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Coupled social and ecological outcomes of agricultural intensification in Costa Rica and the future of biodiversity conservation in tropical agricultural regions

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ABSTRACT

Tropical ecosystem conversion to agriculture has caused widespread habitat loss and created fragmented landscapes composed of remnant forest patches embedded in a matrix of agricultural land uses. Non-traditional agricultural export (NTAE) crops such as pineapple are rapidly replacing multiuse landscapes characterized by a diverse matrix of pasture and smallholder crops with intensive, large-scale, monoculture plantations. Using an interdisciplinary approach, we conduct a case study to examine the coupled social and ecological implications of agricultural intensification in this region, with larger application to regions experiencing similar patterns of agricultural intensification. Guided by frameworks from both political and landscape ecology, we: (1) describe the social and economic implications of pineapple expansion, specifically the concentration of land, labor and financial resources, (2) quantify pineapple cultivation's spatial characteristics, and (3) assess the effects of pineapple expansion on surrounding forest ecosystems, on the agricultural matrix and on biodiversity conservation. Our results indicate that pineapple production concentrates land, labor, and financial resources, which has a homogenizing effect on the agricultural economy in the study region. This constrains farm-based livelihoods, with larger implications for food security and agricultural diversity. Landscape ecology analyses further reveal how pineapple production simplifies and homogenizes the agricultural matrix between forest patches, which is likely to have a negative effect on biodiversity. To offset the effects of pineapple expansion on social and environmental systems, we recommend developing landscape level land use planning capacity. Furthermore, agricultural and conservation policy reform is needed to promote landscape heterogeneity and economic diversity within the agricultural sector. Our interdisciplinary research provides a detailed examination of the social and ecological impacts of agricultural intensification in a tropical landscape, and offers recommendations for improvement relevant not only to our study region but to the many other tropical landscapes currently undergoing non-traditional agricultural export driven agricultural intensification.

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1. Introduction

Tropical forests cover less than 23% of the earth's terrestrial surface, but contain over 50% of its biodiversity and provide essential ecosystem services to the entire globe (Mace et al., 2005). As human populations continue to grow, the demand for food has driven an increase in croplands from an estimated 400 to 1800 million hectares (ha) globally (Lambin et al., 2003). Recently, much of this growth has occurred in tropical regions (Gibbs et al., 2010). The conversion of tropical ecosystems to agriculture has caused widespread habitat loss and created fragmented landscapes composed of remnant forest patches embedded in a matrix of agricultural land uses. In recent years, a new pattern has emerged whereby pasture and smallholder cropping systems are rapidly being replaced by monoculture plantation agriculture (Brannstorm, 2009; Meyfroidt et al., 2014; Rudel et al., 2009b). Impacts of the expansion of agricultural intensification[1] on social and ecological systems are not well understood, but preliminary studies suggest that intensive plantation agriculture may drive demographic and economic change in local human communities (Hecht et al., 2005; Brannstorm, 2009) and affect the structure and function of remnant forest (Tscharntke et al., 2012) and landscapes (Fahrig et al., 2011).

A primary driver of the expansion of agricultural intensification in the tropics is the increased production of non-traditional agricultural export (NTAE[2]) crops (Thrupp, 1995; Morton et al., 2006; MEA, 2007; Galford et al., 2010). From a policy standpoint, NTAE crop production is viewed as an opportunity for raising farm incomes in developing countries in the tropics, which have the attraction of low labor costs and an extended growing season (Thrupp, 1995). Tropical countries therefore now dominate global NTAE production (FAO, 2011), and NTAE crops have become a major driver of economic globalization by closely linking tropical agricultural producers to consumers in temperate locations.

While NTAEs have the potential to positively affect rural economic conditions and livelihoods, their effects on biodiversity conservation are largely negative. NTAEs are generally produced on a large scale, to accommodate greater mechanization and to maximize profits. These increases in productivity ultimately stimulate more demand for land, rather than incentivizing individuals and firms to spare land for conservation (Lambin and Meyfroidt, 2011). Therefore, NTAE production can result in simultaneous agricultural intensification and expansion, a process which homogenizes the agricultural matrix, reduces total forest cover in the landscape, and increases the isolation of native plant and animal species in remnant forest patches (Rudel et al., 2009a). This sequence of events challenges the linearity of the 'intensification-land sparing' hypothesis (Matson and Vitousek, 2006). This hypothesis states that agricultural intensification increases production efficiencies and creates jobs, and therefore may decrease the need for additional deforestation for agricultural expansion, reducing pressure on surrounding ecosystems (Matson and Vitousek, 2006; Grau and Aide, 2008). However, the social, economic and ecological consequences and tradeoffs of intensification differ substantially by the type and scale of the production system (Tomich et al., 2001). This context dependence underscores the importance of evaluating the socio-ecological impacts and tradeoffs of NTAE-driven agricultural intensification in specific regions throughout the tropics.

Although the ecological impacts are not well understood, intensively managed monoculture plantations with high agrochemical inputs can exacerbate biodiversity loss (Tilman et al., 2002; Ormerod et al., 2003; Jackson et al., 2012; Karp et al., 2012), impede native species' movement across the landscape (Vaughan et al., 2007), increase habitat fragmentation (Morton et al., 2006), and degrade soil and water quality (Hyden et al., 1993; Polidoro et al., 2008). However, it may be possible to retain the economic benefits derived from intensive plantation agriculture's productivity increases while reducing negative impacts on surrounding ecosystems. For example, practices such as retaining live fences, scattered trees, and riparian corridors within agricultural fields can enhance some components of biodiversity in agricultural landscapes (Harvey et al., 2006; Chazdon et al., 2009a). In some cases, these changes also lead to higher yields or economic returns, indicating that complementary goals of maintaining ecological integrity and agricultural production may be possible (Harvey and Villalobos, 2007; Robson and Berkes, 2011; van Vliet et al., 2012).

To identify policy and management options that allow for continued rural development and increases in agricultural productivity while mitigating impacts on tropical ecosystems, we need a better understanding of the relationships between NTAE production, agricultural intensification, and biodiversity conservation (Harvey et al., 2006). Such complex problems require an integrated, interdisciplinary approach that recognizes the interdependence of social, economic, and ecological processes inherent in the system (Eigenbrode et al., 2007; Ostrom, 2007; Botey et al., 2014). Here, we utilize such an approach. We first employ a political ecology (PE) analysis to examine the socio-economic implications of intensification from the perspective of local actors in the San Juan-La Selva (SJLS) region in Costa Rica, a rapidly developing agricultural zone where important conservation areas also exist. We then utilize landscape ecology (LE) to quantify and discuss the ecological implications of the composition and configuration of the dominant land cover types in the SJLS region with a special focus on pineapple, the dominant NTAE.

Our ultimate goal is to describe the social and ecological impacts of intensification in this system that are also relevant to other tropical regions where agricultural intensification is now occurring due to NTAE production. Our specific objectives are to: (1) describe the social and economic implications of pineapple expansion, specifically the distribution and concentration of land, labor and financial resources, (2) quantify the spatial characteristics of pineapple cultivation as a landscape component, and (3) assess pineapple expansion's effects on forest ecosystems and on the potential contributions of the agricultural matrix to biodiversity conservation. We conclude by exploring the policy implications of our integrated findings.

2. Theory

2.1. Integrating political ecology and landscape ecology

From this PE perspective natural resource access, use, and control cannot be understood without critically examining how land, labor, and financial resources are distributed among actors (Blaikie and Brookfield, 1987; Turner and Robbins, 2008; Peet et al., 2011). We draw from PE by utilizing stakeholder testimony to develop a qualitative chain of explanation to link sociopolitical drivers of change to local environmental and social outcomes and to assess the tradeoffs and consequences of agricultural intensification among different actors (Robbins, 2004; Turner and Robbins, 2008).

The field of landscape ecology integrates methods from ecology and geography to address questions about the effect of landscape patterns on ecological processes (Turner, 2005). One focus of LE is

[1] We define intensification as a multifaceted, nonlinear process where one or more of the following takes place: the unit of production increases per unit of land area (i.e., yield/hectare), cultivated land is under production for a longer period (i.e., less fallow), labor use is intensified (person-days/hectare), and inputs (fertilizer, pesticides, technology, capital) per hectare increase.

[2] NTAE crops are those that have not previously been central in a country's export profile, such as fresh tropical fruit or off-season temperate fruit, ornamental foliage, oil palm or biofuels.

determining how the composition and spatial configuration of land uses and cover types affect the amount of biodiversity the landscape can support, and the associated amount of ecosystem services that are provided to humans (Turner, 2010; Fahrig et al., 2011; Wu, 2013). Previous studies indicate that some agricultural land use types are frequently used by native species for foraging, breeding, or simply as stepping stones to reach the next habitat patches (Kupfer et al., 2006; Fischer and Lindenmeyer, 2007; Harvey and Villalobos, 2007; Chazdon et al., 2009a; Gilbert-Norton et al., 2010; Vilchez Mendoza et al., 2014). Landscapes that are more heterogeneous, both in composition and configuration, are more likely to include these land use types, and therefore more likely to provide habitat and habitat connectivity for a variety of species than more homogenous landscapes (Daily et al., 2003; Fischer and Lindenmeyer, 2007; Milder et al., 2010; Fahrig et al., 2011).

Combined, PE and LE offer a holistic understanding of human-modified landscapes and link ecology to the social and political implications of environmental change. A PE perspective demonstrates how political, economic, and social dynamics operating across multiple scales produce spatially explicit social and environmental change. The LE analysis quantifies the extent and ecological implications of that environmental change across the landscape. PE and LE thus inform each other and illuminate novel opportunities for sustainable agricultural production and biodiversity conservation in agricultural frontiers.

3. Materials and methods

3.1. Study region

The study region (616,615 ha), was delimited by available remote sensing imagery and the Nicaraguan border (Fig. 1). It includes the landscapes within and surrounding the San Juan-La Selva (SJLS) biological corridor in northeastern Costa Rica (centered at 10.61° N, 84.13° W, Fig. 1). This region has a mean annual temperature of 26.5 °C and annual precipitation ranging from 3000 to 4500 mm (Grieve et al., 1990; McDade et al., 1994), and lies within a wet tropical forest life zone (*sensu* Holdridge et al., 1975). Old- and second-growth forest remnants currently cover an important proportion of the land area (Morse et al., 2009; Fagan et al., 2013; Section 4 in this paper), retaining high tree species diversity and showing quick regeneration rates (Guariguata et al., 1997; Schedlbauer et al., 2007; Chazdon et al., 2009b; Norden et al., 2009; Sesnie et al., 2009; Bouroncle and Finegan, 2011). Soil types are generally acidic (pH ~4.5), primarily Inceptisols and Ultisols (Sollins et al., 1994). The terrain is composed of low hills and mountain slopes that range from 0 to 2696 m in elevation with steep ravines in upper elevation areas, while lowland areas are characterized by alluvial terraces and flood plains that range from 0 to 400 m in elevation (Sesnie et al., 2009). These soil types and the lowland terrain are well suited for the cultivation of crops, like pineapple, that require well-drained acidic soils. The most common pineapple variety planted in the SJLS region, MD2, grows well in soils with 4.5–5.5 pH and slopes <15% (Barrientos and Porras, 2010).

The land use and land cover change history in the SJLS region reflects a recent pattern in the tropics where intensive agriculture followed initial human colonization and associated deforestation (Lambin et al., 2003). The opening of the SJLS region in the 1970s and 1980s drove massive deforestation; redistributive land reform led to the eventual dominance of smallholder farms and pasturelands (Butterfield, 1994; Schelhas and Sánchez-Azofeifa, 2006). In the late 1980s, the policies driving this land rush officially ended, replaced by policies simultaneously encouraging forest conservation and NTAE expansion (Schelhas and Sánchez-Azofeifa, 2006).

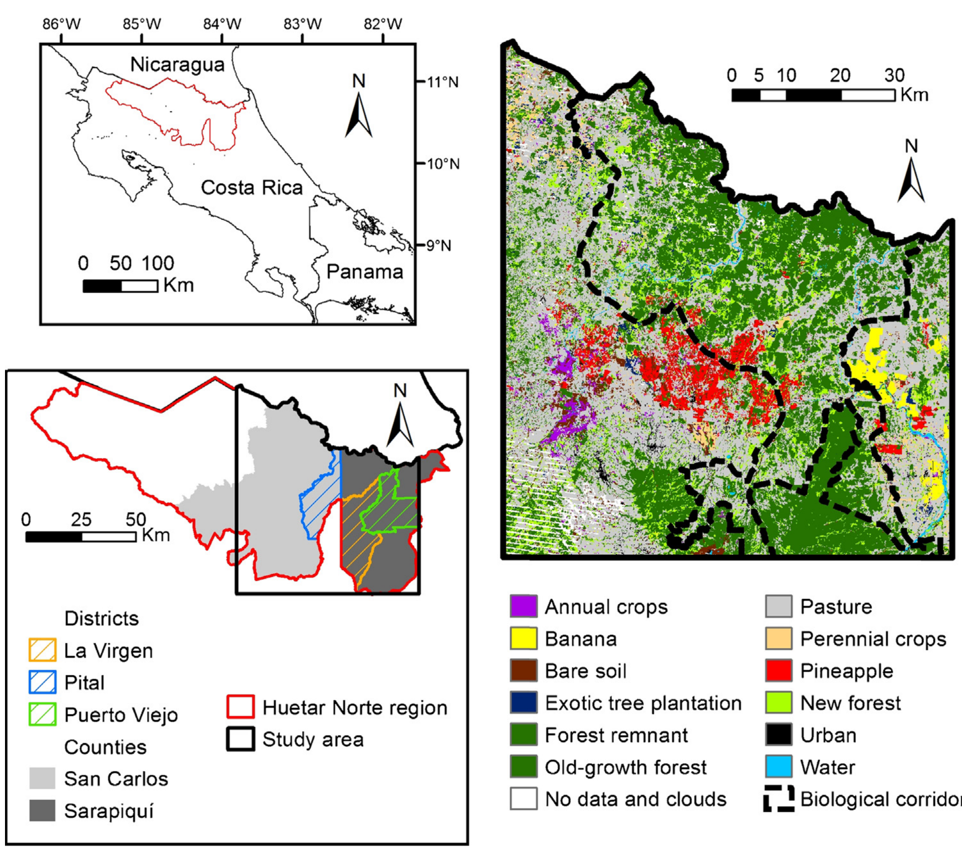

Fig. 1. The San Juan-La Selva biological corridor and surrounding areas are located in northeastern Costa Rica. High resolution Rapid Eye imagery from 2011 was used to identify 12 major land cover types. New forest land cover type includes secondary growth and native tree plantations.

One of these policies, the 1996 Forestry Law of Costa Rica, instituted a national ban on primary forest clearing; this theoretically "froze" remaining forest patches on the landscape (Watson et al., 1998; Morse et al., 2009). The Law also established an incentive system of payments for ecosystem services to encourage landowners to protect primary forest, allow forest regeneration and plant trees (Evans, 1999). To further protect the remaining forest in the region, a committee established the SJLS biological corridor initiative in 2001. The boundaries of the 246,608 ha corridor were delimited to include areas that retained significant primary forest cover and spanned the gap between Indio Maíz Biological Reserve in Nicaragua and Braulio Carrillo National Park in Costa Rica. Together, these protected areas and the SJLS biological corridor form an important link in the larger Mesoamerican Biological Corridor, an initiative begun in 1997 to facilitate regional ecological connectivity from Mexico to Panama while also promoting sustainable development and improving Mesoamericans' quality of life (IEG, 2011).

The primary policy change driving NTAE expansion during the same time period was Costa Rica's participation in Structural Adjustment Programs (SAPs). During SAP reforms Costa Rica restructured its agricultural policies away from protectionist, state-supported production of smallholder food crops toward a liberalized, globalized model promoting NTAE production and direct foreign investment (Edelman, 1999). The SAPs and more recent free-trade agreements with the European Union, the United States and now China continue to drive the expansion of NTAEs such as pineapple, citrus, and melon (Thrupp, 1995; Vagneron et al., 2009), and the decline of in-country production of food crops (Edelman, 1999). Pineapple expansion, similar to the early banana expansion in the 1990s south of the SJLS biological corridor (Vandermeer and Perfecto, 2005), influenced social and demographic changes in communities of the SJLS region. Employment opportunities at these plantations drew migrants from both Costa Rica and Nicaragua. As a result, Sarapiquí County, which covers most of the SJLS biological corridor (Fig. 1), has the fourth highest population of Nicaraguan immigrants in Costa Rica and the second highest population growth rate of all counties in Costa Rica (INEC, 2011). The growth of economic opportunities has led to some gains in economic welfare, such as increased television and car ownership (Table 1). However, farm ownership has not increased substantially, and other analyses demonstrate the population of farmers who own and work their own farm has decreased along with the population earning their primary income from the agricultural sector (Rodriguez and Avendaño, 2005).

The study region is a critical conservation area where 43.8% forest cover is maintained with demonstrated resilient forest dynamics despite population growth and a modernizing agricultural landscape (Letcher and Chazdon, 2009; Norden et al., 2009; Schedlbauer et al., 2007; Bouroncle and Finegan, 2011; Fagan et al., 2013). These factors make the SJLS region an appropriate site to assess the effects of NTAE-based agricultural intensification on rural economies and biodiversity conservation, and to explore the tradeoffs between parallel agricultural growth and conservation objectives.

3.2. Political ecology analysis

From September 2011 to May 2013 we conducted thirty-five semi-structured interviews applying the comprehensive approach (Kaufmann, 2011; Sibelet et al., 2013). Participants in our sample were selected to include a wide range of individuals and organizations involved in land use decisions and policy in the study region, including farmers' organizations, large landholders, conservation organizations and regional and national agricultural government officials. Interviews lasted 1–2 h and were conducted in both Spanish and English. Large landholders were purposively sampled across the study region and represented the range of land cover types in the SJLS biological corridor, from forested tourism reserves to pineapple plantations. All interviewees were asked to describe the factors and policies that influence land use or their business operation decisions in particular, to describe the scale and operation of their farming system or business, and to reflect on social-environmental change in this region. The interviews were digitally voice-recorded, fully transcribed and then coded in ATLAS Ti for themes drawn from PE related to land, labor and financial resource distribution, and perceptions of agricultural and environmental change and vulnerability. In addition to the interviews, we reviewed census data, peer-reviewed publications, and gray literature in both Spanish and English. Where district-level (Puerto Viejo, La Virgen and Pital) data were unavailable, county level data were used (San Carlos and Sarapiquí counties, Fig. 1). Where county-level data were unavailable, data were derived from analyses of the entire Huetar Norte region, which includes San Carlos and Sarapiquí counties as well as the counties of Guatuso, Los Chiles and Upala (Fig. 1).

3.3. Landscape ecology analysis

Several historical land cover maps are available for the SJLS region (Morse et al., 2009; Fagan et al., 2013). Recently, Fagan et al. (2013) used Landsat (30 m resolution) imagery to produce land cover maps for 1986, 1996, 2001, 2005, and 2011. In this study we used 2011 RapidEye multispectral satellite imagery (5 m resolution) and extensive ground truth points to produce the most high-resolution land cover map to date of the region.

Low cloud-cover RapidEye images were chosen from a 2010 to 2011 library of images. For each image, we calculated ten spectral indices based on the red edge band (Schuster et al., 2011) and a texture band based on a 7 × 7 pixel window from the Normalized Difference Red Edge Index (Appendix A). All layers were stacked to obtain a 17-band image, which was then classified in ENVI 4.7 (Exelis, Inc., McLean, VA, USA) using a support vector machine classification algorithm. Training data were obtained from 3000 ground truth points gathered from sources across the region

Table 1
Basic indicators of economic welfare, population composition, and population size in districts that cover the area of the SJLS biological corridor, 1984 and 2011[a].

Districts	1984			2011		
	Puerto Viejo	La Virgen	Pital	Puerto Viejo	La Virgen	Pital
Television ownership	19	8	75	4469	2676	3823
Car ownership	11	20	51	871	727	1159
Farm ownership	336	456	513	442	345	646
Domestic wood or charcoal use	607	822	1015	455	417	348
Nicaraguan immigrants	341	193	181	5249	1701	4114
Population (total)	4107	4451	6614	20,174	10,706	17,325

[a] All values are numbers of individuals. Puerto Viejo and La Virgen are in Sarapiquí County, while Pital is in San Carlos County. These 3 districts cover most of the area of the SJLS biological corridor (see Fig. 1). CCP Census Data (CCP, 2011; http://ccp.ucr.ac.cr/) are presented as number of individuals.

by Sesnie et al. (2010), and Fagan et al. (2013). We classified 12 dominant land cover types (Fig. 1). *Old-growth forests* are forested areas that have not been cleared during recent colonization events and exhibit a different spectral signature than forested areas known to be a product of regeneration within the past 30 years. Although this forest may have been impacted by selective logging, understory clearing or hunting, the resultant composition and structure is not distinctive from original primary forest with its canopy emergent trees canopy palms, lianas and native understory species. (Sesnie et al., 2009). *Forest remnants* corresponds to forest patches that are smaller than 2 ha in total size. *New forests* include both secondary growth, including all stages of natural regeneration, and native tree plantations (Guariguata et al., 1997). *Exotic tree plantations* mainly include species such as *Tectona grandis* and *Gmelina arborea*. Agricultural land cover types are *pasture*, *banana*, *pineapple*, *perennial crops* [e.g. peach palm (*Bactris gasipaes*), black pepper (*Piper nigrum*)] and *annual crops*. *Urban areas*, *water*, and *bare soil* are the remaining land cover types. Several forest classes exhibited spectral overlap, thus to improve classification we first classified all forest within the RapidEye images into a single category, and then subdivided this category into distinct forest types from the Landsat-based map developed by Fagan et al. (2013). Overall accuracy for the 2011 land cover maps is 94%, with different values for each land cover category (Appendix B). Accuracy was assessed using an independent set of 513 ground-truth points gathered in 2011; this data set was not used for image classification purposes.

To assess landscape composition and measure the effects of agricultural land uses on forest fragmentation, we selected a set of metrics related to area, contrast and aggregation available in the FRAGSTATS spatial statistics program (V.4.2, University of Massachusetts, Amherst, MA, USA) (Appendix C, Table C1). Metrics were selected based on their universality and consistency as independent components of landscape structure at the class and landscape level as identified by Cushman et al. (2008) and McGarigal et al. (2012). We then calculated all metrics within and outside the biological corridor separately (Fig. 1). More detailed information on the FRAGSTATS analysis is given in Appendix C.

Additionally, we conducted an analysis in Arc Map 10.1 (ESRI, 2011) to compare the amount of fine-scale landscape elements such as single trees, live fences, and riparian corridors, that are present in pineapple plantations versus other agricultural land cover types. These fine-scale habitat features cannot be identified using lower-resolution (30 m Landsat) imagery; the availability of high-resolution (5 m RapidEye) maps provides a new opportunity to assess the contributions of these fine-scale features to forest connectivity and to determine which land cover types are most likely to retain these features (Boyle et al., 2014). To quantify the fine-scale landscape features in each land cover type in the SJLS region, we used a tree cover map based on 5 m RapidEye and the zonal statistics tool in ArcMap 10.1. Considering single trees and groups of trees with a size <0.5 ha, we calculated the mean percentage area covered by trees for the entire area of each individual land cover type: pineapple, annual crops, perennial crops, banana and pasture.

To understand the potential growth boundaries of pineapple, we calculated the percentage of the SJLS biological corridor and surrounding landscape that is suitable for its cultivation. We used the following criteria to identify optimal land for pineapple cultivation: (a) slope of less than 15%, (b) characterized by Inceptisol or Histosol soils, and (c) occurring within 3 km of a well-developed (i.e., paved or well-maintained dirt) road (Enríquez, 1994; Pitácuar, 2010). Slope, soil type and distance from an improved road were obtained using layers from the Atlas of Costa Rica (ITCR, 2008). Although these are agro-ecological criteria for pineapple production, their use is supported by an economic analysis conducted in the SJLS biological corridor that verified pineapple production is the most profitable land use and consistently occurs closest to major road networks when compared to other crops, pasture and forest (Pitácuar, 2010).

4. Results and discussion

Our findings link spatial patterns of land use in the study region to historical and current economic policy, and reveal the impacts of pineapple expansion on both social and ecological systems. Our LE analyses indicate that the study region (Fig. 1) is dominated by pasturelands (39%), old-growth forest (34%) and new forest (9.1%) (Table 2). Pineapple plantations and patches of bare soil (likely including land in preparation for agricultural uses) respectively cover 3.6% and 2.9% of the landscape. The rest of the landscape is occupied by other types of agricultural lands, tree plantations, urban areas and small (<2 ha) patches of remnant forest; each of these land cover types represents between 2.1% and 0.72% of the landscape (Table 2).

4.1. Pineapple expansion and intensification as a social, economic and ecological process

As illustrated in Fig. 2, pineapple was almost non-existent in the landscape in 1986, around the time of the SAP reforms, but increased markedly by 1996 and showed the greatest expansion from 2001 to 2011. This pattern of expansion was not limited to the SJLS region; from 2006 to 2010 the land area across Costa Rica used for pineapple cultivation doubled from 22,400 ha to 45,000 ha

Table 2
FRAGSTATS analysis results summarizing area and subdivision metrics for all land cover classes in the San Juan-La Selva region. Metric units are given in parenthesis, and a detailed definition of each metric is available in Appendix C, Table C1. Land cover categories are listed from highest to lowest according to their total area in the landscape.

Land cover type	Area				Subdivision		Isolation	
	CA (ha)	PLAND (%)	LPI (%)	AREA (ha)	SPLIT	NP	PROX	ENN (m)
Pasture	244,959	39.7	12.3	57	45	4299	337,372.10	84
Old-growth forest	210,022	34.0	6.7	50	105	4185	28,891.80	120.9
New forest[a]	56,448	9.1	0.1	6	160,503	10,120	113.4	141.6
Pineapple	22,139	3.6	0.9	33	7017	672	25,759.70	241.9
Bare soil	17,968	2.9	0.1	6	248,864	3290	127.5	273
Perennial crop	13,259	2.1	0.1	6	337,451	2291	259.6	238.7
Banana	8919	1.4	0.6	29	21,397	312	1571.60	968.2
Annual crop	7815	1.3	0.1	5	268,389	1462	625.7	379.2
Exotic tree plantation	6609	1.1	0.04	4	1,551,421	1528	43.4	455.8
Urban	4565	0.7	0.1	5	1,298,114	980	246	329.3
Forest remnant	4424	0.7	0.001	1	56,602,757	3088	5.5	429.3

CA: total area, PLAND: percentage of landscape, LPI: largest patch index, AREA: mean patch size, SPLIT: splitting index, NP: number of patches, PROX: proximity index, ENN: mean Euclidean nearest-neighbor distance.
[a] This land cover type includes secondary growth and native tree plantations.

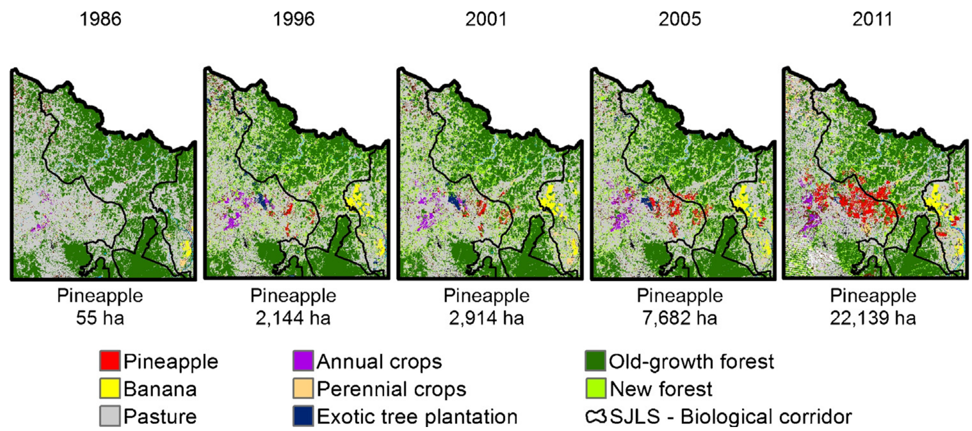

Fig. 2. The expansion of pineapple in the San Juan-La Selva biological corridor and surrounding landscape, 1986–2011. The 1986, 1996, 2001 and 2005 maps are from Fagan et al. (2013), and the 2011 map was produced for the current study. The legend shows major land use types and forest cover types. The "new forest" class includes secondary growth and native tree plantations.

while the crop export value increased 55% (Barquero, 2011). By 2011, pineapple had become the second most important agricultural export for Costa Rica (worth $666 million in 2010) and had created 27,000 direct jobs and 110,000 indirect jobs in production, harvesting, and processing (Barquero, 2011). Nicaraguan immigrants are the principal labor force for the majority of these unskilled jobs, where wages range from $1.20 to $2.00 per hour (Acuña-González, 2009). Although field interviews confirmed these wages are comparatively better than in less regulated sectors of the agricultural economy (i.e., cassava) and migration for work is the primarily pull to this region, the work in pineapple plantations is physically demanding, results in high exposure to pesticides, and can have low job and wage security especially for undocumented workers (ILRF, 2008; Acuña-González, 2009; Shaver, 2014). Nearly 50% (22,138.9 ha) of the total national land area in pineapple lies within our study region. Fagan et al. (2013) found that pineapple production in the SJLS region from 2001 to 2011 was largely not replacing old-growth forest, but was instead expanding primarily into lands previously used for pasture or annual and perennial crops such as cassava, peach palm, and ornamental plants, as well as young regenerating forests, which experienced high rates of clearing during this time period.

In the SJLS region, pineapple plantations currently occupy a higher percentage of total land than traditional agricultural production systems including annual and perennial crops (Table 2). Although pineapple plantations cover less than 4% of the total study region, they usually occupy large patches, second in size only to pasture and forest patches (Table 2). Of total land dedicated to pineapple plantations in the study region, 78% occurs outside the SJLS biological corridor and 22% lies within (Table 3). Outside the corridor, pineapple patches are 10 ha larger on average and more aggregated than those found within. Pineapple's more aggregated spatial configuration relative to other crops (Tables 2 and 3) illustrate how pineapple homogenizes the agricultural matrix, converting smaller farm parcels and pasturelands into large-scale plantations.

Our pineapple suitability analysis suggests that this trend of homogenization is likely to spread across more of the landscape, especially if road development continues at its current pace. We found that in the entire study region, 26.2% of the land is highly suitable for pineapple cultivation and an additional 15.7% is moderately suitable (Fig. 3). Considering only land within the corridor, currently 2% is under pineapple cultivation (Table 4). However, 17.1% is highly suitable for future pineapple cultivation and an additional 16.6% is moderately suitable. Both our suitability analysis and current economic trends (Fold and Gough, 2008; Vagneron et al., 2009) suggest future pineapple production will likely expand both within and outside of the corridor.

Table 3
Comparison of the spatial characteristics of dominant land cover types both within (245,008 ha) and outside (371,607 ha) of the San Juan-La Selva biological corridor. Metrics units are given in parenthesis. Core area and contrast metrics are given only for old-growth forest.

	Metric	Old-growth forest	New forest[a]	Pasture	Pineapple
Within	PLAND (%)	47.2	11.3	32.0	2.0
	LPI (%)	13.7	0.1	3.0	0.9
	AREA (ha)	76	6	37	26
	SPLIT	33	44,863	269	9892
	PROX	47,516	129	22,451	9659
	ENN (m)	94	123	87	407
	CORE (ha)	62			
	TECI (%)	57			
Outside	PLAND (%)	25.3	7.7	44.7	4.6
	LPI (%)	7.6	0.1	13.3	1.1
	AREA (ha)	30	5	59	33
	SPLIT	146	142,119	36	4552
	PROX	10,596	92	253,769	20,329
	ENN (m)	128	156	80	197
	CORE (ha)	22			
	TECI (%)	63			

AREA: mean patch size, CORE: mean core area per patch, ENN: mean Euclidean nearest-neighbor distance, LPI: largest patch index, PLAND: percentage of landscape, PROX: mean proximity index, TECI: total edge contrast index: mean edge contrast index, SPLIT: splitting index.
[a] This land cover type includes secondary growth and native tree plantations.

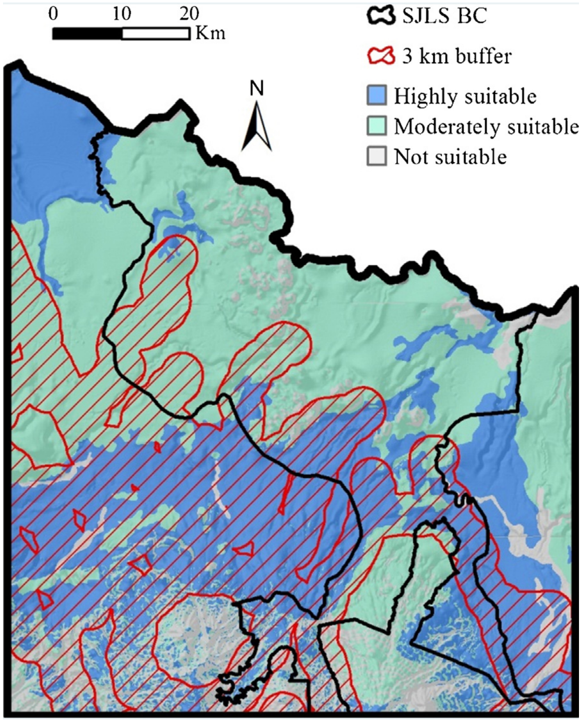

Fig. 3. Pineapple suitability analysis. Suitable areas for pineapple cultivation were identified according to soil type and slope. Because the probability of pineapple cultivation increases with accessibility to roads, a 3 km buffer (hatched area) around principal roads is also shown.

In addition to changing the composition and configuration of land cover types, pineapple is also driving a social economic shift within the agricultural sector away from smallholder crops and toward intensive, large-scale, agribusiness-dominated production systems (Table 4). The NTAE sector's social and economic organization is related to cost advantages associated with larger scale operations that favor agribusinesses and inhibit smallholder participation (Table 4). For example, in the Huetar Norte region, the average investment to begin planting pineapple is $9900/ha (Villegas et al., 2007). In an area where the median monthly income of agricultural households is $625, this investment capital requirement is prohibitive for most households (Programa Estado de la Nación, 2010). Furthermore, in a survey of pineapple producers in the northern part of the corridor, Piñero and Díaz Ríos (2007) found it cost small and medium pineapple producers between 0.036 and 0.013 cents to produce 1 kg of fruit whereas it cost large producers 0.003 cents. When the last pineapple census was conducted in 2004, pineapple farms in the Huetar Norte region with less than 10 ha accounted for only 12.9% of the land in pineapple production, while farms larger than 100 ha accounted for 76.8% (MAG census, 2005). These large farms range in size from 200 to 1200 ha, with an average of 492 ha under cultivation (Villegas et al., 2007). In our FRAGSTATS analysis (Table 3), the largest patch of pineapple outside the SJLS biological corridor was 5466 ha and the largest within the corridor was 2308 ha; this suggests individual pineapple plantations are large and tend to border each other to form contiguous mega-patches of pineapple across the landscape.

The market structure of the pineapple sector also favors large-scale plantations over small pineapple farms. The pineapple variety MD2 is densely planted, and the proportion of labor done by hand requires a large, year-round hired labor force. Conventional pineapple cultivation relies on high agrochemical and infrastructural investments (Table 4), an expense most small farmers cannot afford (Piñero and Díaz Ríos, 2007). Large agribusinesses is vertically integrated in this sector (i.e., it dominates all stages of production and market distribution) (Lee et al., 2012), or fulfills contracts for a larger company, typically Dole or Del Monte, who together control 85% of all pineapple exported from Costa Rica (Vagneron et al., 2009; Blacio et al., 2010; Amanor, 2012). This market structure favors economies of scale and is high risk for smallholders who are easily outcompeted by larger companies (Piñero and Díaz Ríos, 2007; Lee et al., 2012).

Local government officials in the SJLS biological corridor are aware of how large agribusinesses dominate pineapple production and of how untenable pineapple is as a primary rural development strategy for small farmers. A Ministry of Agriculture representative

Table 4
Comparison of different production system variables demonstrating that intensification occurs across multiple components of a production system and shifts the socio-economic organization of agricultural production [a].

Component of the production system	Smallholder farm	Extensive cattle ranch	Agribusiness pineapple plantation
Labor type and intensity	Family labor	Family and hired labor: 0.001 person-days/ha.	Hired labor: 0.5 person-days/ha.
Cost of production	Varies; most costly product is pepper at $2500/ha	Low	High (average $9900/ha for international export) up to $22,000/ha for organic production[b]
Use of inputs	Varies	Low	High (average of 1000 kg/ha/yr of fertilizer); uses machinery, continuous production
Land cover type	Diversified, often including subsistence food crops and remnant trees	Pasture, sometimes with remnant trees and live fences Density: 1–3 cow/ha.	Monoculture Density: 72,000 plants/ha
Average size	0.9–6 ha	35 ha	492 ha
Market destination	Sold at national farmers' markets, to packing plants or to intermediaries at farm gate	Sold at regional auctions for international export or for national consumption	Exported internationally to major supermarket chains via direct contracts
Principal reason for land use	Low investment, easy market accessibility, low technical/labor requirements.	Easy market accessibility, low labor requirements, culture	Price, international demand

[a] Interviews 2011–2013. Smallholder data: Sáenz-Segura et al. (2007); MAG (2005). Pineapple data: FAO (2007). Cattle data: Holmann et al. (2008). All data are for the Huetar Norte region (see Fig. 1).
[b] Organic production is more costly than conventional production due to increased labor and production costs (e.g. manual weeding/pest management, covering fields in plastic), limited availability of research on optimal production techniques and plant varieties, and lower yields per hectare.

remarked, "With MD2, there was an explosion of big producers . . . some small and medium farmers also got involved who were in other crops, were in livestock, tubers or palm and they got into pineapple. Why? Because in 2003–2008, it was profitable. There were good prices, costs were good, but with the 2008 crisis which erupted in the U.S. . . . followed [by] Europe in the years 2010–2012 . . . we were in a bad situation, and people moved away from the activity, especially smallholders."

Several times interviewees described land conversion to pineapple as a duel process of concentrating land and reducing smallholder land ownership. A prominent farmer and rancher's organization leader explained "Many farmers who produced not only cattle but also tubers, very few of them changed their activities to grow pineapple because those that had 50 hectares or less – in pineapple that is very little – so many of them sold their land to [pineapple] companies and have left the activity [farming]." For example, one of the larger pineapple plantations in the region covers 1500 ha, 43% of which is rented land from neighboring farms. This trend of 'land grabbing' has been documented in pineapple in Ghana (Amanor, 2012) as well as for other NTAEs like oil palm in southern Costa Rica (Piñero and Díaz Ríos, 2007). Although, this may provide immediate rent-based income for smallholders or income in the short term from the sale of their land, often small farmers struggle to transfer into another profession due to low education and professional experience. These losses of control either in land use decision-making or in land ownership are often detrimental in the long term as they can lead to land degradation and foster insecurity in the rural poor through dependency on wages and commodity booms that are typically temporary and unsustainable ecologically and economically (Amanor, 2012).

In reflecting on the social and environmental change caused by the expansion of pineapple, different stakeholders have distinct interpretations of how pineapple expansion plays into the larger vision of rural development. Stakeholders interested in sustainable development for both local farmers and local biodiversity often expressed concern about the economic and ecological vulnerability to pineapple expansion. As one representative of the SJLS biological corridor initiative said "I have a very encompassing vision of sustainability and I see that the pineapple scheme is not what is going to make the country advance in the theme of sustainable development or for the local people. We are betting on an export product that in any given moment the market changes, at an international level, the next day it is going to be Philippines or Ecuador or Hawaii . . . If the prices fall, the farmers here will be left in complete ruin because they are not owners of their farms, many times they sell or rent, lose control of the production, they lose control of their land and they all have big loans for machines, fertilizers and costly technology packages. It is a very big risk and for [forest] connectivity it is fatal."

In contrast, a pineapple company manager saw this expansion increasing employment and therefore development in an economically marginalized region. He explained, "Always, this type of company [agribusiness] brings development. For example, with 400 ha someone can handle more or less 300 cows. To handle 300 cows, they have to employ about three people. Pineapple needs one person per half hectare. That is to say, yes it brings development." One of the largest forest landowners in the region reiterated this idea that pineapple companies develop the region and facilitate economic growth: "the town was here, but it was a very small town. There was no economic activity to speak of, I mean, a lot of people were just living off their land . . . when these pineapple guys came here, they improved a lot of stuff. They had the money to improve roads, they had the money to talk to politicians and bring infrastructure in here, I mean, you see now in this area, a lot of nice pick-ups driving around – those are people that sold land for a good price here, so a lot of stuff has changed here." These diverging descriptions demonstrate that people living and working in this landscape have conflicting ideas about a desirable path to development in this region and the long and short-term benefits of pineapple. This rural development model, with its emphasis on large-scale production of pineapple and exclusion of smallholders, demonstrates the tradeoffs between national economic objectives for export growth and job creation and regional issues of equity, household food security and rural poverty alleviation (Tomich et al., 2001).

On a global scale, large agribusiness prevalence and smallholder exclusion do not always characterize NTAE crop production. For example, prior to 2000, the majority of the fresh pineapple imported to the European Union (E.U.) came from West African countries, where smallholder production and smallholder integration into the value chain predominated (Fold and Gough, 2008). The primary reason pineapple production in Costa Rica has not followed a similar pattern is Del Monte's dominance in its market, which until 2003 held the exclusive patent to the MD2 pineapple variety. This monopoly excluded initial smallholder participation in the production boom and consolidated the pineapple value chain into the hands of large agribusinesses (Fold and Gough, 2008). MD2s recent introduction in Ghana is driving a shift from smallholder to agribusiness production systems, resulting in land concentration, increased dependence on wage labor for agricultural livelihoods, and prohibitive production costs for smallholders (Fold and Gough, 2008; Amanor, 2012). As these aspects of the 'Costa Rican' model of pineapple production continue to be replicated globally in other NTAE crops, other regions may also experience similar changes to socio-economic characteristics and landscape composition.

4.2. Impacts of pineapple expansion on forest and future biodiversity conservation in the agricultural matrix

Given the proportion of original forest cover remaining, the study landscape can be categorized as fragmented (Table 2; McIntyre and Hobbs, 1999). However, results from FRAGSTATS analysis indicate the remaining old-growth forest is not highly subdivided, as the aggregation metrics SPLIT, PROX, ENN and LPI show (Table 3); the largest old-growth forest patch covers almost 7% of the total study region (Table 2). In accordance with the original criteria selected to establish the SJLS biological corridor, our results show that more than half of the total old-growth forest cover within the SJLS region is located within the corridor limits, and in contrast to the landscape outside the SJLS biological corridor, forest remnants within the corridor are considerably larger and less isolated (Table 3).

These results confirm the findings of Morse et al. (2009) and Fagan et al. (2013) that showed the 1996 Forestry Law and the system of payment for ecosystem services have been successful in promoting conservation of old-growth forest in this landscape. The matrix between these forest patches continues to change, though, and the assessment of how these changes affect remaining forest should become a priority.

Previous studies document that forest directly adjacent to agricultural land uses suffers from "edge effects", which drive changes in forest microclimate, tree mortality, and in the abundance and distribution of animal species; the severity of edge effects vary depending on the type of adjacent land use (Fischer and Lindenmeyer, 2007; Schedlbauer et al., 2007; Bouroncle and Finegan, 2011; Laurance et al., 2011). FRAGSTATS metrics such as core area (CORE), which describes the patch area free of edge effects, and edge contrast indices (TECI), which describe the proportion of forest edge in maximum contrast (Table A1), are useful metrics for assessing the impact of edge effects. TECI is based on the dissimilarity in vegetation structure between two adjacent land cover types; for example, new forest and old-growth forest would have low contrast values, whereas pineapple and old-growth forest would have high contrast values. When higher contrast land covers, such as bare soil, pineapple, or pasture are adjacent to forest, it reduces the core area of the forest patch that is free of edge effects (CORE) (Table 3). In the SJLS biological corridor there is a high incidence of old-growth forest patches that border high contrast land covers like pasture or pineapple and are thus vulnerable to strong edge effects (Table 3).

Euclidian distance to the nearest patch of the same type (ENN) and the proximity index metric (PROX) are also useful for assessing how old-growth forest patches are affected by the agricultural matrix (Table 5). A low value of the proximity metric indicates that the patch is more isolated and has more forest fragmentation in its surroundings (Whitcomb et al., 1981). Our results reveal that old-growth forest patches sharing a border with pineapple have higher ENN values and lower PROX values than similar patches bordered by pasture (Table 5), meaning that the patches surrounded by pineapple are dramatically more isolated. Interestingly, old-growth forest patches that share a boundary with pineapple have a larger mean area than those surrounded by pasture (Table 5). This is due to differences in production strategies between pasture and pineapple. Pastures often retain small old-growth forest patches, groups of trees, and riparian areas, which serve to provide water and shade for livestock. In contrast, pineapple plantations seek to maximize continuous planted area, and therefore retain the old-growth forest patches protected by law but eliminate single trees or groups of trees within the production area, which can be important for connectivity. The isolating effect of pineapple on forest patches is a concern that conservation interests in the corridor identified. One reserve owner noted, "We have a small [forested] area that depends on the larger [protected] areas to have a diversity of organisms ... we want to generate connectivity so that we do not become converted into an island surrounded by pineapple." Furthermore, Fagan et al. (2013) found that between 2001 and 2011, pasture was three times more likely to revert to natural secondary regeneration than were croplands, including pineapple.

Although the new forests land cover type occupies more than 55,000 ha in the landscape, the high number of patches (NP) of small mean size (AREA) with low mean proximity values (PROX) to other similar patches indicates that this type of vegetation cover is subdivided and isolated (Tables 2 and 3). The new forest land cover type is equally distributed outside and within the SJLS biological corridor, but within the corridor, patches are less subdivided and represent a higher percentage of the total land area (Table 3). Within this land cover type, later stages of secondary growth are known to have different species composition but similar vegetation structure and tree species richness to old-growth forest (Finegan, 1996; Guariguata and Ostertag, 2001), and provide habitat for species of conservation concern (Fischer et al., 2006). Using high-resolution imagery allowed us to detect small (<2 ha) old-growth and new forest patches not detected in previous studies using Landsat imagery (Fagan et al., 2013). These small forest patches grouped within the forest remnant land cover type represent a very low percentage of the landscape, but potentially serve as stepping-stones to enhance forest connectivity (Harvey et al., 2005; Hanson et al., 2007). For example, Hanson et al. (2008) found long-distance gene flow can be maintained among separated populations of canopy tree species through the connectivity stepping-stones of isolated trees or small forest patches provide.

Results of our analysis of fine-scale landscape features indicate that, among all land covers types analyzed, pineapple has the lowest percentage of tree cover per unit area, with the exception of banana plantations (Fig. 4). The greatest differences in tree cover were observed between pineapple and perennial crops, such as peach palm or fruit trees and pasture, which have twice the percentage of tree cover (3.9–4.7%) than pineapple plantations. Another important difference between pineapple versus pasture or perennial crops is the spatial distribution of tree cover. In pasture and crops, single trees and small groups of trees are retained within the land use rather than just at the edges, as in pineapple (Fig. 4). A pineapple producer explained the practice of maintaining only legally mandated tree cover within the plantations. There is a river that cuts across the plantation, and as he said, "I have to leave 60 meters or 30 meters on each side [of the river] and that makes lot[s] of hectares. Over there – there is a spring and with a spring you have to leave 1000 meters around it. So that's how they form patches of forest. There are patches all over but when you combine them it's a lot of forested land." The practice of retaining forest cover only along riparian corridors is evident in Fig. 4, where it can be seen that trees in pineapple plantations (a) are confined to depressions or river corridors within the plots, leaving most of the plantation void of tree cover. In contrast, trees in pasture (b) are usually dispersed across a large area, creating patches of low and high tree density and maintaining heterogeneity within this land use.

Land cover types characterized by having either more scattered trees and live fences (Perfecto et al., 2003; Vaughan et al., 2007; Harvey et al., 2008), or vegetation structure that is more similar to natural forest cover (Brotons et al., 2003; DeClerck et al., 2010; Prevedello and Vieira, 2010; Eycott et al., 2012; Vílchez Mendoza et al., 2014), are more likely to be used by wildlife for foraging, breeding, or as stepping stones to reach other habitat patches (Kupfer et al., 2006; Fischer and Lindenmeyer, 2007; Harvey and Villalobos, 2007; Chazdon et al., 2009a; Gilbert-Norton et al., 2010; Vílchez Mendoza et al., 2014). The reduced tree cover within pineapple plantations and the pronounced difference in vegetation structure between pineapple and natural forest suggest that pineapple likely reduces habitat availability and connectivity when compared to other land cover types such as pasture or annual and perennial crops.

The SJLS region retains a significant proportion of old-growth forest cover, but our analyses show conversion of smallholder crops and pasturelands to pineapple plantations affects forest cover, leading to loss of total tree cover and of landscape heterogeneity. Furthermore, our pineapple suitability analysis suggests that if road development and favorable market conditions continue, pineapple plantations will further spread into the SJLS

Table 5
Mean patch area and isolation metrics for forested land cover classes.

	All patches			Share boundary with pasture (n = 3559)			Share boundary with pineapple (n = 402)		
	AREA (ha)	PROX	ENN. (m)	AREA (ha)	PROX	ENN (m)	AREA (ha)	PROX	ENN (m)
Old-growth forest	57	28,892	121	29	31,459	115	44	3202	176
New forest[a]		113	142						
Forest remnant		6	429						

[a] This land cover type includes secondary growth and native tree plantations. AREA: mean patch size, PROX: proximity index, ENN: mean Euclidean nearest-neighbor distance.

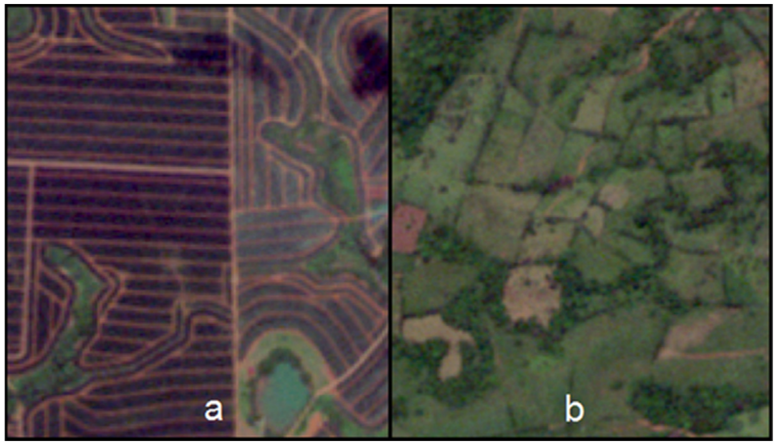

Fig. 4. Mean percentage of area covered by fine-scale forest features such as single trees, groups of trees and live fences, in the dominant agricultural land cover categories: (a) pineapple, (b) pasture. Pictures correspond to 5 m resolution RapidEye imagery. STD is standard deviation.

biological corridor. These findings emphasize the importance of developing effective policies to mitigate current and future impacts of pineapple expansion on the linked social and ecological systems in the study region.

4.3. Current policy on pineapple at a landscape scale

Policy discussions about the future of pineapple in Costa Rica have been occurring at the national level through the National Pineapple Platform (Plataforma Nacional de Piña – PNP), which is a two-year participatory dialog hosted by the United Nations Development Program, the Ministry of Agriculture and the Ministry of the Environment. Participants in this dialog have developed an action plan for 2013–2017 (http://www.pnp.cr/plan.php), focusing mostly on actions to improve practices at the farm level; an issue the leaders in the SJLS biological corridor initiative have identified, "There are management standards but they are focused completely on the plantation; there is no vision of the landscape."

Municipalities are also important players in forming policies to regulate pineapple. They have legal power to develop a territorial land use-zoning plan called a "plan regulador" which can direct where pineapple expands and limit its growth if desired. This plan is the best mechanism municipalities have to effectively partition public and private land and exclude certain land uses or developments, but most rural municipalities do not have current or well-developed plans (Pérez Pelaez and Alvarado Salas, 2003). "Sometimes, there are not sufficient resources to do studies, because of this they [municipalities] get behind a bit ... so until they do the studies, they cannot determine legally, under their land use zoning plan, what is the zone for this [X] land use," explained a representative of the National Environmental Technical Secretariat (Secretaría Técnica Nacional Ambiental).

5. Conclusions

Our results reveal how pineapple expansion produces social and environmental change with local conservation implications. In particular, our synthesis of data suggests that pineapple concentrates land, labor, and financial resources on the landscape, thereby increasing the homogeneity of the agricultural economy in the study region. When spatially heterogeneous pastures with tree cover or smallholder farms are converted to monoculture plantations dominated by agribusinesses, the loss of autonomy (i.e., land ownership or land use decision-making) constrains farm-based livelihoods, food security and agricultural diversity. Pineapple production also simplifies and homogenizes the agricultural matrix between forest patches. It further isolates old-growth forest patches, and reduces total tree cover, all of which are critical for maintaining connectivity of remnant forest patches. Since biodiversity in agricultural landscapes is positively associated with percent of tree cover and landscape heterogeneity, the continued spread of pineapple plantations is likely to have a negative effect on biodiversity conservation.

Despite pineapple's negative influence on some social and ecological components of the landscape, in some ways the SJLS region represents a best-case scenario. Strict and innovative regulatory and incentive schemes have successfully promoted retention of old-growth forest cover, and pineapple is just beginning to dominate agricultural land use. Spatially heterogeneous smallholder production systems and pasture with tree cover are still abundant within the corridor and contribute to forest connectivity.

To protect biodiversity and promote inclusive rural development in the face of pineapple expansion we propose several landscape-level policy and management approaches. First, management approaches should implement plans that have already been developed. In the SJLS region there has been unprecedented inter-institutional dialog and coordination to develop an action plan for sustainable pineapple production, which is summarized in the PNP action plan. Second, policies that encourage landscape-level planning (Sayer et al., 2012) should be established to promote land use heterogeneity and economic diversity within the agricultural sector. Retaining smallholder agriculture as a viable livelihood should be a priority for both conservation and agricultural policy makers, as smallholders are critical contributors to rural poverty alleviation, food security, landscape heterogeneity and crop diversity (Dahlquist et al., 2007; Perfecto and Vandermeer, 2008; Tscharntke et al., 2012). Third, landscape level planning should follow national level policies such as the Costa Rican 2021 carbon neutrality goal. This goal has already motivated several multinational agribusinesses to establish carbon neutral production strategies (Kilian et al., 2012). Agribusinesses could also commit to retaining more forest cover within plantations or to forest offset programs; this would contribute to their goals of offsetting carbon emissions while also increasing habitat connectivity. However, any investments toward carbon neutrality or sustainable production by agribusinesses need to be matched throughout the value chain by retailers in marketing and setting higher selling prices to offset these investments. Fourth, the Forestry Law of 1996 should be updated to more effectively target conservation and restoration of both riparian and secondary forest to promote increased habitat connectivity

(Fremier et al., 2013) and move Costa Rica closer to its goal of carbon neutrality. Current conservation regulations in Costa Rica protect old-growth forest, while creating perverse incentives that block regrowth of secondary forest (Sierra and Russman, 2006; Morse et al., 2009; Fagan et al., 2013) despite evidence that secondary forests contribute to carbon sequestration (Pan et al., 2011).

Due to the global relevance of balancing local economic growth with biodiversity conservation, this Costa Rican case study can serve as a model against which to compare other regions currently undergoing rapid expansion of NTAE crop production. Indeed, understanding the social-ecological impacts of agricultural intensification in tropical regions is a critical piece of promoting the sustainability of rural agrarian development around the world. As shown in this study, landscapes operate as integrated social-ecological systems, and must be managed holistically to retain spatially and economically diverse land uses that support sustainable rural livelihoods and create a balance between agricultural production and biodiversity conservation.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.gloenvcha.2015.02.006.

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