is excluded in this calculation. Water production = Lateral flow + Groundwater

Table 6

Net present value of income (in US$) for a typical farm with and without PES in Palahurco, Ecuador[a]

Discount rate	Hypothetical "business as usual" scenario[b]	Hypothetical "conservation without PES" scenario[d]	Current "conservation with PES" scenario[c]
5%	$48,349.12	$35,190.81	$37,016.23
15%	$29,848.15	$23,052.37	$24,238.80
20%	$24,471.48	$19,432.42	$20,423.52
Water production (m^3) [e,f]	1,637,125	1,644,048	1,644,048
Sediment production (ton) [f]	1414	1103	1103

[a] The simulated period is 10 years.

[b] Continued land clearing at 0.5 ha yr^{-1} without PES, no land-use restrictions

[c] With-PES scenario (without deforestation but with payments for conserving on-farm páramo and forest)

[d] Neither receiving PES nor deforesting

[e] Water production = Lateral flow + Groundwater

[f] All environmental service values are at farm level

Table 7

Prioritized hydrologic response units in the Mishquiyacu watershed (Peru) under the “business as usual” scenario

HRU code #	Area size (ha)	Sediments over 7 years		% contribution to total sediments produced in micro watershed
		(t ha^{-1})	(t)	
18	9.1	903	8,217	16.5
02	5.8	500	2,902	5.8
06	0.9	396	356	0.7
09	0.9	323	291	0.6
12	1.2	261	313	0.6
22	2.2	374	823	1.7
03	1.9	292	555	1.1
19	1.1	239	263	0.5
Total	**23.1**	**3,289**	**13,720**	**27.6**

Table 8

Integrating environmental and socioeconomic assessments of land-use scenarios in Mishciyacu watershed, Peru

Indicator	Land use system			
	Traditional (“business as usual”)[a]	Traditional[a] with live barriers	Shade-grown coffee planted on pastures	Forest planted on pastures
NPV (US$), 10 year horizon[b]	12,949	9,668	32,057	967
Marginal income[c]	n.a.	-3,281	19,108	-11,982
Initial cash investment (US$)	9	13	176	470
Sediments ($t\ ha^{-1}$)	21,247	10,623	11,766	10,620
Marginal sediments (%) [c]	n.a.	-50	-44	-50
Water production (m^3)	2,707,711	2,707,711	2,395,627	2,334,858
Marginal change (%) [c]	n.a.	0	-11	-14
Use of work days	5,682	5,807	10,071	5,266
Marginal change [c]	n.a.	125	4,389	-416

[a] Burning-maize-pastures land-use cycle

[b] Includes labor cost. Discount rate = 15%. Converted from Peruvian *soles*; exchange rate 1 US$ = 3 soles (January 2009)

[c] Vis-à-vis baseline of traditional slash and burn land-use sequence

n.a. – not applicable

Table 9

Unit costs of reducing sediment yields under different land-use scenarios in Mishquiyacu watershed, Peru

Parameter	Current scenario, with live barriers	Shade-grown coffee	Forest plantation
Cost of reducing one ton of sediments (US$/t)	0.36	1.16	1.10
Cost of reducing erosion on one hectare of land (US$/ha)	16.6	47.4	51

Figures

Figure 1. Simulated Flow Duration curve for Palahurco watershed, Ecuador

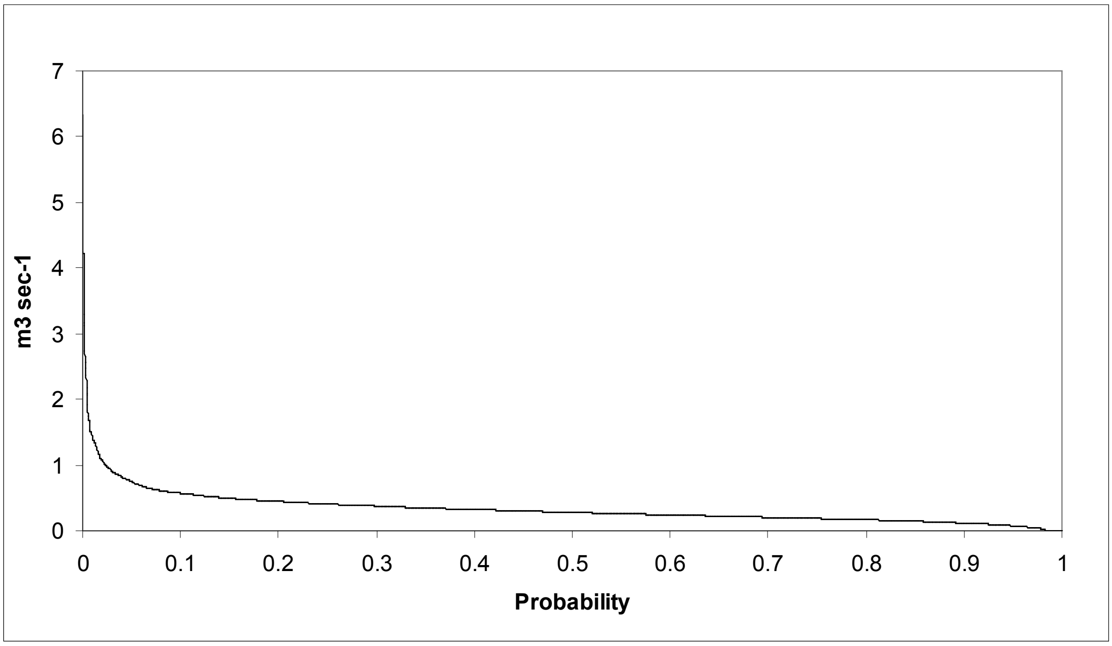
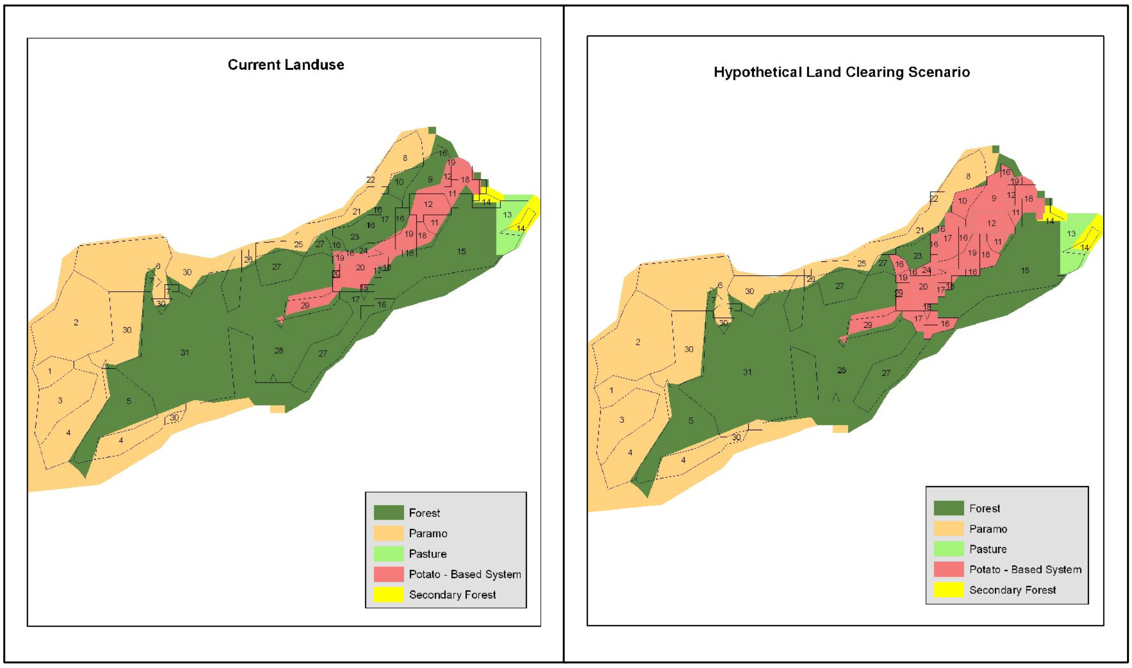


Figure 2

Hypothetical land-clearing scenario in Palahurco watershed in selected HRUs. Ten-year projection of ‘without PES’ resumed land-use expansion.



Dear editors:

First, as authors of this manuscript we thank you for your pertinent and insightful comments. We apologize for the delayed submission of this revised version and we hope that this includes all your comments and suggestions.

Best regards,

Marcela Quintero, Sven Wunder, and Ruben D. Estrada

Dear editors:

First, as authors of this manuscript we thank you for the last comments that encourage us to discuss more in depth the methodological approach and to improve the article. We have made major effort to take them comprehensively into account. As a result, this new version of the manuscript contains punctual but many revisions throughout the paper. Please find below our detailed replies to your comments and suggestions,

Best regards,

Marcela Quintero, Sven Wunder, and Ruben D. Estrada

REPLY TO REVIEWERS AND EDITORS

Reviewer comments fell basically in three areas:

1. SWAT VALIDITY: It was questioned to what extent SWAT was a scientifically accurate and cost-effective way of analyzing our two cases. We have now added a new sub-section in the "Discussion" section, answering these problems in a fairly detailed and explicit way (respecting space constraints). We have explained in what cases SWAT estimates might differ from measurements (incl. because of limitations in the latter), under what circumstances SWAT is recommendable, and it what cases much simpler (lumped, non-distributed) models would be preferable due to the lower data requirements and costs.

2. SCIENTIFIC PRESENTATION & SENSITITIVTY ANALYSIS: In principle, we can see that it would be both possible and interesting to investigate further into the impact of specific critical variables and assumptions through sensitivity analysis. Unfortunately, the complexity of the SWAT analysis, and some logistical problems (the main author is now based in Lima whereas the original analysis was done out of CIAT-Cali) would mean that additional full model calibrations at this late stage would be very challenging to implement – at best, they would cause further significant delays in the article. We thus abstained from this, but explained instead in greater detail how the calibration was done (which includes a kind of "ex-ante sensitivity analysis"), what variables in particular were used for the corresponding calibration of the model, and it what range they were varied in the process. This should hopefully add to the transparency in the presentation of our scientific method.

3. HINTS FOR PRACTITIONERS: We were asked to add some guidance for the reader that is looking for advice whether to implement our method in his or her study case. Is this a widely replicable, practical methodology, or is it eventually constrained to science lab experiments? Throughout the last two sections, we have now added some more practically oriented remarks, including about the possible SWAT pitfalls and data challenges. We have also added some quantitative

estimates on how much it has approximately cost to carry out the analysis in different sizes of watersheds.

4. To make place for the new elements required by the reviewers, the entire text was reviewed again, and shortened to make for a more compact presentation.

5. In addition all suggested editions done by the Special Issue editor were considered and only few of them were not applied such us:

   `p. 26 line 8.  "[robust] discrimination" perhaps?`

   `p. 26 line 11. insert "habitat" before "conservation`