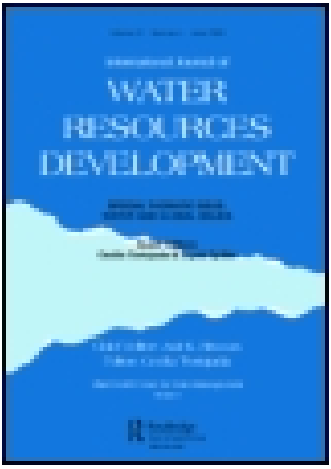

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Water Resources and Regional Land Cover Change in Costa Rica: Impacts and Economics

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ABSTRACT *This paper evaluates the relationships between sediment production, economic losses and land cover change in Costa Rica. Results suggest that the relationship between sediment production and the deterioration of land resources in Costa Rica is less understood than expected, and that new sediment monitoring systems must be implemented in order to be able to detect the overall impact of tropical deforestation and habitat fragmentation on sediment production. The results also indicate that the correlation between economic losses due to flooding and landscape fragmentation can be counteracted by promoting 'payment for environmental services' initiatives; a new concept that takes into consideration the role that tropical ecosystems play in protecting the environment.*

Introduction

Water resource management is becoming a source of conflict in Costa Rica. Agricultural, industrial and domestic demands, hydropower generation, the demand for clean drinking water coupled with fast population growth, and unsustainable land use and land cover change (LUCC) practices, are all major socio-economic forces competing for a share of the country's water resources (Sanchez-Azofeifa & Quesada-Mateo, 1996). Already at the beginning of the new century, the demands of, and the interactions between, these forces are resulting in a new sense of urgency to effectively manage currently uncontrolled urban development, population growth and an expanding tourism industry (Rosero-Bixby & Palloni, 1998; SeShazo & Monestel-Vega, 1999).

Costa Rica is a country rich in hydropower resources and by the early 1990s only 13% of the total available national hydropower potential was being used; an amount that accounted for 90% of the total demand for electricity in the country by 1995. The Costa Rica Electricity Institute (Instituto Costarricense de Electricidad) (ICE) estimates that the country has a total hydropower potential of 8742 MW for projects capable of producing 20 MW or more; with an additional 1500 MW identified for projects capable of producing less than 20

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MW. Since 1950, hydropower generation capacity in Costa Rica has increased 20 times, and initial projections of a sustained energy demand growth rate of 6% per year increased to between 8% and 9% per year by the end of the century (Quesada-Mateo, 1990). In fact, between 1972 and 1992, total energy consumption for Costa Rica more than doubled from 41 646 terajoules (TJ) to 84 172 TJ. During this time, energy consumption per capita changed from 24.1 TJ to 26.6 TJ (per 1000 persons) and public investment in energy generation changed from 16.6% to 45.1% of the total amount of the gross national product dedicated to energy generation. By 1992, the external debt of the energy sector represented 14.4% of the national external debt and 17.8% of the internal debt (Costa Rica, 1995).

The dependency of Costa Rica on hydropower generation is jeopardized by uncontrolled LUCC processes that are contributing to the environmental degradation of the country's water resources (Solorzano *et al.*, 1991). One of the most important LUCC-associated problems facing Costa Rica is the accelerated environmental damage to its drainage basins from the effects of deforestation and forest fragmentation (Sanchez-Azofeifa, 1996). Even though it is estimated that 64% of the country has potential for forestry use and forest protection, by 1997 only 44% of the country was covered with forest (Castro-Salazar & Arias-Murillo, 1998). In addition, Sanchez-Azofeifa *et al.* (2001) have reported that the deforestation rate between 1986 and 1992 remained in the order of 4% per year, and that by the end of 1992 the country presented severe forest fragmentation nation-wide.

These figures pose important questions relating to the linkages that exist between the conservation of drainage basins and the management of water resources in Costa Rica. Important questions that must, therefore, be addressed include the following. (1) Is the current nation-wide sediment monitoring system in the country capable of detecting basin response (e.g. sediment production) as a function of LUCC? (2) From a landscape fragmentation point of view, which basins have the greatest long-term recuperation potential and should, therefore, be targeted to receive the largest portion of current scarce financial resources? (3) What types of economic measures will have the most potential to result in the recuperation of the landscape, and promote, at the same time, the sustainable management of water resources in the country? In this paper the authors try to answer these questions by first documenting, and later analysing, landscape fragmentation indices vs. economic losses and sediment production in Costa Rica. They conduct this study on 12 of the 33 drainage basins in Costa Rica (Figure 1). These drainage basins were selected because they have the most comprehensive and long-term sediment production statistics (sediment record length is 20 years on average). Additionally, these basins represent areas with existing or proposed hydropower plants (Table 1).

LUCC and Watershed Response in Costa Rica

Hydropower generation is a resource that is strongly affected by LUCC in Costa Rica. Previous studies by Mojica (1972), Rodriguez (1989) and Sanchez-Azofeifa & Harriss (1994) have documented the relevance of the LUCC process at the watershed level in Costa Rica. These studies analyse the linkages between LUCC and sediment transport, deposition and the increased costs associated with hydropower generation. The Reventazon drainage basin, the home of several

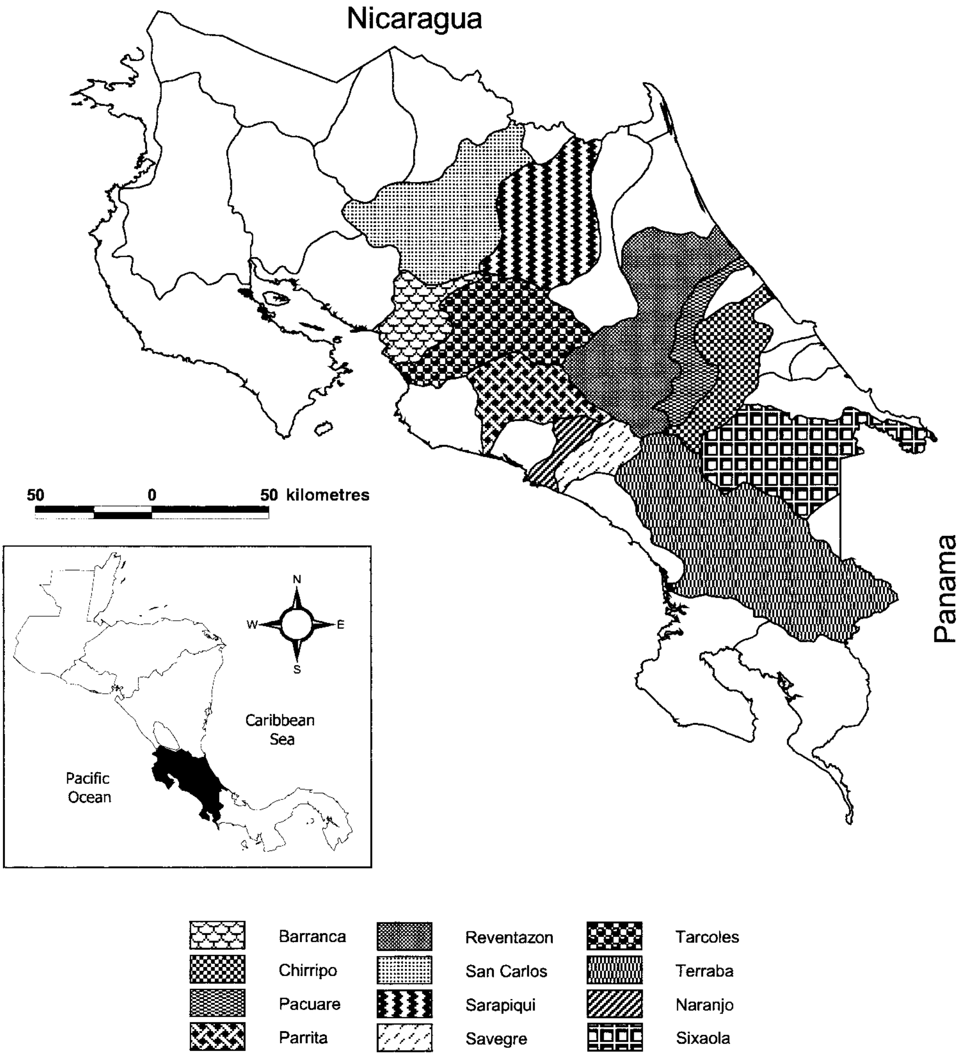

Figure 1. Location of selected basins. Twelve of 33 drainage basins were selected because of the high potential for hydropower generation.

hydropower plants, represents a specific example of the linkages between these factors. Here, Sanchez & Harriss (1994) documented the fact that the La Troya watershed, a sub-basin under intensive agricultural practices, with 34% of crop agriculture and 43% of pasture on slopes greater than 30%, produced 64% more suspended sediment in stream discharge per year than did an adjacent forest watershed.

LUCC processes, such as the enhanced erosion rates from shifting agriculture and deforestation, add significant costs to downstream hydropower generation due to losses in electricity generation due to sediment accumulation. Soil erosion also increases the costs of hydropower reservoir management through siltation (Jansson & Rodriguez, 1992). In the Reventazon drainage basin, for example, the Cachi reservoir needs to be flushed once a year in order to remove sediment accumulated from the upper part of the basin. During 1992, annual losses

Table 1. Drainage basins in Costa Rica ranked as a function of the hydropower generation capacity

Watershed name (code)	Power (MW)	Energy (GWh)	Basin area (km^2)	1991 forest cover (%)	1991 sediment production (tonnes)
Terraba (TE)	2 607	10 944	4 991	32.6	1 356 547
Sixaola (SX)	1 273	8 012	2 457	85.4	2 415 916
Pacuare (PC)	940	4 859	833	73.2	340 217
Reventazon (RE)	640	3 534	3 033	48.7	819 748
Savegre (SV)	487	2 497	592	67.8	144 606
Tarcoles (TA)	372	1 942	2 128	12.5	944 811
Chirripo (CH)	377	1 900	1 476	42.8	537 014
Sarapiqui (SA)	332	1 711	2 293	41.7	186 488
San Carlos (SC)	283	1 667	2 754	23.3	730 095
Parrita (PA)	375	1 618	1 294	23.0	157 338
Naranjo (NA)	174	1 017	375	44.3	100 923
Barranca (BA)	84	318	919	9.8	574 470

attributable to sedimentation at the Cachi reservoir amounted to $287 000 (US dollars throughout); an amount equivalent to 13% of the annual production value. Of these losses, $169 600 was related to maintenance costs due to sedimentation, $38 200 was related to losses due to the reduction of energy attributable to diminished flow at the dam (and accounted for as an increased demand for fossil fuel and electricity imports) and $74 400 was due to losses from work stoppages during plant dredging (an average of 15 days per year) (Rodriguez, personal communication).

Although exact figures are not available, erosion and sedimentation processes attributed to LUCC also affect water resources in other areas of the country. In the Grande de Terraba drainage basin, for example, where a large hydropower project (Boruca) is under consideration, new pasture areas (created principally by the deforestation of primary forest) have increased on average 16% per year during the last 40 years (Sanchez-Azofeifa, 1996). This basin now suffers from a sediment production rate of 180 tonnes per year (average over 20 years), the highest in the Pacific region. The Grande de Tarcoles drainage basin is subject to urbanization as a result of the expansion of San Jose and adjacent satellite cities. Sediment production here is the second highest in the region (154.8 tonnes of sediment per year). Sediment problems affecting water-collecting sites at the Orosi reservoir have produced critical shortages of drinking water for the urban population of San Jose and Cartago. More than 500 000 people depend on drinking water from inter-basin water transfers from the Orosi reservoir in the Upper Reventazon drainage basin. According to Costa Rica's Drinking Water Institute this figure represents 55% of the water requirements for the San Jose metropolitan area (Sanchez-Azofeifa & Quesada-Mateo, 1996). Additionally, at the Sixaola drainage basin, where sets of chain hydropower plants are under consideration, annual sediment production has been estimated to be 360 tonnes per year (ICE, 1992).

LUCC, and its relationship to soil erosion and sediment production, clearly plays an important role in Costa Rica's economy, and has a significant impact on the country's overall productivity. In the last 20 years, Solorzano *et al.* (1991)

have estimated that soil depreciation amounts to almost 10% of Costa Rica's annual agricultural production. These authors indicate that even though pastures are the largest component of agricultural land use at the national level, they contribute less to total erosion than do annual crops. The study estimates, for example, that pasture lands erode at an estimated average rate of 33.8 tonnes per hectare per year, compared to the 289 tonnes per hectare per year for annual crops. This resulted in the conclusion that 2.2 billion tonnes of soil eroded from the landscape over the period 1970–89 (61% from annual crops, 33.8% from pasture land and 5.1% from permanent crops). These authors also state that total soil losses account for between 6.5% and 13.3% of the annual value lost from the gross national product associated with agriculture activity.

Materials and Methods

For this study remote sensing-derived forest cover information, obtained through the interpretation of four Landsat Thematic Mapper 5 satellite scenes acquired in 1991, was utilized (Figure 2). Images were classified to forest/non-forest classes using a minimum mapping unit of 0.03 km^2 and the overall accuracy of these forest classes is estimated to be 91%. Additional information on the generation of this database can be found in Sanchez-Azofeifa (1996) and Sanchez-Azofeifa *et al.* (2001). For each of the selected drainage basins the following landscape fragmentation indices were extracted using FRAGSTATS-ARC: number of forest islands; forest cover density; total forest cover; patch density; and mean forest patch size (McGarigal & Marks, 1994). In addition to further establishing and comparing the degree of fragmentation in the basins, the landscape division metric proposed by Jaeger (2000) was used. The degree of landscape division (D) is the probability that two random points in the landscape do not belong to the same patch:

$$D = 1 - \sum_{i=1}^{n} \left(\frac{A_i}{A_t} \right) \tag{1}$$

where A_i is the area of patch i and A_t is the total area. A landscape division of $D = 0$ means that the probability of two points in the landscape being connected is 1 (1-D). As landscape division approaches 1, there is high division of the landscape and possibly high fragmentation.

Annual suspended sediment production for each of the 12 drainage basins selected was provided by ICE (1992). These suspended sediment data sets represent the total production of sediment for the 1991 hydrology year (May 1990 to April 1991), which is concurrent with the derived land cover fragmentation statistics. ICE's sediment monitoring programme is part of a larger Central American hydro-meteorological monitoring programme. The sampling procedure followed by ICE is sporadic rather than systematic, and follows the inter-agency sedimentation project procedures set out under the US Water Resources Council. A detailed description of ICE's methodology is available in Sanchez-Azofeifa (1993).

Information on economic losses was obtained from reported damage caused by flooding during the 1991 hydrologic year. These figures represent the total damage incurred, and primarily affected roads, bridges and housing. It should be noted that total damage, as a result of crop losses, is not systematically

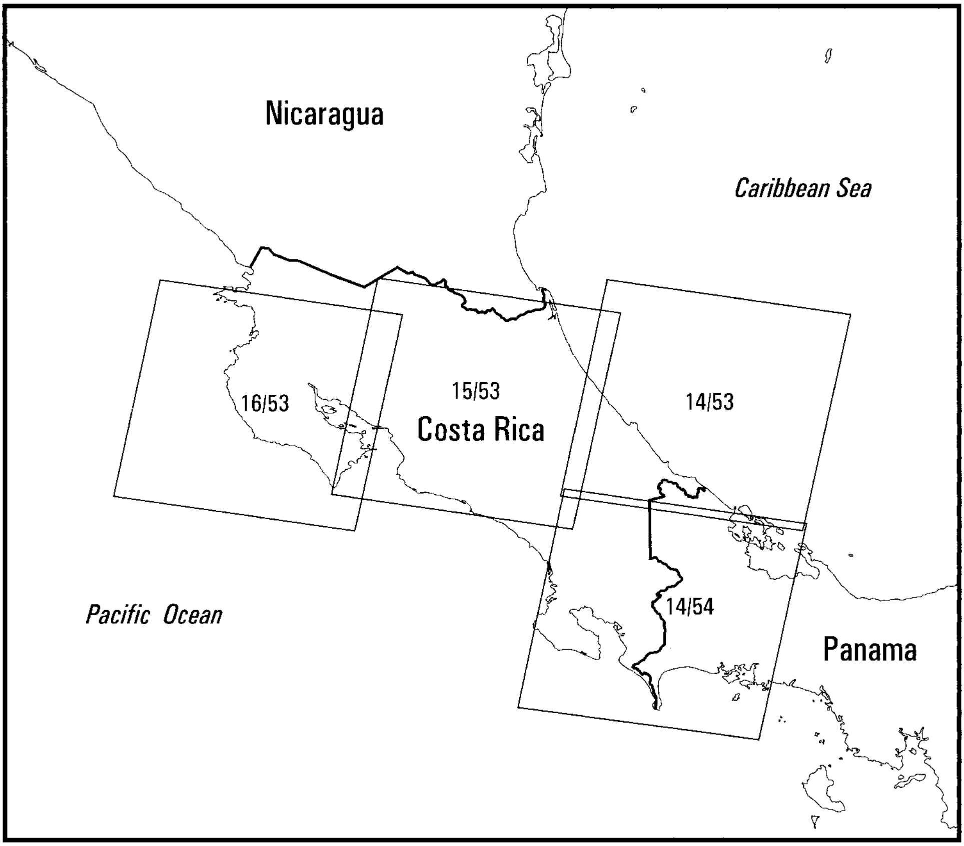

Figure 2. Path and row of Landsat Thematic Mapper 5 selected for the forest/non-forest study.

documented at the drainage basin level, only at national levels. Total economic losses are reported in US dollars, and this information was provided by several sources including the National Emergency Commission, the Ministry of Public Works and the Costa Rica National Insurance Institute.

The statistical analysis of the derived data sets was implemented using paired relations among all of the variables measured (landscape fragmentation indices, sediment production and economic losses). Linear and quadratic regression analysis was implemented using Mathematica 4.0 (Wolfram Research, 1999). A good linear or quadratic relation was accepted when the R^2 was greater than 0.70, and quadratic relationships were chosen over linear ones when the quadratic R^2 values were higher than the linear R^2 values for the same variables.

Finally, information on the spatial distribution of private lands participating in incentive programmes for the conservation of tropical forests was used (Castro-Salazar & Arias-Murillo, 1998). The Costa Rica National Forest Financing Fund (FONAFIFO) produced this data set. The FONAFIFO programme of environmental service payments is intended to pay private land holders for supporting the maintenance or development of land uses that increase forest cover: timber plantations, sustainable forest management, reforestation, natural regeneration and conservation of primary forests (Busch *et al.*, 2000). These databases consist of the spatial location of the farm receiving payments for environmental services as provided by tropical ecosystems. These payments are part of a comprehensive programme developed to promote tropical forests under the umbrella of the Kyoto Protocol's Clean Development Mechanism and are divided into the following mechanisms: income tax credit; forest protection; forest management; and forest savings certificates.

Results

Table 1 presents the percentage of forest cover remaining for each drainage basin as per the remote sensing analysis performed. Main river headwaters draining into the Caribbean typically have the most remaining primary forest protection as compared to the watersheds draining to the Pacific Ocean. These patterns of remaining forest are important to the hydropower generation potential that Caribbean watersheds have presently, and will have in the future. It is currently estimated, for example, that the Caribbean watersheds will hold more than 50% of all hydropower plants to be constructed in Costa Rica in the next few years. Table 1 also indicates that key drainage basins for hydropower generation and drinking water, such as the Grande de Tarcoles, Grande de Terraba, Sarapiqui and Reventazon, have less than 50% forest cover, with estimates of only 12.5%, 32.6%, 41.7% and 48.7% forest cover remaining within the total watershed area, respectively. Watersheds with little infrastructure development, such as the Pacuare and Sixaola, present the highest forest cover, 73.2% and 85.4% respectively.

These results permit the authors to rank the 12 most important drainage basins in the country as a function of their degree of forest fragmentation using path density as the key fragmentation variable for ranking (Table 2). Patch density was selected as the key indicator of landscape fragmentation, since the higher the patch density the higher the level of landscape fragmentation. Basins with the highest degree of forest fragmentation are: Grande de Terraba (patch density = 1.3), Parrita (patch density = 0.79), Naranjo (patch density = 0.52), Reventazon (patch density = 0.48) and Barranca (patch density = 0.44). Watersheds with less forest fragmentation are the Chirripo (patch density = 0.11) and the Sixaola (patch density = 0.09). The remaining basins can be considered to represent intermediate levels of fragmentation. In addition, path density presents a negative correlation against mean patch size ($R^2 = 0.83$) as an indication that drainage basins with low fragmentation have the higher forest islands (Figure 3).

Results using landscape division are interesting since they help to provide a clear understanding of the potential capacity of a specific landscape to recuperate after experiencing a strong fragmentation process. When landscape division for the selected drainage basins is compared against forest density in the context of percolation theory (Figure 4), and considering the theoretical point of percolation will occur when forest density is less than 0.5928 (Gardner & O'Neill, 1991), the authors' results indicate that the Barranca, Grande de Tarcoles and Parrita drainage basins are in areas where the forest cover can be considered highly isolated and fragmented with little chance for recuperation. On the other hand, drainage basins such as Grande de Terraba, San Carlos, Reventazon and Sarapiqui are in areas considered to present a high level of forest fragmentation but with a good chance for recuperation. Additionally, drainage basins such as

Table 2. Ranking of selected drainage basins as function of forest fragmentation

Watershed name	Patch density (numbers of patches/100 km^2)	Mean patch size (km^2)	Landscape division	Number of forest patches
Terraba (TE)	1.30	25.1	0.69	1 567
Parrita (PA)	0.79	29.2	1.00	781
Naranjo (NA)	0.52	88.9	0.22	84
Reventazon (RE)	0.48	100.6	0.71	1 138
Barranca (BA)	0.44	22.3	0.98	270
Tarcoles (TA)	0.39	32.4	0.84	478
Sarapiqui (SA)	0.37	111.7	0.63	684
San Carlos (SC)	0.35	66.5	0.73	950
Pacuare (PC)	0.33	224.3	0.15	123
Savegre (SV)	0.22	311.1	0.33	115
Chirripo (CH)	0.20	210.6	0.92	83
Sixaola (SX)	0.09	985.6	0.06	84

the Chirripo, Savegre, Pacuare and Sixaola could be considered to suffer from little fragmentation, while Naranjo could be considered to represent little fragmentation but with low forest cover.

The results also indicate that sediment transport is correlated to the total forest cover at the basin level ($R^2 = 0.85$) (Figure 5). This relationship suggests a general trend in the country: higher sediment production in low forest cover basins (e.g. Barranca and Tarcoles) and low sediment production in well-protected watersheds (e.g. Pacuare and Savegre). When sediment production is analysed using

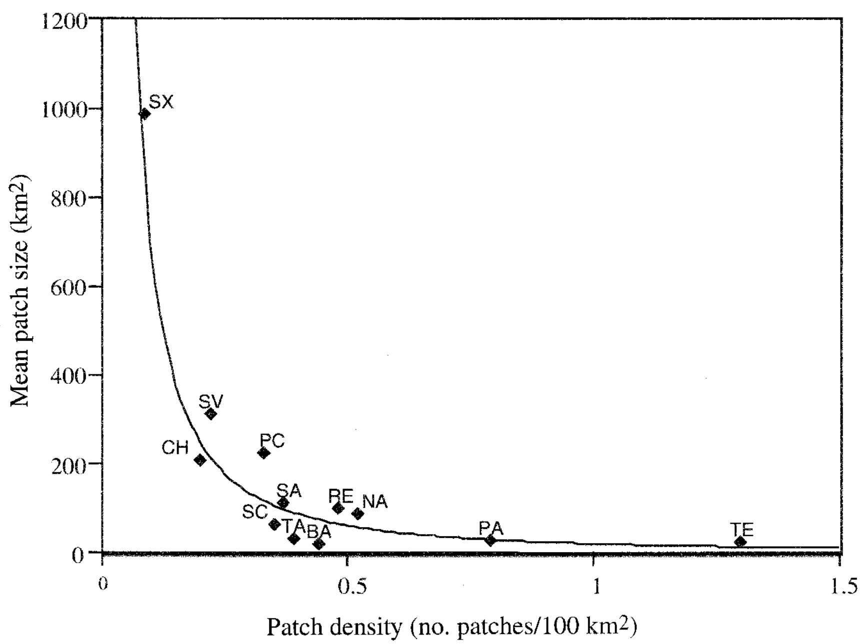

Figure 3. Correlation between mean patch size and patch density in Costa Rica (1991) at the drainage basin level ($R^2 = 0.83$).

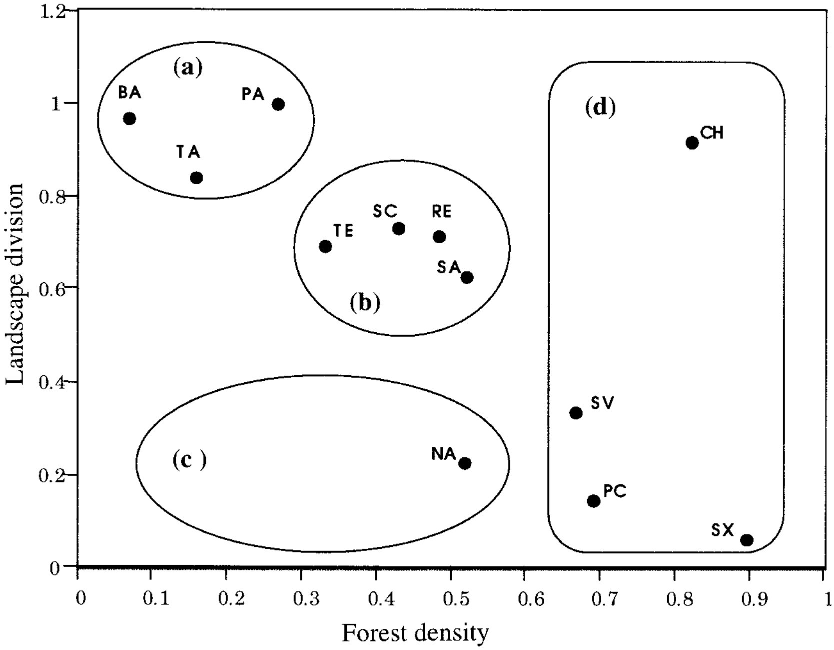

Figure 4. Landscape division as a function of forest density for the selected drainage basins. (a) Drainage basins with high fragmentation and few restoration options. (b) Drainage basins with some potential for recuperation. (c) Drainage basins with high potential for recuperation. (d) Drainage basins with little landscape fragmentation.

the selected landscape structure statistics, the correlations between sediment production and patch density ($R^2 = 0.19$), landscape division ($R^2 = 0.25$), number of patches ($R^2 = 0.36$) and forest density ($R^2 = 0.33$) are not statistically significant ($p < 0.01$). Some correlation is observed between sediment production and mean patch size ($R^2 = 0.73$) (Figure 6), indicating that higher sediment production is actually occurring in highly fragmented drainage basins with small forest patches.

Economic losses as result of flooding in the selected drainage basins are correlated with non-forest area ($R^2 = 0.75$) (Figure 7) and patch density ($R^2 = 0.85$) (Figure 8). Additionally, a weak correlation is observed between economic losses, the number of forest patches at the basin level ($R^2 = 0.63$) and mean patch size ($R^2 = 0.66$). Results indicate that drainage basins with higher fragmentation and non-forest areas, such as Terraba, Parrita and Naranjo, are most likely to continue to be impacted by economic losses as a result of extreme flooding events. These three drainage basins are also ranked first, second and third in terms of forest fragmentation nation-wide, indicating that severe landscape fragmentation is correlated to economic losses by flooding.

Over the past 10 years the Costa Rican government has invested a total of \$116 million promoting the concept of, and programmes related to, the payment of environmental services (Castro-Salazar & Arias-Murillo, 1998). The present authors' results indicate that only a fraction (512 km^2 or 40.2%) of the total land selected for payment of environmental services (1276 km^2) is in the 12 drainage

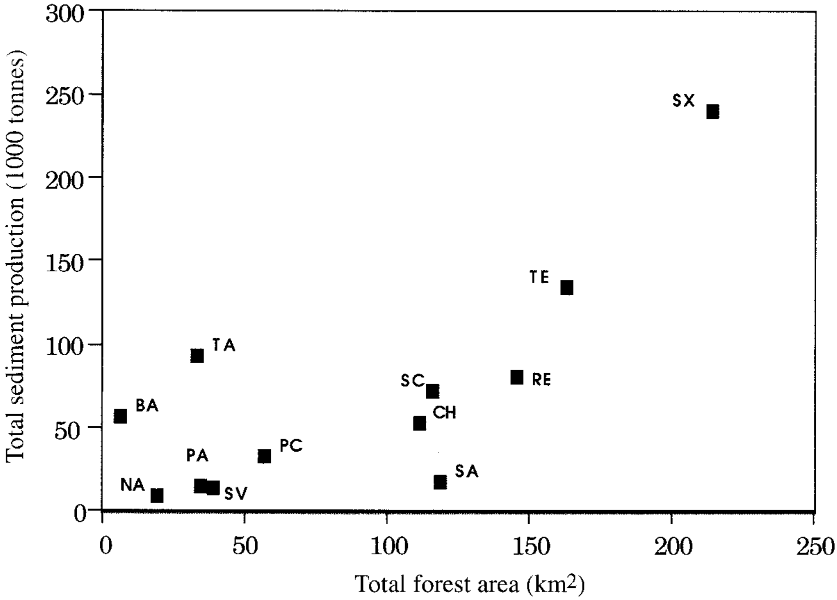

Figure 5. Sediment production as a function of percentage of forest cover. Sediment production is for the 1991 hydrologic year (May 1990 to April 1991) ($R^2 = 0.85$).

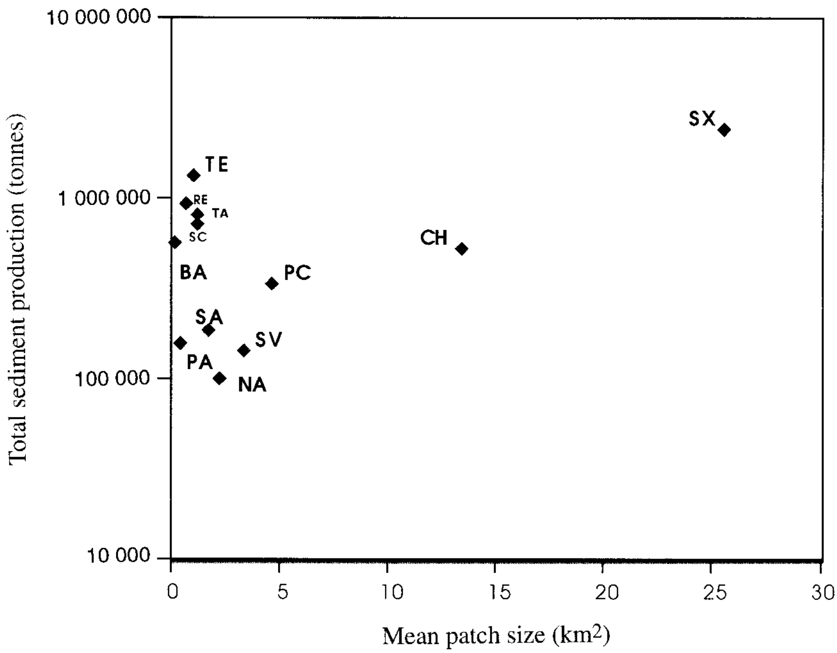

Figure 6. Total sediment production as a function of mean patch size. Sediment production is for the 1991 hydrologic year (May 1990 to April 1991) ($R^2 = 0.73$).

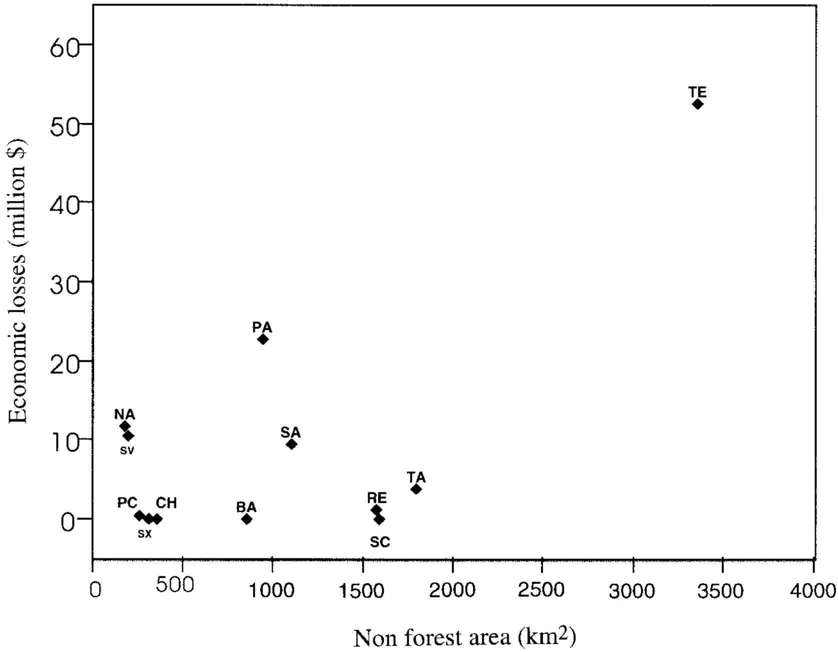

Figure 7. Economic losses (1990–91) vs. non-forested area for selected study sites in Costa Rica ($R^2 = 0.75$).

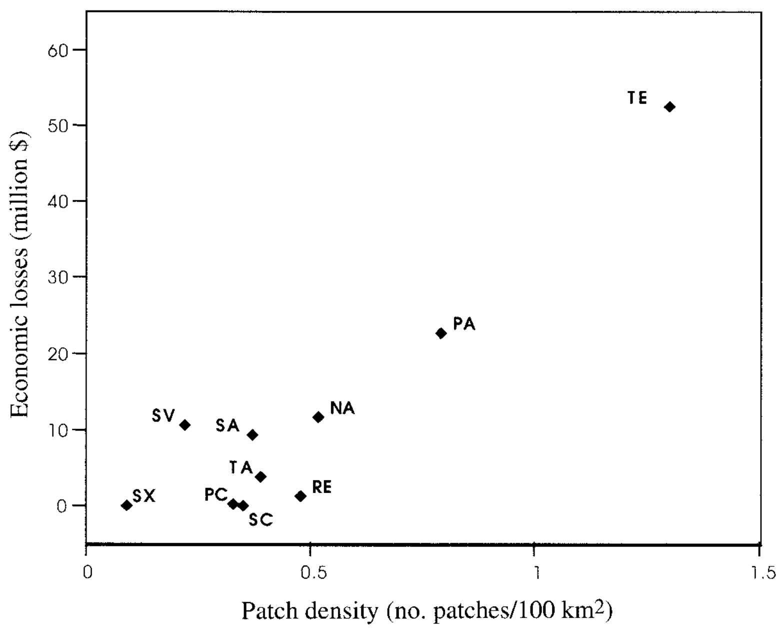

Figure 8. Economic losses (1990–91) as a result of flooding during 1991 vs. patch density of selected study sites in Costa Rica ($R^2 = 0.85$).

basins studied in this paper. A desegregated analysis by incentive type indicates that investments are marginal across all protection types: income tax breaks (10%), promotion of forest management activities (4.1%), payment of forest savings certificates (9.5%) and the use of incentives to promote forest protection (16.5%) are almost non-existent for most drainage basins with high potential for hydropower generation and high sediment production.

Discussion

These results pose important questions that impact on the management of water resources in the 21st century in Costa Rica. (1) Why can current monitoring systems not detect trends between sediment production and the regional land cover change process in Costa Rica even though the level of landscape degradation is significant enough in most drainage basins for them to have distinct responses? (2) How can we take full advantage of landscape characterization techniques to better understand and prioritize selected drainage basins with a high degree of importance in terms of hydropower generation? (3) What kinds of new financial mechanisms must be implemented in order to achieve adequate sustainable water resources management, taking into consideration societal demands, and the need for development vs. the need to protect natural resources?

The lack of apparent trends shown by some landscape fragmentation indices can be related to the data collection procedures used by ICE (1992). ICE's sampling scheme is selective rather than intensive. Monthly and annual sediment estimates are based on sediment rating curves. These curves are developed from sporadic samples of suspended sediment concentrations, and from the discharge measured when the sample is taken. Suspended sediment samples are collected randomly, with 12 samples per year or sometimes fewer. Therefore, the methods developed by the Central American hydro-meteorological monitoring programme are not able to detect the drainage basin system's response to sediment transport as a function of land use and land cover change. Secondly, the lack of suspended sediment trends can be related to intra-basin storage. After erosional processes take place, sediment can be stored on stream-banks, gullies, forest roads, forest ditches and local slips. These geographic features all act as sediment storage elements, defined as the medium through which the transport processes act. In low-order channels stream transport has little opportunity to communicate short- and even longer-term changes in sediment supply, as a result of land cover change and hill slope processes, because of their high capacity for sediment storage. This transport process has been suggested by Meade (1969) and Dietrich *et al.* (1991) when they point out that observed sediment transport in many cases cannot be related to contemporary land cover change processes but are the result of a combination of facts (such as extreme events) linked to long-term sediment residence times at intra-storage elements in a watershed. For example, Meade (1969) suggests that the lack of sediment trends in selected drainage basins in the Atlantic region of the USA is a function of the average residence time of sediment in storage elements, when he explains the discrepancies between expected and observed changes in sediment loads due to land cover change. Meanwhile, Dietrich *et al.* (1991) indicated that sediment residence time in storage elements could average up to 100 years, even in low-order drainage basins. In summary, significant efforts must be implemented to continue with adequate monitoring systems on selected drainage basins. These monitoring systems must be continuous rather than sporadic. In those cases where it is not possible to implement a full-scale system for the country, a priority-based resource allocation process must be implemented that strongly focuses on the 12 drainage basins studied in this paper (Kozloff *et al.*, 1992). Unfortunately, globalization policies are not following this proposed scheme, and the long-term monitoring systems that have been used as a basic source of information are no longer in place or operational.

Quantifying changes in land cover and land use at the basin label is critical not only to conceptualizing sustainable water resources management policies but also to evaluating their success or failure over time. Currently, one of the major limitations of evaluating long-term policies is the lack of indicators at the landscape level that could provide decision makers with a regional picture of their success or failure. Lack of funding to support long-term landscape monitoring programmes by the various agencies involved in water resources management in the country is probably the main reason for this lack of information.

In the case of Costa Rica, the data indicate that there is not a statistically significant ($p < 0.01$) correlation between sediment production and selective landscape fragmentation metrics, though the trends observed pose a clear message: highly fragmented drainage basins are not only the main source of suspended sediment, but are also the ones suffering from higher economic losses as a result of extreme events. According to the authors' landscape division analysis, the most highly fragmented drainage basins are also posting higher economic losses and the greatest overall sediment production, and are least likely to be able to recuperate over the long term. New watershed management policies in Costa Rica therefore need to consider landscape fragmentation and its dynamics in order to be effective. The integration of landscape structure with the human, social and economic dimensions associated with land cover change is critical to the success of sound and sustainable land management policies. Unfortunately, and despite the significance of these findings, current policies do not take into consideration landscape fragmentation metrics as part of their strategies for watershed prioritization. Clearly, new policies for monitoring key watersheds in the country need to start taking into consideration LUCC dynamics and their imprint on the landscape if we want them to be successful in the years to come. Without taking these dynamics and their effects into consideration, mechanisms to control the impact of tropical deforestation and habitat fragmentation on water resource management, and the policies under which they are implemented, are not likely to succeed.

Current payments aimed at promoting forest protection under the Kyoto Protocol Clean Development Mechanism need to be extended to cover not only the aggregated value of carbon sequestration but also the role that watersheds play in providing drinking water and controlling soil loss. Current efforts and mechanisms implemented by FONAFIFO must start to address this important issue. Strategies for the allocation of incentives need to move away from the traditional approach of 'first come first served' and start focusing on investments in selected areas, such as those identified in this paper. This would not only help with carbon sequestration efforts but would also enhance the chance of landscape restoration, and minimize the economic losses suffered as a result of extreme events.

Conclusion

There are a number of conclusions that can be drawn from the comparison of observed sediment production, economic losses, allocation of payments for environmental services and contemporary forest cover change in Costa Rica.

(1) Deforestation and forest fragmentation increases in Costa Rica are having critical implications for the national watershed systems. This paper documents that most of the drainage basins in Costa Rica have less than 50% forest cover, and that forest fragmentation is highest in the Terraba, Parrita, Naranjo and Reventazon river basins, areas that are also correlated with substantial economic losses during extreme events.
(2) Since the same sediment monitoring system used in Costa Rica is also standard for the other five countries in the Central American region (with the exception of Belize), it is expected that the current sediment monitoring programme may be failing to detect important responses within the entire Central American watershed system to land cover change. Consequently, the problems associated with the use of a selective rather than intensive sampling methodology will affect the modelling of sedimentation in other Central American countries—thus limiting our ability to clearly and definitively evaluate its impact in a comprehensive manner.
(3) Researchers, watershed managers and decision makers must be made aware that available sediment data sets in Costa Rica are not accounting for the land cover change dynamics observed using remote sensing approaches. The lack of more detailed information on the linkage between sediment production and land cover change prevents decision makers from better understanding the different forces that are affecting sediment transport and the erosional processes in the country.
(4) The current monitoring programme, a programme selective rather than intensive in nature, is designed to produce broad estimates of sediment production, but is not designed to show regional or temporal sediment production trends. Erosional processes in Costa Rica occur in very localized areas, such as in high-relief and other vulnerable areas, and their response to climatic or land use change processes cannot be detected with the selective sampling techniques currently in use.
(5) The authors have found that there is an important correlation between landscape fragmentation and economic losses at the watershed level in Costa Rica. They have found also that some of the drainage basins with higher economic losses are also watersheds with highest sediment production. These are, therefore, areas where significant mitigation and restorative efforts need to be undertaken if recuperation is to be facilitated.
(6) New policies aimed at controlling deforestation and habitat fragmentation need to start looking into the possibility of integrating the value of services provided by tropical ecosystems at the watershed level (e.g. production of drinking water). Integrated with current programmes for the payment for environmental services, these policies need to encourage, on a priority basis, the sustainability and recuperation of forest in selected drainage basins; not just in conservation areas.
(7) Furthermore, new approaches aimed at achieving sustainable water resources management in the country need to use complex systems approaches. For example, a better and more effective allocation of scarce

resources could be attained if techniques such as 'micro-targeting' were used. Micro-targeting is a maximization technique that ranks land parcels for the purposes of channelling public resources based on parcel-specific measures. This is in contrast to 'regional targeting' approaches, where the unit of attention is a major land resource area (Kozloff *et al.*, 1992). Since the allocation of the resources supporting the payment of environmental services is based on payments to small landowners, prioritization based on patch density and number of patches, in combination with micro-targeting, can be used as a good prioritization solution during the optimization process of a watershed. This combination can help to achieve more efficient and balanced allocations of incentives for the conservation of tropical forest in the context of water resource management. The linkage between landscape structure and micro-targeting in the context of sustainable management of water resources is an issue that requires further exploration.

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