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Integrity and isolation of Costa Rica's national parks and biological reserves: examining the dynamics of land-cover change

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Abstract

The transformation and degradation of tropical forest is thought to be the primary driving force in the loss of biodiversity worldwide. Developing countries are trying to counter act this massive lost of biodiversity by implementing national parks and biological reserves. Costa Rica is no exception to this rule. National development strategies in Costa Rica, since the early 1970s, have involved the creation of several National Parks and Biological Reserves. This has led to monitoring the integrity of and interactions between these protected areas. Key questions include: "Are these areas' boundaries respected?"; "Do they create a functioning network?"; and "Are they effective conservation tools?". This paper quantifies deforestation and secondary growth trends within and around protected areas between 1960 and 1997. We find that inside of national parks and biological reserves, deforestation rates were negligible. For areas outside of National Parks and Biological reserves we report that for 1-km buffer zones around such protected areas, there is a net forest gain for the 1987/1997 time period. Thus, it appears that to this point the boundaries of protected areas are respected. However, in the 10-km buffer zones we find significant forest loss for all study periods. This suggests that increasing isolation of protected areas may prevent them from functioning as an effective network.

Keywords: Costa Rica; Tropical deforestation; National parks; Biodiversity conservation

1. Introduction

The loss of biodiversity may be the single most important consequence of global environmental change driven by land-use and land cover change. Finding relatively undisturbed ecosystems, as well as seeking a place for biological resources within human-dominated ecosystems, will be increasingly difficult as the size and resource demands of the human population continue to increase. Finding a balance between the twin needs for production and conservation will require comprehensive and fair policies, along with sound monitoring for implementation of agreements and assessment of policy goals (Daily and Ellison, 2002). Monitoring will not only track global and regional deforestation trends, but will also permit more spatially disaggregated analysis of regional landscape transformation and conservation policies.

Costa Rica's history exemplifies the tension between economic development and environmental conservation. While reported deforestation rates vary depending on the assumptions used by different analysts (Sánchez-Azofeifa, 1996), there is agreement that the country has had one of the highest tropical deforestation rates in the world. That rate averaged in the vicinity of 3.7% from the early 1970s until the early 1990s before dropping to less than 1.5% at the end of the twentieth century (Castro-Salazar and Arias-Murillo, 1998; FAO, 1990; Sanchez-Azofeifa et al., 2001). The tension arises from

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the fact that many population sectors derived benefits from this pattern of land use. From the Spanish arrival until the end of the 1950s and beginning of the 1960s, thousands of hectares of forest were converted to cropland and pasture (Sader and Joyce, 1988). Official policies prioritized demographic growth and new agricultural production systems (Harrison, 1991; Solorzano et al., 1991; Rosero-Bixby and Palloni, 1998; Sader and Joyce, 1988; Sanchez-Azofeifa, 2000; Sanchez-Azofeifa et al., 1999). Thus, as indicated in the national Strategy for Sustainable Development (ECODES), if 50-year land-use/land-cover trends had continued, primary forest commercial timber would have been depleted by 1995 (Quesada-Mateo, 1990).

However, the trends changed. While precise knowledge of why this occurred will require more research, there are some clear candidate factors. Econometric analysis of deforestation over space and time suggests that both reduction of forest stocks on productive lands and changes in development strategies were significant factors (Kerr et al., 2000). Consider that some land in Costa Rica is productive for coffee, while other land is not. Clearing may be rapid on good coffee land, but when that is cleared the deforestation rate is likely to fall. Additionally, production and employment that does not involve forest clearing can reduce deforestation pressure. Urban population and employment have increased, as have both the attention given to and the revenue derived from eco-tourism. The former draws people away from forest clearing, while the latter creates direct monetary returns from the conservation of intact forest, and can even lead to reforestation.

The government has taken an active role in changing development strategies. Steps taken by government bodies include the establishment and consolidation of a national park system, limited programs promoting sustainable management of tropical forests, and financial compensation of private landowners for environmental services derived from their land (Castro-Salazar and Arias-Murillo, 1998). Public payments for environmental services in Costa Rica are estimated to have totaled over $115 million dollar over the past 10 years (Heindrichs, 1997).

Given such a significant public investment, there is a clear need for understanding how these areas have fared, how they interact, and whether they are effective conservation tools. Our analyses are not sufficient for conclusions regarding the latter. However, they do indicate that National Parks and Biological Reserves may lower local deforestation rates, as to this point these areas have fared quite well. Further, our analyses suggest that ecological services requiring a park network appear threatened, and the spatial linkages between parks are threatened by land-cover change.

Specifically, this paper addresses the following questions: (1) what is the status of protection of native habitats in Costa Rica? (2) what are the contemporary (1986–1997) rates of deforestation within protected areas' boundaries? (3) what are the long-term (1960–1997) rates of tropical deforestation in areas surrounding national parks and biological reserves? (4) what are the long-term deforestation rates in proposed biological corridors? and (5) given the current level of degradation of the proposed corridors, would they allow for connectivity between parks?

2. The conservation areas

In response to rapid land-cover change during the first part of the twentieth century, over the past 30 years the Costa Rican government has been creating a comprehensive protected areas system (Table 1). Between 1974 and 1978 the area covered by National Parks and Biological Reserves expanded from 3 to 12% of the national territory (Table 1). Currently, Costa Rica has 25% of the national territory dedicated to conservation, which involves the prohibition of productive activities that could damage renewable or non-renewable resources (Castro-Salazar and Arias-Murillo, 1998).

Though the current conservation network is extraordinary in extent, it does not cover all of the different

Table 1
Establishment dates and characteristics of 132 protected areas in Costa Rica

Category	Number	Area (km^2)	No./decade					% Of National Territory
			Before 1960	60s	70s	80s	90s	
National Parks	24	5415	1	1	11	1	10	10.6
Biological Preserves	9	396	–	–	5	2	2	0.8
National Wildlife Refuges	39	1810	–	–	–	9	30	3.5
Forestry Reserves	12	2915	–	2	6	1	3	5.7
Protection Zones	31	1786	–	–	10	11	10	3.5
Wetlands	14	504	–	–	1	1	12	1.0
Special categories	3	16	–	1	1	–	1	<0.1
Total	132	12,842	1	4	34	25	68	25.1

"life zones" (Powell et al., 2000, Table 2). A life zone is defined by a combination of elevation, relative humidity and biotemperature; life zones differ in the nature of the climax vegetation they produce [see Holdridge (1967) for a clear explanation of the concept of life zones and application to Costa Rica]. Generally, when considering the benefits of additional protected areas, it will be worth analyzing the gains to covering unique habitats, given all of the habitats already covered in the network. This might include protecting pieces of additional life zones. It might also mean protecting forests that connect existing components of the reserve network, as the remaining forest is significantly fragmented (Sanchez-Azofeifa et al., 2001).

During the last 20 years, Costa Rica has also seen the conceptualization, implementation and enactment of three Forestry Laws (1979, 1986 and 1996). These changing laws reflect the dynamic nature of the country's conservation system, and the adaptation of this system to the country's evolving development policies. In addition to the Forestry Laws, a Biodiversity Law (1998) was enacted to provide a legal definition of conservation. Furthermore, in the last 10 years, there have been changes in the composition of the government agencies in charge of conservation. The National System of Conservation Areas (SINAC) was consolidated in 1995 from the three major agencies in charge of the protection of the conservation systems (The Forestry General Direction, the National Parks Direction and the Wildlife General Direction).

To date, SINAC has established 11 Conservation Areas (different from National Parks and Biological Reserves) scattered over the country. These are territorial units, regulated by the same administrative and development program that carries out private and governmental activities for the management and conservation of natural resources. The territories dedicated to conservation inside of these regions are designated either "Level-1" or "Level-2". Level-1 denotes areas under absolute protection such as national parks and biological reserves, where no land-cover change is allowed. Level-2 conservation areas comprise a mix of conservation areas with more relaxed regulations concerning land cover change. Level-2 conservation areas include, in general, forest reserves and wildlife refuges.

Though a steady process to consolidate National Parks and Biological reserves has been in place over the last 30 years, the integrity of forests within Costa Rica's protected areas cannot be taken for granted (Busch et al., 2000). A 1994 constitutional ruling by Costa Rica's Supreme Court held that the government could seize land from private owners only if the latter are fairly compensated. Much of the land within SINAC has not yet been purchased, as the government seized without purchase an estimated 76% of the land in protected zones; 74% in forest reserves; 15% in national parks; 46% in biological reserves, national monuments and absolute natural reserves; 59% in national wildlife refuges and 12% in mangroves (Segnini, 2000). While to this point the owners of that land have largely been convinced not to convert the forest areas to other uses, eventually such conversion will take place unless the land is purchased and permanently protected. Several efforts, at the international level, are currently in place to try to buy these lands. The example of the Guanacaste Conservation Area is a clear example of the potential success of such an initiative.

Although Costa Rica's success in creating and starting to fully consolidate a true conservation network of protected areas is unique in Latin America, questions are arising about the ability of the current areas to function effectively as a network. For instance, the Level-1 conservation areas are thought to be becoming isolated in an ever more intensively used landscape, and the government and environmental organizations seem to feel that the intended function of national parks and

Table 2
Percentage of total life zone protected by both national parks and biological reserves in Costa Rica. Life zones ranked as percentage of total area non-protected

Life zone type	Total area (km^2)	% Total area protected	% Total area protected (NP)	% Total area protected (BR)
Moist lower-montane	23,925	0.0	0.0	0.0
Wet montane	1728	0.0	0.0	0.0
Tropical humid	1,068,499	1.3	1.2	0.1
Wet forest premontane	1,198,697	1.8	1.4	0.3
Tropical humid	113,790	2.5	2.5	0.0
Tropical dry	141,544	3.7	3.7	0.0
Wet tropical	1,151,777	12.1	11.3	0.8
Moist premontane	553,550	12.8	12.3	0.5
Wet montane	373,038	25.5	23.2	2.3
Rain lower-montane	348,464	45.1	44.9	0.1
Rain forest montane	127,785	54.5	53.7	0.7
Sub-Alpine paramo	4590	93.1	93.1	0.0

NP, National Park; BR, Biological Reserve.

biological reserves may not be achieved if connectivity between these areas does not exist.

Some current efforts are aiming to connect Level-1 conservation areas. The Costa Rican government and environmental organizations had recognized since the mid 1990s that the conservation and integrity of national parks and biological reserves could not be achieved if connectivity between then does not exist. In order to account for integration at the country level, as well as at a regional level (Mesoamerican Biological Corridor), a series of biological corridors have been recommended for implementation. This network of biological corridors is known as GRUAS and represent the result of a multi-disciplinary discussion processes between the government and private groups in Costa Rica. Additional information on the nature of the participatory processes followed to design this biological corridors can be found on Garcia (1995). A key question, of course, is whether these proposed corridors can be, and in fact will be, effective in integration.

3. Materials and methods

In order to assess long-term land-cover change we used three digital land-cover (forest / non-forest) data sets. The first was derived from 1:250,000 topographic maps produced in 1960 from aerial photography acquired by the US Defense Mapping Agency. This serves as the baseline for our study, since major deforestation was initiated in the early 1970s (Sanchez-Azofeifa, 2000). The second data set was created from digitizing a total of ten 1:200,000 scale land cover maps. The 1979 land cover map was produced by the Costa Rica National Meteorological Institute (IMN, 1992) using black and white prints of images acquired from the Landsat Multispectral Scanner Satellite (MSS). This map reveals the height of the deforestation process in the country. There are no validation/ground truth studies (field verification) available for these two data sets. Both maps were integrated into a Geographic Information System using a minimum mapping unit of 0.03-km^2. Additional description of these two data sets can be found in Pfaff et al. (2000).

The third set of digital, forest/non-forest information was provided by Costa Rica's National Forest Financing Fund (FONAFIFO; Castro-Salazar and Arias-Murillo, 1998). FONAFIFO's data set was produced from the interpretation of Landsat 5 Thematic Mapper (TM) scenes (seven spectral bands and 28.5 m spatial resolution) acquired during the years 1986 and 1997. The data set had the following categories: forest, non-forest, cloud, shadow, secondary growth (1986–1997), deforestation (1986–1997), continental water bodies, and mangroves. The minimum mapping unit was 0.03-km^2. Methods regarding the production of FONAFIFO data sets have been explained elsewhere (Chomentowski et al., 1994; Sanchez-Azofeifa, 1996, 2000; Skole and Tucker, 1993). This map was validated using a total of 800 control points collected by the Tropical Science Center. Overall accuracy of the map, for the forest/non-forest classification, is estimated to be 92% for all forest units with a minimum mapping unit of 0.03-km^2 and canopy closure equal or higher than 80%.

Cloud cover over the Talamanca region, the Osa Peninsula and a section of northwest Costa Rica limited interpretation of landscape characteristics using the FONAFIFO data set. This problem was corrected by integrating three new satellite images acquired by the Cotopaxi Landsat TM receiving station. Images were acquired for 1987 and 1998; processed using the same algorithms used by FONAFIFO and were later integrated into the original Geographic Information System (GIS). Despite the availability of new satellite images, cloud cover still obscured the most north-central part of Costa Rica, but this did not present a serious problem for our analyses since there are no national parks or biological reserves in the region.

The following data sets were also digitized and used to create a GIS database: location of national parks, biological reserves and proposed biological corridors scale 1:50,000 (Fig. 1), boundaries for conservation regions (1:200,000), and Holdridge life zones (1:200,000). Additionally, a derived data set consisting of a buffer zone of 0.5-, 1- and 10-km around all national parks and biological reserves was generated using the GIS. The 0.5- and 1-km buffer zones were selected to study which parks are currently being most affected by local deforestation while the 10-km seeks to document the potential isolation of the parks and biological reserves at a regional scale. A long-term analysis of deforestation rates (1960–1979, 1979–1986 and 1986–1997) was performed for the 10-km buffer zone and all Biological Corridors to quantify the land cover change dynamics. Fig. 2 presents the 10-km buffer zone around all Level-1 conservation areas.

Connectivity between national parks was studied considering two landscape structure variables: percolation probability (Gardner and O'Neill, 1991; Stauffer, 1985) and landscape division (Jaeger, 2000). Connectivity, defined for this study as the possibility of linkage between Level-1 conservation areas by means of connected forest fragments, was studied using two different approaches (a) biological corridors plus National Parks and Biological Reserves; and (b) just biological corridors without any connection to National Parks or Biological Reserves. We implemented this analysis to quantify the relative impacts additional parks could have in promoting connectivity between the Level-1 conservation areas. Although we recognized that the definitions of connectivity and percolation are both in fact species dependent, in this study we focus our questions on landscape

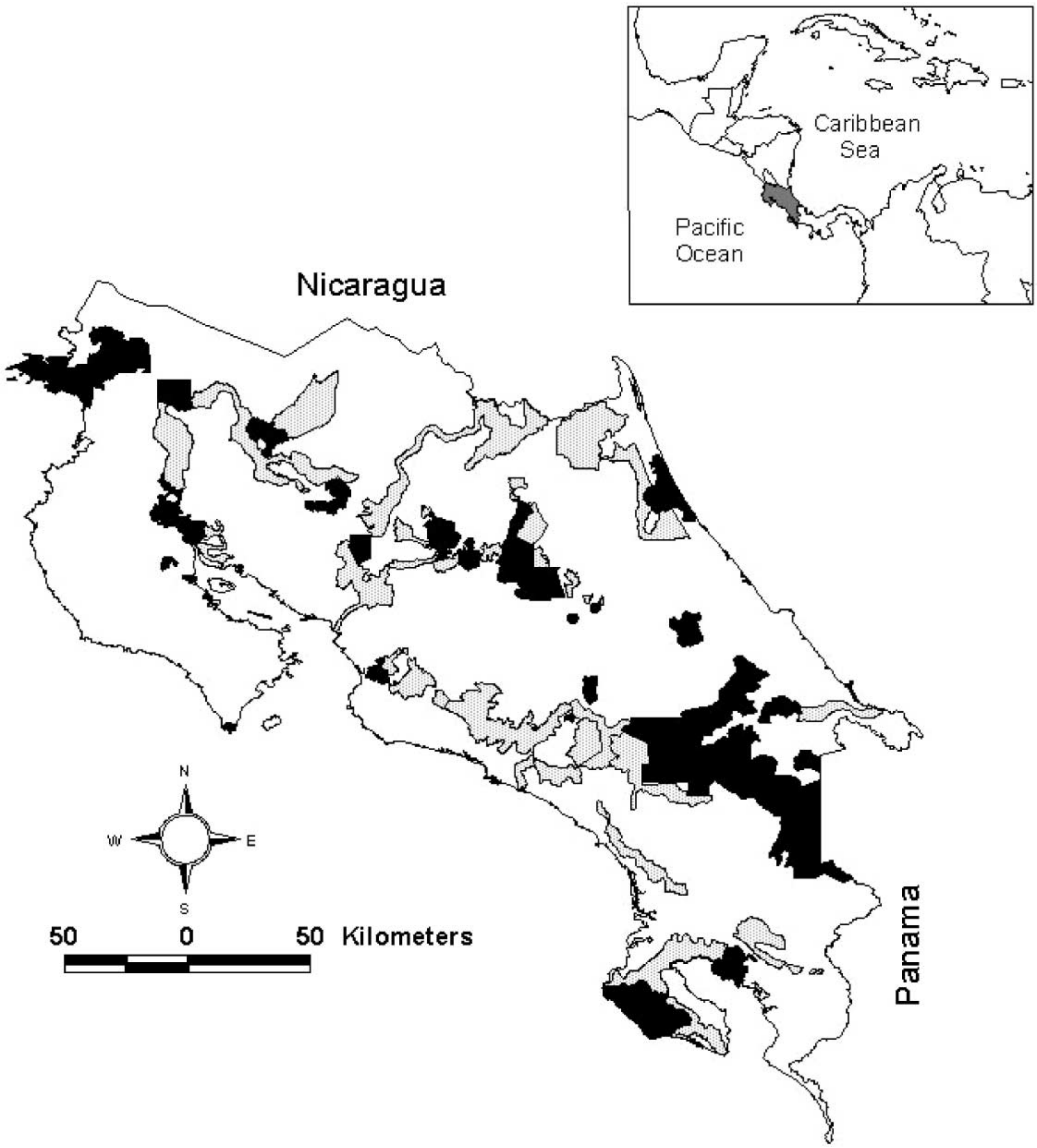

Fig. 1. Spatial distribution of Level-1 conservation areas (Black) and proposed level-1 and biological corridors (Gray).

fragmentation and the potential connectivity that may exist between the different forest islands.

4. Results

4.1. Countrywide analysis

Table 2 presents the results from a countrywide analysis taking into consideration the 12 Holdridge (1967) life zones existing in the country. Our results indicate that efforts to promote conservation in different life zones are not uniform across the national landscape. No Level-1 conservation area currently exists for the moist forest lower-montane and wet forest montane life zones. These two life zones account for the most fertile soils in the country (Tosi, personal communication). Minimal protection is also present on the tropical humid (1.3%), wet forest premontane (1.8%), tropical humid (2.5%) and tropical dry (3.7%). These findings are not a surprise since in general this ecosystems are more suitable for agricultural activities (Ewel, 1999) and more pressure exists against the implementation of conservation activities. Higher protection exists for life zones with less productive soils and those at high elevations (rain forest montane, rain forest lower-montane), in which exploitation of forest and agricultural resources is hampered by both poor accessibility and rough terrain. Most of this protection is based on the presence of National Parks rather than Biological Reserves.

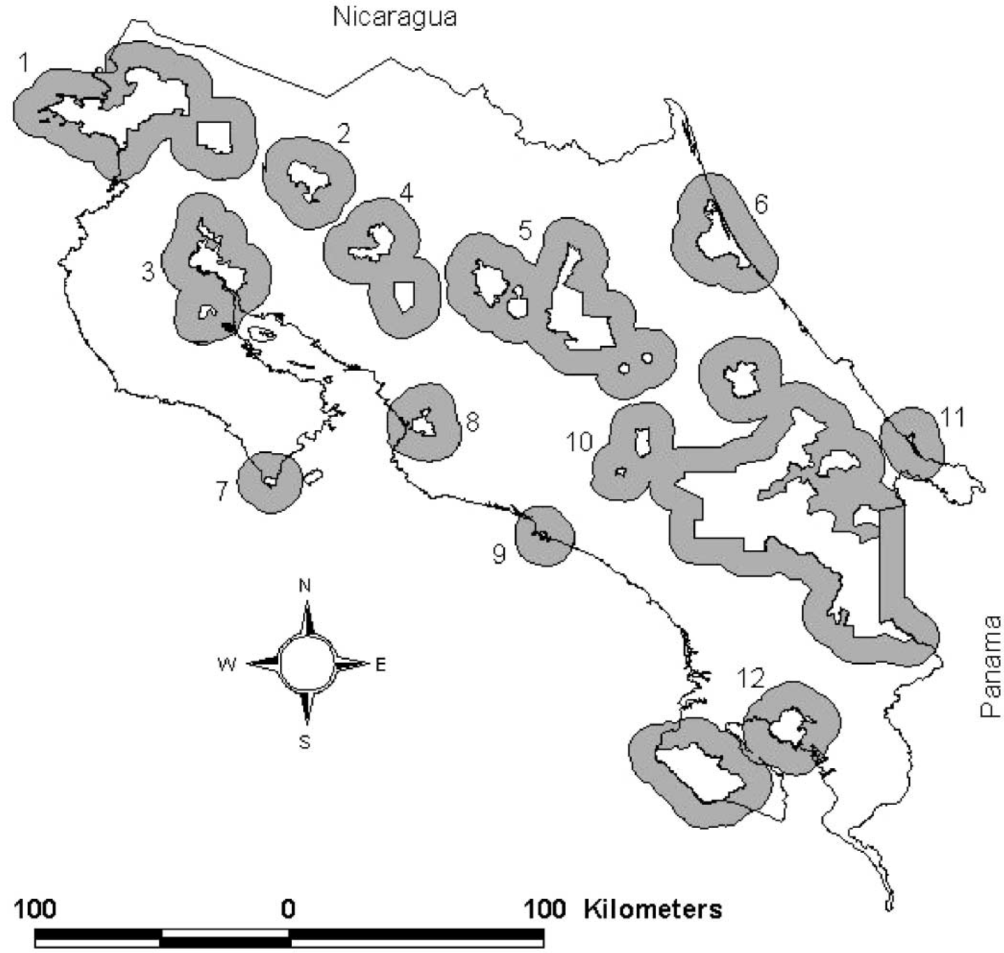

Fig. 2. 10-Km buffer zones around Level-1 Conservation Areas, National Parks NP and Biological Reserves BR. Buffer zone are coded as follows: 1—Guanacaste/Santa Rosa NP, 2—Tenorio Volcano NP, 3—Lomas de Barbudal NP, 4—Arenal Volcano NP, 5—Braulio Carrillo NP, 6—Tortuguero NP, 7—Cabo Blanco NP, 8—Carara BR, 9—Manuel Antonio NP, 10—Chirripo/La Amistad NP, 11—Cahuita NP, and 12—Corcovado-Piedras Blancas NP.

4.2. Regional analysis

Our results indicate that deforestation rates have been negligible inside of national parks and biological reserves over the last 10-years (Table 3). Thus, while again it would require additional analysis to conclude that areas aimed at preventing land cover change were effective, our results suggest that this type of protection may have been effective. Further, human impacts may be even lower than indicated in Table 3 as, in many cases, observable large changes in forest cover inside protected areas are the result of landslides triggered by earthquakes and storms. For example, the 1991 earthquake centered outside the port of Limon (7.5 on the Ritcher Scale) produced important landslides on the Atlantic side of Costa Rica specifically on the Talamanca region covered by several of the National Parks. This was verified by using 1:40,000 scale aerial photography provided by FONAFIFO during 1997/1998.

Also, it is important to note limitations of this approach in terms of spatial (30 m) and spectral (seven bands) resolution of Landsat TM. These could obscure the detection of small encroachments, illegal deforestation, and illegal mining (i.e. Corcovado National Park) or selective logging within a national forest inventory. While we believe the basic conclusions of this paper are robust, such potential errors are worth noting, and perhaps suggest the value of having a good on-the-ground understanding of land-use activities.

Our results (Table 4) also indicate that as distance increases from national parks and biological reserves, total deforestation and deforestation rates also increase. Deforestation in the 0.5- and 1-km buffer zones is low compared with that in the 10-km buffer area. A total of 17.02 km^2 (0.29%/year assuming a constant rate), 35.96 km^2 (0.32%/year) and 549.91 km^2 (1.0%/year) were deforested within the 0.5-, 1- and 10-km buffers respectively.

The Level-1 areas most affected by tropical deforestation close to their boundaries (within the 0.5- and 1.0-km buffer zones) are Alberto Manuel Brenes, Corcovado, Chirripo/Amistad, Braulio Carrillo, Juan Castro Blanco,

Table 3
Total land cover change in national parks and biological reserves between 1986 and 1997

Name	Status	Deforestation (km^2)	Secondary growth (km^2)	Net forest change (km^2)
Amistad	NP	−1.92	4.77	6.69
Barbilla	NP	−3.24	0.00	−3.24
Barra Honda	NP	0.00	0.00	0.00
Braulio Carrillo	NP	−1.67	2.31	0.65
Cabo Blanco	NP	0.00	0.00	0.00
Cahuita	NP	0.00	0.01	0.01
Chirripo	NP	−1.77	0.33	−1.43
Corcovado	NP	−1.99	1.06	−0.93
Guanacaste	NP	−2.40	4.22	1.83
Juan Castro Blanco	NP	−2.10	1.93	−0.18
Manuel Antonio	NP	−0.07	0.00	−0.07
Palo Verde	NP	0.00	0.00	0.00
Piedras Blancas	NP	−1.08	2.79	1.71
Rincon de la Vieja	NP	−2.21	2.07	−0.13
Santa Rosa	NP	0.00	0.00	0.00
Tapanti	NP	−0.55	0.00	−0.55
Tortuguero	NP	−0.56	0.23	−0.33
Volcan Arenal	NP	−2.80	6.26	3.46
Volcan Irazu	NP	−0.23	2.28	2.05
Volcan Poas	NP	−0.14	0.51	0.36
Volcan Tenorio	NP	−0.62	1.54	0.91
Volcan Turrialba	NP	−0.19	2.06	1.87
Alberto Manuel Brenes	BR	0.00	0.28	0.28
Carara	BR	−0.43	5.15	4.72
Cerro Vueltas	BR	0.00	0.12	0.12
Hitoy Cerere	BR	−0.18	0.00	−0.18
Lomas de Barbudal	BR	0.00	0.00	0.00

NP, National Park; BR, Biological Reserve.

Hitoy-Cerere, Tortuguero and Volcan Tenorio (Table 4). At a regional scale (10-km buffer zone) deforestation (Table 5) rates were significantly high during the 1979–1986 period when compared against the other two time periods. Average annual deforestation rates for the 1960–1979, 1979–1986 and 1986–1997 time periods are estimated to be 1.3, 2.9 and 0.8%. The high deforestation rate observed during the 1979–1986 time period is comparable with national deforestation rates observed reported by FAO (1970s to 1990s) and Sanchez-Azofeifa et al. (2001) for 1986–1992. Deforestation was greatest around Braulio Carrillo, Cahuita, Tortuguero and Volcan Tenorio. Parks on the Atlantic slopes are experiencing higher deforestation on surrounding lands than those on the Pacific slopes, specifically the Cahuita, Tortuguero and Braulio Carrillo National Parks.

Three main trends are observed when deforestation rates are compared across time periods. The first trend is observed for the Guanacaste, Volcan Tenorio and Carara 10-km buffers where high deforestation rates during the first two periods were followed by a sharp reduction during the 1976–1997 period. The second trend reveals almost no deforestation during the first period, a significant increase during the second one and a dramatic reduction during the third time period. Volcan Arenal, Chirripo, Cahuita and Corcovado regions present the former tendency. Third, we have those regions that show a tendency toward increased deforestation rates during the last 10-years, specifically the buffer zones around the Tortuguero, Braulio Carrillo and Manuel Antonio National Parks. These results are in contrast to the with current and long-term investment coordinated by the national government and conservation non-governmental organizations trying to control deforestation trends in those areas.

Our results also indicate that areas surrounding Level-1 conservation areas are highly fragmented (Fig. 3) and with a domination of non-forest classes over forest fragments (Fig. 4). Level-1 areas such as Braulio Carrillo and Cahuita are surrounded by highly fragmented landscapes (Fig. 5). Some outcomes can be linked to land use choices. High deforestation and habitat fragmentation of Level-1 conservation areas in the Atlantic region is attributable to the intensification and expansion of agricultural cash crops such as banana, and pineapple (Sanchez-Azofeifa et al., 1999, 2001).

Deforestation rates for all biological corridors are significantly reduced for the 1986–1997-time period (Table 6). The same trend observed at the regional level for buffer zones (Table 5) is also observed for the

Table 4
Total deforestation (1986–1997) and deforestation rates in 0.5- and 1.0-km buffer zones around all national parks and biological reserves, Costa Rica

Name	Status	Total deforestation (km^2) 0.5-km	Mean annual deforestation rate (%) 0.5-km	Total deforestation (km^2) 1-km	Mean annual deforestation rate (%) 1-km
Barbilla	NP	1.26	0.44	3.00	0.53
Barra Honda	NP	0.00	0.00	0.00	0.00
Braulio Carrillo	NP	2.26	0.32	5.44	0.40
Cabo Blanco	NP	0.00	0.00	0.00	0.00
Cahuita	NP	0.00	0.00	0.00	0.00
Chirripo/Amistad	NP	2.02	0.10	5.32	0.14
Corcovado	NP	0.47	0.14	1.36	0.22
Guanacaste	NP	0.51	0.26	1.24	0.36
Juan Castro Blanco	NP	2.32	1.40	4.04	1.40
Manuel Antonio	NP	0.23	2.11	0.64	3.08
Palo Verde	NP	0.00	0.00	0.00	0.00
Piedras Blancas	NP	0.72	0.79	1.04	0.56
Rincon de la Vieja	NP	0.64	0.34	1.08	0.29
Tapanti	NP	0.39	0.24	0.64	0.20
Tortuguero	NP	2.19	0.70	3.04	0.53
Volcan Arenal	NP	0.72	0.30	1.16	0.25
Volcan Irazu	NP	0.43	1.23	0.96	1.25
Volcan Poas	NP	0.03	0.02	0.04	0.01
Volcan Tenorio	NP	1.52	0.76	4.12	1.09
Volcan Turrialba	NP	0.23	0.49	0.40	0.47
Alberto Manuel Brenes	BR	0.00	0.00	0.00	0.00
Carara	BR	0.55	0.97	0.72	0.77
Cerro Vueltas	BR	0.00	0.00	0.04	0.02
Hitoy Cerere	BR	0.53	0.23	1.68	0.35

Table 5
Deforestation rates in a 10-km buffer zones around all national parks and biological reserves, Costa Rica (1960–1997)

Buffer zone name	Deforestation rate (1960–1979)	Deforestation rate (1979–1986)	Deforestation rate (1986–1997)
Guanacaste	2.8	5.0	0.5
Volcan Tenorio	1.8	5.9	2.4
Tortuguero	1.0	1.7	1.9
Lomas de Barbudal	3.1	0.0	0.0
Volcan Arenal	0.4	3.7	0.6
Braulio Carrillo	0.8	0.8	1.2
Chirripo	0.5	1.1	0.4
Carara	1.6	6.7	0.2
Cahuita	0.9	6.1	1.1
Cabo Blanco	0.0	0.0	0.0
Manuel Antonio	3.0	0.0	1.1
Corcovado	0.0	3.8	0.5

biological corridors (Table 6) where a significantly higher-than-average deforestation rate (3.1% per year) is observed for the 1979–1986 time period versus 1.1% and 0.8% per year for the 1960–1979 and 1986–1997 time periods. With the exception of the Juan-Northwest (2% per year), the Volcanoes Rinco-Tenorio-Arenal (3% per year) and Tortuguero (1.9% per year) corridors, all other connectivity regions present minimum deforestation rates under 1% per year. Of major concern is the Tortuguero proposed biological corridor that shows no significant changes on deforestation rates during the last 20 years (1979–1997), been them in average 1.9% per year.

4.3. Connectivity between Level-1 conservation areas

Our results considering both percolation theory and landscape division indicate, when carried out at a local scale eliminating the Level-1 areas, indicate a high degree of landscape division and low percolation (Fig. 6). This suggests that currently proposed biological corridors are not allowing for connectivity between

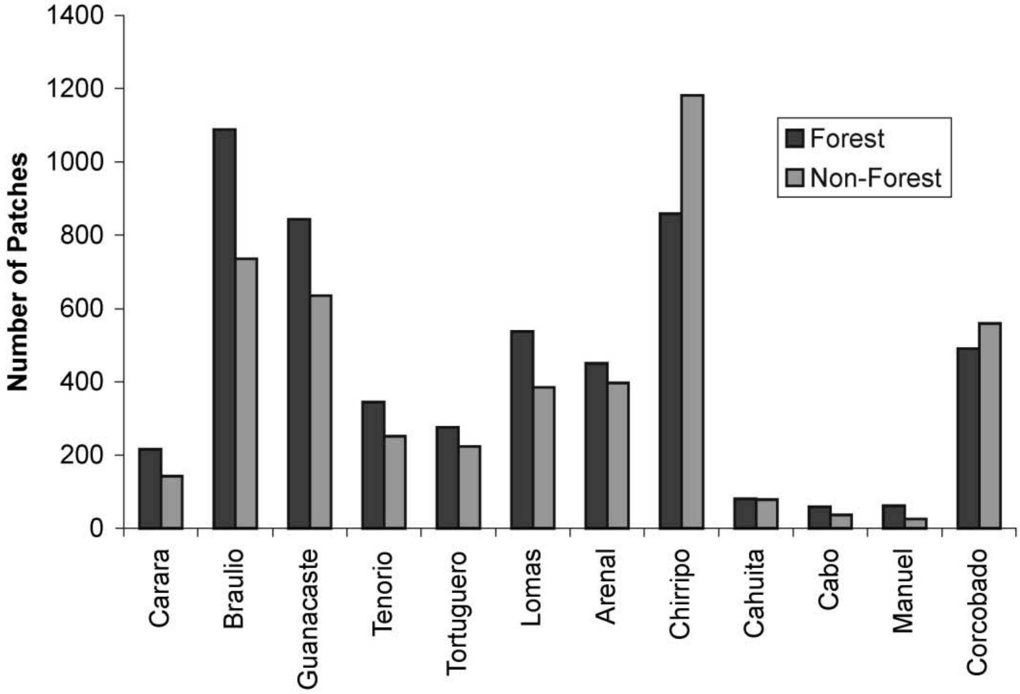

Fig. 3. Distribution of forest patches in 10-km buffer zones around Level-1 conservation areas in Costa Rica. Areas around Braulio Carrillo, Chirripo/Amistad and Guanacaste/Santa Rosa National Parks present the highest levels of forest fragmentation. Black represents forest and gray represents non-forest.

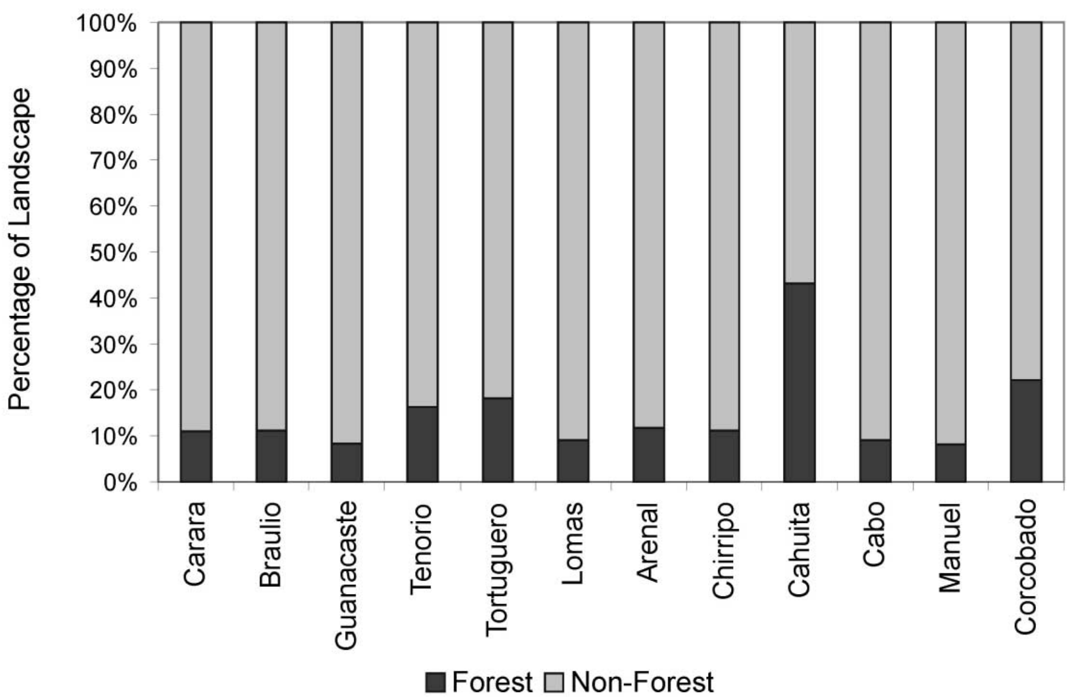

Fig. 4. Percentage of the total area of buffer zone (10-km) covered with forest around Level-1 conservation areas in Costa Rica. Black represents forest cover and gray non-forest cover.

Level-1 areas, due to the high level of landscape division. Our analysis indicates that 5 out of 22 biological corridors present high landscape division and low percolation (upper left corner of Fig. 6: Rincon-Tenorio-Arenal, Costena, Braulio, Carara-Northeast and Palo Verde-Rincon). Based on De-Camino-Beck and Sanchez-Azofeifa (2001), it seems that re-establishment of connectivity between these corridors and parks would

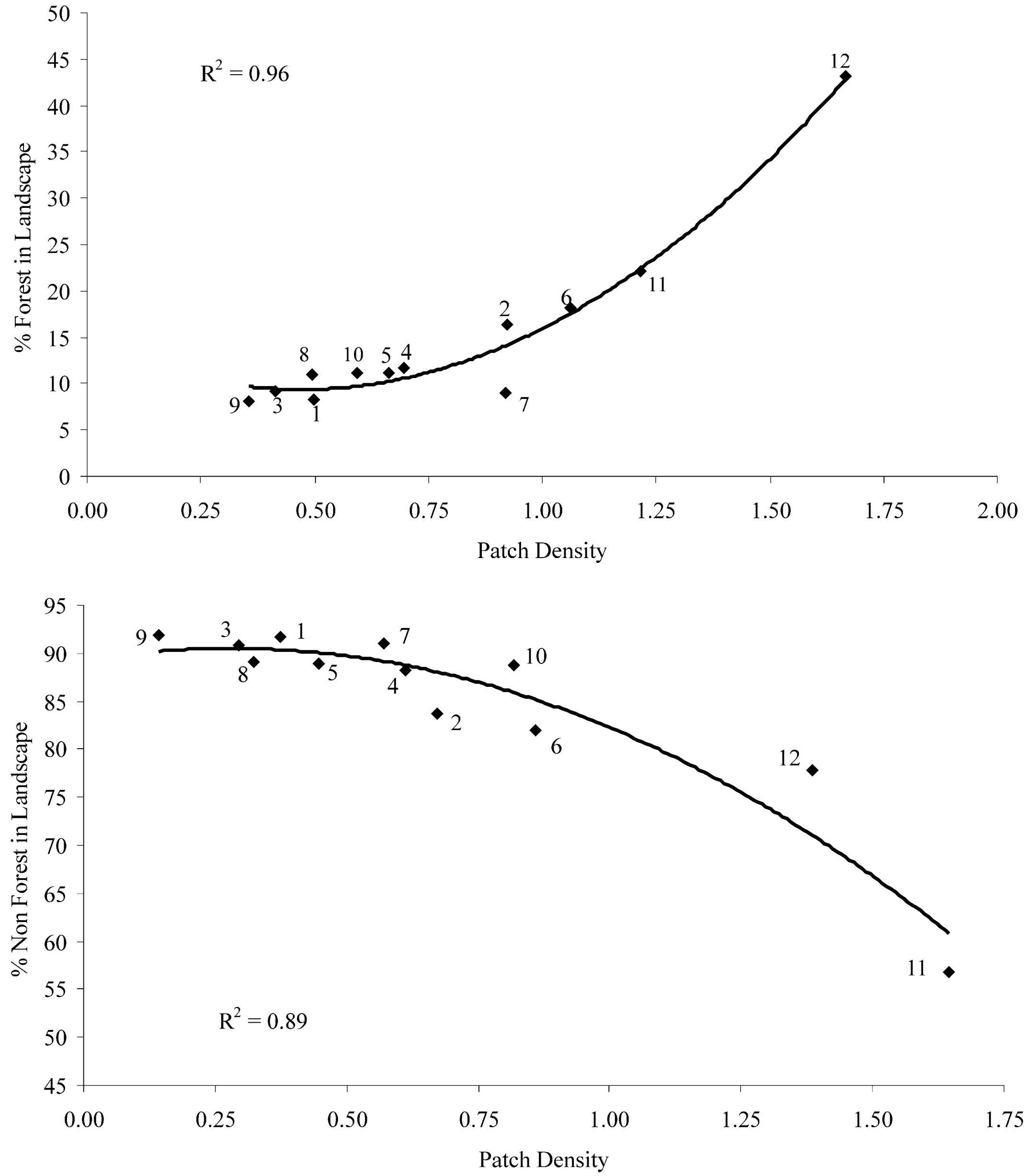

Fig. 5. Percentage of forest and non-forest cover as function of patch density in the 10-km buffers around Level-1 areas in Costa Rica. Each diamond signifies a Level-1 conservation area with numbers corresponding the regions outlined on Fig. 2. Areas are becoming isolated as non-forest area increases and the number of forest fragments decreases.

require significant additional investment in ecosystem restoration.

5. Discussion and conclusion

Although Costa Rica has made significant efforts over the last 30 years to produce one of the most comprehensive national park systems in the world, our study is one of the first to try to meet the demand for monitoring one aspect of the success of the implementation of this conservation network. We find that 1986–1997 deforestation inside and within small buffers around the Level-1 conservation areas (national parks and biological reserves) was negligible. This result can be see as in contrast with the high levels of implied deforestation in some regional land-use-change simulations done by others (e.g. Pontius et al., 2001). Thus, in answer to our first question of interest, it seems conservation-area boundaries are being respected to this point.

However, as we moved even just to larger buffer zones, the story changed. We found significant clearing in proximate areas. In many cases, such as at the Corcovado and Braulio Carrillo National Parks, deforestation has closely approached the park, and the Tortuguero National Park is becoming isolated from

Table 6
Deforestation rates for all proposed biological corridors in Costa Rica

Corridor name	Deforestation rate (1960–1979)	Deforestation rate (1979–1986)	Deforestation rate (1986–1997)
Alberto-Tortuguero	0.6 (72.0)	3.8 (63.4)	1.0 (46.5)
Alberto-Juan-Poas	1.2 (38.6)	1.6 (30.1)	0.4 (26.7)
Braulio	0.6 (93.9)	0.2 (83.3)	0.6 (82.1)
Carara-Chirripo	0.8 (74.4)	2.5 (63.2)	0.5 (52.2)
Carara-Northeast	2.7 (30.6)	−5.2 (14.7)	0.8 (20.0)
Corcovado-Piedras	−0.2 (89.1)	5.7 (93)	0.5 (56.1)
Costena	0 (80.1)	6.7 (79.5)	0.6 (41.9)
Hitoy-Cahuita	0.8 (98.3)	0.6 (83.6)	0.9 (80.3)
Juan-Northwest	0.7 (43.0)	−0.5 (37.6)	2.0 (38.9)
Palo Verde-Rincon	2.7 (38.6)	−5.4 (19.0)	0.4 (26.1)
Palo Verde-Southeast	1.3 (41.1)	−6.8 (41.1)	0.0 (45.9)
Rincon-Tenorio-Arenal	2.6 (54.8)	−1.4 (27.4)	3.0 (30.1)
Tenorio-Northeast	1.1 (56.3)	14.3 (44.1)	N/A
Tortuguero	0.1 (85.5)	2.0 (84.4	1.9 (72.7)
Turrialba	−0.3 (94.8)	8.5 (100)	0 (40.7)

Deforestation rate defined as percentage per year for the study period, data in parentheses represent percentage of forest cover for the corridor at the beginning of the analyzed time period. N/A: area affected by cloud cover, negative values indicate secondary growth processes.

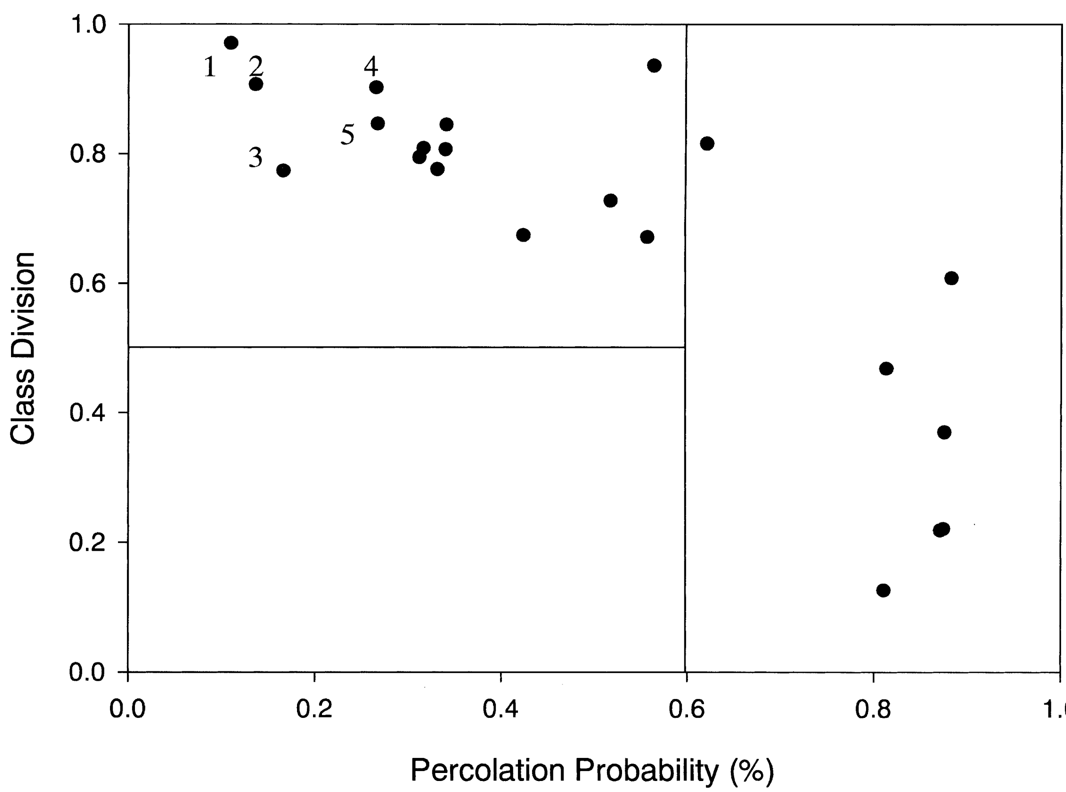

Fig. 6. Relationship between percolation probability and landscape division for all biological corridors connecting Level-1 conservation areas in Costa Rica. Results indicate that 5 (1—Rincon-Tenorio-Arenal, 2—Costena, 3—Braulio, 4—Carara-Northeast and 5—Palo Verde-Rincon) out of 22 of the proposed biological corridors are current beyond recuperation in this generation and the amount of energy necessary to convert them to functional corridors (increasing or creating the possibility of percolation) is too high.

the national conservation system due to high deforestation rates and an increase in cash crops such as banana and palm heart plantations. Should the current conditions continue, we would expect that Tortuguero would become completely isolated within the Costa Rica landscape during this given time span, receiving the same fate accorded to many other Costa Rican parks like Braulio Carrillo, Volcan Rincon de La Vieja and Volcan Tenorio.

Unfortunately, for provision of some forest services, such as species habitat, there is reason to believe that conserved forest areas must be linked in an effective network (Forman, 1995; Noss and Cooperrider, 1994; Soulé and Ternorgh, 1999). For instance, if forest patches are too small and/or too isolated, they are susceptible to loss of both genetic and species diversity, especially during extreme climatic and other disturbance events. Gene flow is restricted and extinction of local plant and animal populations becomes a significant possibility. For these reasons, corridors that link conservation areas are thought to be important for habitat services, and thus for the long-term protection of biodiversity. In light of such value of linkages, it is unfortunate that in answer to our second question, increasingly Costa Rican National Parks and Biologic Reserves are not functioning as a linked conservation network. Highly fragmented forest corridors, in conjunction with forests on areas not suitable for agricultural expansion, or in regions on which timber extraction occurred long ago, cannot necessarily be considered a conservation success.

This raises the issue of the effects of past policies aimed to stop tropical deforestation, and of the effects of current incentives and mechanisms aimed to promote forest conservation. We cannot simply assert that the lack of deforestation observed in conservation areas identifies those areas as effective conservation tools. These National Parks and Biological reserves are not randomly located, but may have been located in places where there is less deforestation pressure. However, controlling for other drivers of deforestation and the process of park location in testing for the effects of these policies is part of our future research agenda. Joining the current analyses with econometric analyses of Costa Rican land use cited earlier will permit precisely such tests.

In terms of future policy actions, if it is determined that the forest services that could be provided by a linked conservation network would be of sufficient value, then Costa Rica needs to act to protect rich biologic resources by affecting land use outside of current national parks and biologic reserves. Policies must be aimed to seek a balance between the goals of conservation and the need to use these lands for agricultural production (Daily et al., 1998). New approaches and mechanisms, such as developing regional conservation networks through greater protection of buffer zones around protected areas, creating protected biological corridors among protected areas, and strategically locating new areas, would have to rise on the government's agenda.

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References

Busch, C., Sathaye, J., Sanchez-Azofeifa, G.A., 2000. Estimating the Greenhouse Gas Benefits of Forestry Projects: A Costa Rican Case Study. LBNL-42289, Lawrence Berkeley National Laboratory, Berkeley, CA.

Castro-Salazar, R., Arias-Murillo, G., 1998. Costa Rica: Toward the Sustainability of its Forest Resources (Technical Report). Fondo Nacional de Financiamiento Forestal, San Jose, Costa Rica.

Chomentowski, W., Salas, B., Skole, D., 1994. Landsat Pathfinder project advances deforestation mapping. GIS World 7 (4), 34–38.

Daily, G.C., Ehrlich, P.R., Sanchez-Azofeifa, G.A., 1998. Countryside biogeography: Utilization of human-dominated habitats by the avifauna of southern Costa Rica. Ecological Applications 11 (1), 1–13.

Daily, G.C., Ellison, K., 2002. The New Economy of Nature: The Quest Make Conservation Profitable. Island Press, Washington, DC.

De-Camino-Beck, T., Sanchez-Azofeifa, G.A., 2001. Percolation in neutral landscapes: Landscape metric sensitivity to critical thresholds and a new class division index. National Network of Centers of Excellence-Sustainable Forest Management Network. Working paper no. 2001–4.

Ewel, J.J., 1999. Natural Systems as models for the design of sustainable systems of land use. Agroforestry Systems 45, 1–21.

FAO, 1990. 1990 Forest Resources Assessment. United Nations Food and Agriculture Organization, FAO, Rome: Italy.

Forman, R., 1995. Land Mosaics the Ecology of Landscapes and Regions. Cambridge University Press, New York.

Garcia, R., 1996. Propuesta tecnica de ordenamiento territorial con fines de conservacion de biodiversidad. Informe de pais: Costa Rica. Project Corredor Biological Mesoamericano CCA-PNUD/GEF RLA/95/G41.

Gardner, R.H., O'Neill, R.V., 1991. Pattern, process, and predictability: the use of neutral models for landscape analysis. In: Turner, M.G., Gardner, R.H. (Eds.), In Quantitative Methods in Landscape Ecology. Springer-Verlag, New York, pp. 289–307.

Harrison, S., 1991. Population growth, land use and deforestation in Costa Rica, 1950–1984. Interciencia 16 (2), 83–93.

Heindrichs, T., 1997. Innovative Financing Instruments in the Forestry and Nature Conservation Sector of Costa Rica, Sector Project. Deustche Gesellschaft fur Technische Zusammenarbeit, GTZ, Eschborn, Germany.

Holdrighe, L., 1967. Life Zone Ecology. Tropical Science Center, San Jose.

IMN, 1992. Mapa de cobertura de la Tiena para 1992. Instituto Meteorologico Nacional, Ministerio del Ambiente y Energia, San Jose, Costa Rica.

Jaeger, J., 2000. Landscape division, splitting index, and effective mesh size: new measures of landscape fragmentation. Landscape Ecology 15, 115–130.

Kerr, S., Pfaff, A., Sanchez-Azofeifa, G.A., 2000. The Dynamics of Deforestation and the Supply of Carbon Sequestration: Illustrative

Results from Costa Rica, Central America Project, Environment: Conservation and Competitiveness. Harvard Institute for International Development, Harvard University, Boston.

Noss, R.F., Cooperrider, A.Y., 1994. Saving Nature's Legacy: Protecting and Restoring Biodiversity. Island Press, Washington, DC.

Pfaff, A., Kerr, S., Hughes, F., Liu, S., Sanchez-Azofeifa, G.A., Schimel, D., Tosi, J., Watson, V., 2000. The Kyoto protocol and payments for tropical forest: an interdisciplinary method for estimating carbon-offset supply and increasing the feasibility of a carbon market under the CDM. Ecological Economics 35, 203–221.

Pontius, R., Cornell, J., Hall, C., 2001. Modeling the spatial pattern of land-use change with GEOMOD2: application and validation for Costa Rica. Agriculture, Ecosystems and Environment 81, 191–203.

Powell, G., Barborak, J., Rodriguez, M., 2000. Assessing representativeness of protected natural areas in Costa Rica for conservation biodiversity: a preliminary gap analysis. Biological Conservation 93, 41–53.

Quesada-Mateo, C., 1990. Estrategia de Conservacion para el Desarrollo Sostenible de Costa Rica. Ministerio de Recursos Naturales Energia y Minas, San Jose, Costa Rica.

Rosero-Bixby, L., Palloni, A., 1998. Poblacion y deforestacion en Costa Rica, Conservacion del Bosque en Costa Rica. Academia Nacional de Ciencias, San Jose, Costa Rica.

Sader, S., Joyce, A., 1988. Deforestation Rates and Trends in Costa Rica, 1940 to 1983. Biotropica 20, 11–19.

Sanchez-Azofeifa, G.A., 1996. Assessing Land Use/Cover Change in Costa Rica. Unpublished Doctoral Dissertation, University of New Hampshire, Durham, New Hampshire.

Sanchez-Azofeifa, G.A., 2000. Land use and cover change in Costa Rica. In: Hall, C. (Ed.), Quantifying Sustainable Development. Academic Press, New York, pp. 477–505.

Sanchez-Azofeifa, G.A., Harriss, R.C., Skole, D.L., 2001. Deforestation in Costa Rica: a quantitative analysis using remote sensing imagery. Biotropica 33 (3), 378–384.

Sanchez-Azofeifa, G.A., Quesada-Mateo, C.A., Gonzalez-Quesada, P., Dayanandan, S., Bawa, K., 1999. Protected areas and conservation of biodiversity in the tropics. Conservation Biology 13 (2), 407–411.

Segnini, G., 2000. Gran deuda por conservacion. La Nacion (10 February).

Skole, D., Tucker, C., 1993. Tropical Deforestation and Habital Fragmentation in the Amazon: Satellite Data from 1978 to 1988. Science 260, 1905–1910.

Solorzano, R., de Camino, R., Woodward, R., Tosi, J., Watson, V., Vasquez, A., Villalobos, C., Jimenez, J., Repetto, R., Cruz, W., 1991. Accounts Overdue: Natural Resource Depreciation in Costa Rica. World Resources Institute, Washington, DC.

Soulé, M.E., Ternorgh, J., 1999. Continental Conservation: Scientific Foundations of Regional Reserve Networks. Island Press, Washington, DC.

Stauffer, D., 1985. Introduction to Percolation Theory. Taylor & Francis (Printers) Ltd, London, UK.