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Land cover dynamics following a deforestation ban in northern Costa Rica

M E Fagan[1], R S DeFries[1], S E Sesnie[2], J P Arroyo[3], W Walker[4], C Soto[3], R L Chazdon[5] and A Sanchun[6]

[1] Department of Ecology, Evolution, and Environmental Biology, Columbia University, USA
[2] US Fish and Wildlife Service, Southwest Region, Albuquerque, NM, USA
[3] Department of Geography, McGill University, Canada
[4] Woods Hole Research Center, Falmouth, MA, USA
[5] Department of Ecology and Evolutionary Biology, University of Connecticut, USA
[6] EARTH University, Guacimo, Costa Rica

E-mail: mef2153@columbia.edu

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Abstract
Forest protection policies potentially reduce deforestation and re-direct agricultural expansion to already-cleared areas. Using satellite imagery, we assessed whether deforestation for conversion to pasture and cropland decreased in the lowlands of northern Costa Rica following the 1996 ban on forest clearing, despite a tripling of area under pineapple cultivation in the last decade. We observed that following the ban, mature forest loss decreased from 2.2% to 1.2% per year, and the proportion of pineapple and other export-oriented cropland derived from mature forest declined from 16.4% to 1.9%. The post-ban expansion of pineapples and other crops largely replaced pasture, exotic and native tree plantations, and secondary forests. Overall, there was a small net gain in forest cover due to a shifting mosaic of regrowth and clearing in pastures, but cropland expansion decreased reforestation rates. We conclude that forest protection efforts in northern Costa Rica have likely slowed mature forest loss and succeeded in re-directing expansion of cropland to areas outside mature forest. Our results suggest that deforestation bans may protect mature forests better than older forest regrowth and may restrict clearing for large-scale crops more effectively than clearing for pasture.

Keywords: Costa Rica, deforestation, agricultural intensification, land sparing, protected areas, payments for environmental services (PES), tree plantations, remote sensing
S Online supplementary data available from stacks.iop.org/ERL/8/034017/mmedia

1. Introduction

Lowland tropical rainforests are under threat from agricultural expansion, particularly in areas with fertile soils [1–4]. Increases in global agricultural production are needed to meet the projected 70–100% growth in food demand by 2050 [5, 6]. Higher yields are likely to account for most of the production increase, but tropical forests are threatened with future conversion to staple and luxury crops [7]. Although high-yield, high-input ('intensive') agricultural production has been proposed to relieve agricultural pressure on natural habitats through 'land-sparing' [5, 8, 9], export-oriented, intensive agriculture remains a leading driver of habitat destruction in many tropical regions [2, 10–12]. By increasing the profitability of agriculture, intensive cropping systems have the potential to increase expansion into forests [13, 14], or become 'land-hungry.' To promote agricultural intensification while protecting tropical forests, effective and enforce-

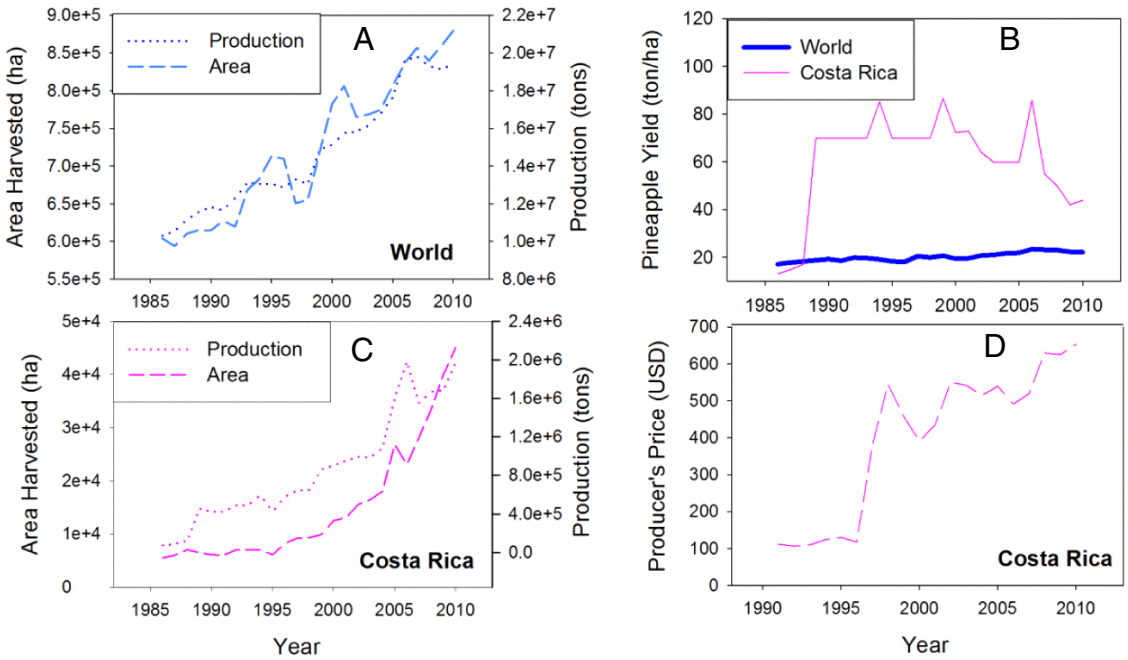

Figure 1. Pineapple production in Costa Rica and globally over the last two decades [40]. Both global and Costa Rican production have grown along with area harvested (panels (A) and (B)). Pineapple yield per hectare has been dropping in Costa Rica in the last decade (panel (C)), so most new production has come from expansion as farm-gate prices have risen (panel (D)).

able policy mechanisms are needed to combat deforestation from cropland expansion [15, 16].

Unfortunately, options to protect forests on private land are limited in regions with high potential return from agriculture [14]. Protected areas have been successful in limiting agricultural expansion into forest [17–19], but establishing parks in productive agricultural regions increases their negative economic impact [14, 20, 21]. Payments for environmental services (PES) can give landowners incentives to retain forest cover, but they directly compete with high returns from agriculture [14, 22] and depend on volunteer subscription [23]. Partial land-use restrictions (e.g., slope protections, riparian buffers, logging bans) have had mixed success in combating deforestation for agriculture, in part because of the difficulties in enforcing selective bans on clearing activities across large areas [16, 24–30]. All forest protection efforts may displace deforestation to unprotected areas [16, 31–34].

Can policies that mandate forest protection outside parks maintain forest cover without negatively affecting production in regions under agricultural pressure? In the fertile humid lowlands of northern Costa Rica, we examined changes in deforestation and regrowth in the context of rising agricultural pressure and the implementation of a country-wide deforestation ban. Regional moratoriums on forest clearing, which have been tried in a few countries [28, 35–38], may be hard to maintain long-term in the face of economic trade-offs [7, 16, 21, 39]. The Brazilian soy moratorium and Chinese logging ban contributed to local declines in forest loss ([17, 32], although see [33]), and the recent Indonesian forest concession ban is restricted to primary and peat forest [38]. Costa Rica's ban may be the most restrictive in that it covers the entire country, it provides few exceptions for acceptable deforestation, and it allows only regulated logging under its own guidelines for sustainable forestry [39].

Costa Rica is a global leader in both conservation and intensive tropical agriculture; a fifth of the country has some type of protected status [7], and it has some of the highest yields per hectare of bananas and pineapples in the world [40]. In the last two decades, Costa Rica has extended its conservation efforts to private lands, banning deforestation country-wide in 1996 [37, 39] and implementing a payments for environmental services (PES) program to protect forests and promote reforestation within nationally designated biological corridors [23, 37, 41, 42]. The 1996 Forest Law was the outcome of several decades of increasingly conservation-oriented forest policies, including establishing the national park system (1969) and subsidies for tree plantations (1979) [43]. If Costa Rica truly represents a 'model' for conservation in developing countries, the success of its policies on private lands should indicate their potential applicability elsewhere [23, 44]. The 1996 Forest Law lowered deforestation rates shortly after its passing [37, 45], but its long-term effectiveness has not been evaluated, especially in light of the recent boom in pineapple production (figure 1). In the last decade, production of pineapples in Costa Rica has soared due to cheap labor, improved varieties, and extensive pesticide and fertilizer use [46, 47]; this reflects an 88% increase in global pineapple area from 1986 to 2010 ([17]; figure 1).

In this letter, we quantify the changes in forest cover and agricultural expansion in northeastern Costa Rica to examine the effectiveness of the 1996 Forest Law in reducing

deforestation. The Law banned clearing of forests, legally defined as at least 70% cover over 2 ha by 60 diverse tree species >15 cm DBH [48]; this definition omits most natural regeneration less than 8–12 yr in age [49]. We expected that if forest protection policies have been effective, deforestation would have declined and pressure on available land would have risen, lowering the rate of forest regrowth and directing agricultural expansion onto land not defined as forest. A decline in deforestation accompanied by increasing agricultural production would indicate that these two objectives are potentially achievable simultaneously through forest protection policies.

2. Methods

We used a time series of five Landsat images and field validation data to quantify agricultural expansion, deforestation, and regrowth from 1986 to 2011 in the lowlands of northeastern Costa Rica. The northeastern lowlands are an agricultural frontier whose settlement expanded rapidly in the late 1960s [50]. Government policies granting land title for forest clearing and facilitating cattle production promoted deforestation and colonization [43] while agrarian reform programs were largely limited to redistribution of already-cleared estates [50]. In the 1980s a drop in beef prices and end of beef subsidies led to pasture abandonment in other regions of Costa Rica [51], but the northeast experienced a consolidation of producers without a decline in deforestation for pasture [52]. Recent decades have seen rapid local population increase, improved road connections to the capital, rising export-oriented crop production, and increased PES payments through the Forest Law [37, 52].

The northeastern lowlands retain some of the largest patches of forest outside protected areas in Costa Rica [43]. Much of this region is now part of the San Juan-La Selva Biological Corridor (SJLSBC), a highly forested area of private land (2466 km^2) that connects two large, forested parks (figures 2(A) and (B)). We mapped the SJLSBC and adjacent areas (20 km buffer) within Costa Rica (hereafter, the 'study region'), focusing on the wide coastal plain drained by the San Juan River (<500 m elevation) along the Nicaraguan border. This large region (6617 km^2) has low variability in rainfall (3.2 ± 0.8 m yr^{-1}) and elevation (108 ± 98 m), with central ranges of low hills cut by broad river valleys giving way to coastal plains to the east. In this focus area, we mapped changes over time in two types of legally protected mature forest (forest >30 years in age: includes mature lowland forest and swamp forest), two types of regrowth (exotic tree plantations, and native reforestation (natural regeneration and native tree plantations)), four crop types (banana, pineapple, sugarcane, heart-of-palm), pasture, urban areas, and bare soil (table S2 and a detailed description of methods are available at stacks.iop.org/ERL/8/034017/mmedia). Native reforestation includes both natural regeneration and native tree plantations because of our inability to separate them due to their spectral similarity. Overall accuracy for the resulting land cover maps for each year ranged between 90% and 96% (table S4), with forest change over time classified with 93% accuracy

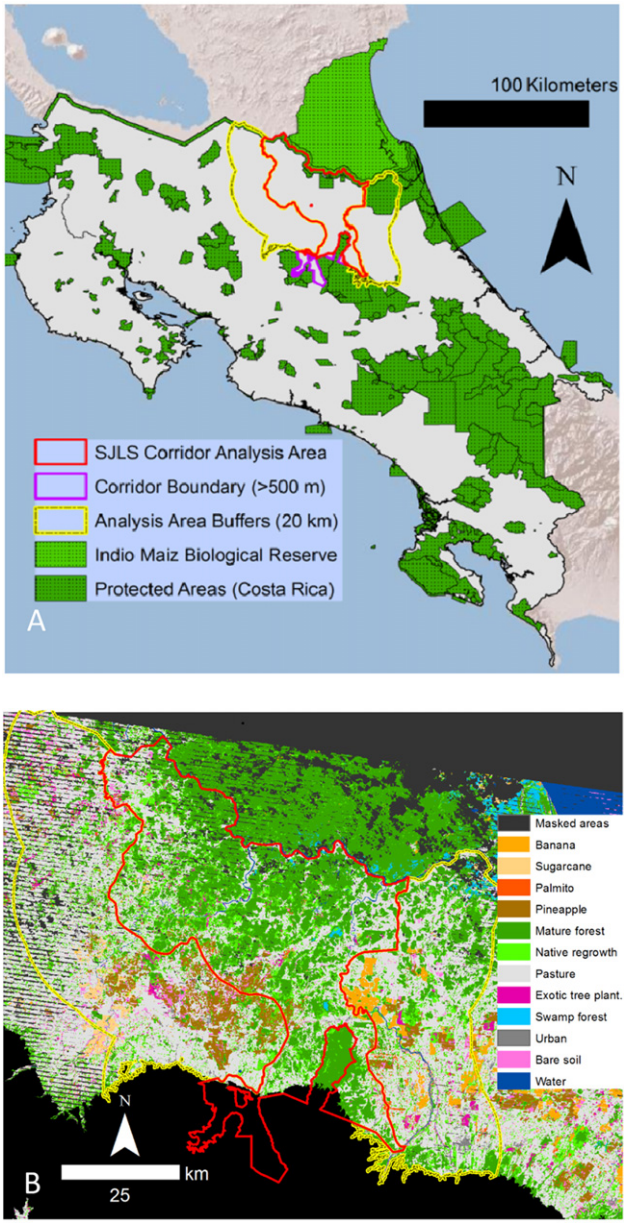

Figure 2. (A) Location of national reserves and the area under study in Costa Rica. The SJLS Biological Corridor connects Nicaragua's Indio Maíz Biological Reserve and several Costa Rican national parks in the Central Volcanic Range. (B) Land cover map of the area under study (outlined in red and yellow) in 2011. Note that 5% of the area is under pineapple cultivation.

(table S5). Using these land cover maps, we first assessed whether deforestation and regrowth rates changed over time in a manner consistent with an effective deforestation ban, and second whether the expansion of croplands and pastures into forest changed following the ban.

3. Results

From 1986 to 2011, the region experienced persistent losses of mature forest cover that were spatially concentrated in remote portions of the study area (figure 3, figure S2). The loss of mature forest slowed after the 1996 deforestation ban,

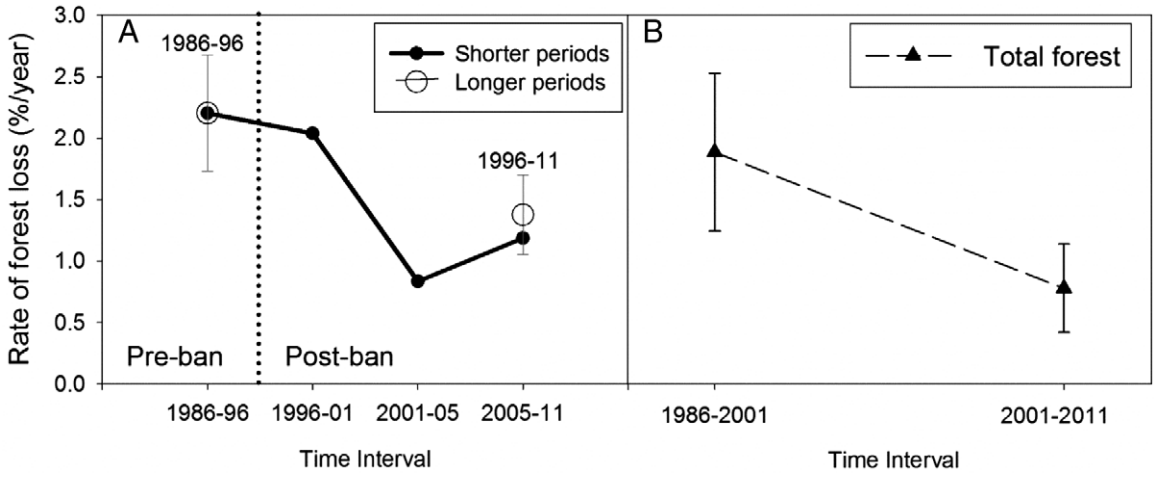

Figure 3. (A) Rate of mature forest loss at each time interval, estimated from single-date image classification. The mean rates of forest loss declined from 2.20% yr^{-1} pre-ban (1986–1996) to −1.38% yr^{-1} post-ban (1996–2011). Means and non-overlapping 95% confidence intervals for the pre-ban and post-ban periods are shown, in addition to the rate of forest loss over shorter time periods. (B) Total forest (mature forest, native reforestation, and exotic tree plantations) loss rate, with non-overlapping 95% confidence intervals. The rate of total forest loss was derived from three image dates and change detection analysis independent from mature forest area estimates (see supplementary materials available at stacks.iop.org/ERL/8/034017/mmedia).

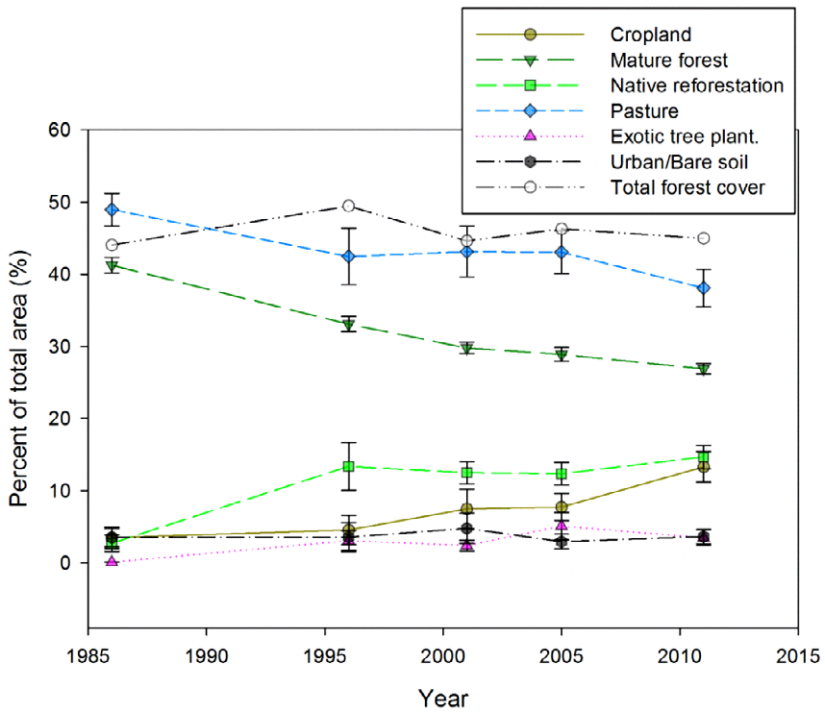

Figure 4. Per cent of total land area in each land cover category over time within the study area. Error bars are 95% confidence intervals. Total forest cover is the sum of mature forest, native reforestation (natural regeneration and native tree plantations), and exotic tree plantations.

but remained at ∼1% rate of annual loss (figures 3 and 4). Most mature forest cleared was converted to pasture, both before and after the 1996 ban (figure S3). However, after 1996, clearing of mature forest for cropland declined as the amount of cropland increased (figures 5 and 6 and figure S7).

Cropland has expanded rapidly in the region, led by an increase in pineapple cultivation in the last decade (figures 2(B), 4 and 6). Cropland expansion after 1996 has primarily replaced pasture and exotic tree plantations, with some cropland clearing expanding into native reforestation (figure 6). Expansion of all three dominant types of agriculture (banana, pineapple, and pasture) sharply shifted away from mature forest after 1996, with banana having the largest proportional decline in forest expansion (figure 5). Pineapple did not expand into forest extensively at any time, but the proportion of pineapple expansion derived from mature forest

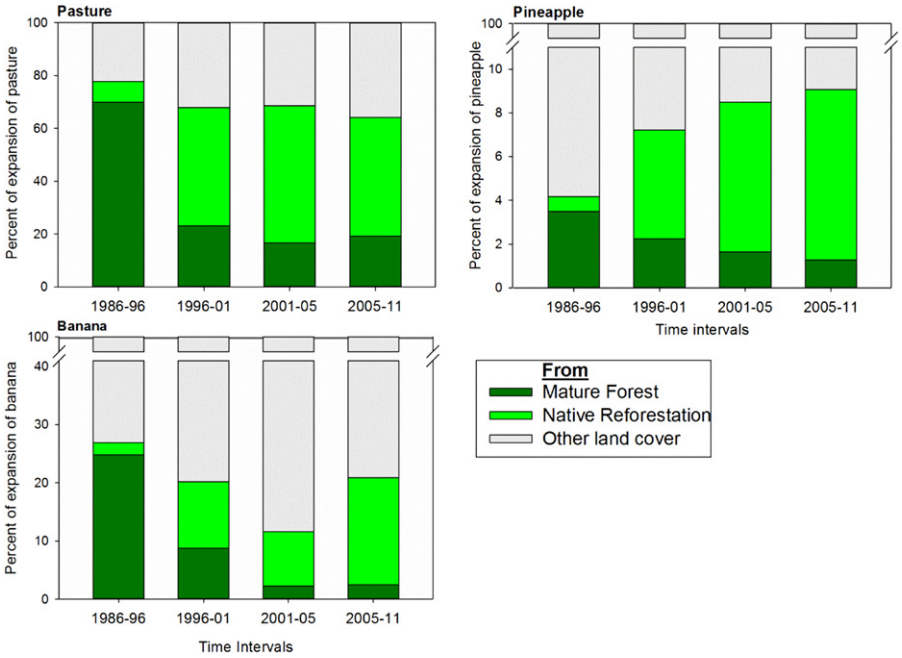

Figure 5. The expansion of banana, pineapple, and pasture into other land covers over time; note the different axis scales. From 1986 to 1996, pasture expanded into mature forest proportionally more often than it was represented in the landscape (see figure 4). After 1996, all land covers decreased their proportional expansion into mature forest and increased their proportional expansion into native reforestation and other habitats.

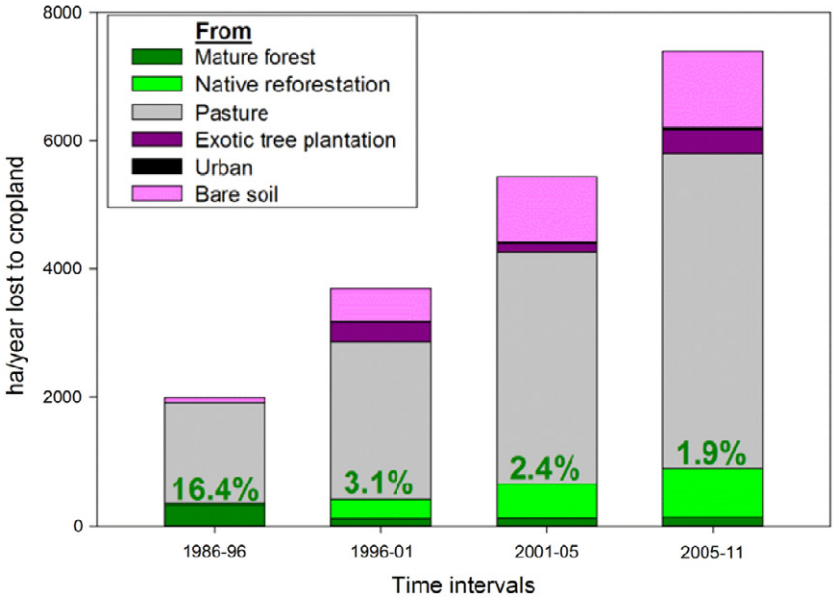

Figure 6. Conversions of other land uses to cropland. The percentage of total land converted to cropland from mature forest is labeled in dark green.

dropped by 50% post-ban (figure 5). The expansion of pasture into mature forest was less frequent after 1996, but the proportion of pasture expansion derived from mature forest clearing remained high relative to clearing for pineapple and banana (figure 5, figure S7).

Because of extensive native reforestation (∼1428 ha yr^{-1} of natural regeneration and native tree plantations), total forest cover (including all mature and regrowth forest types) has remained relatively constant (figure 4). The loss of secondary forests from 1996 to 2001 observed by Morse *et al* [37] for this study region appears to have been compensated recently by a rise in reforestation from 2005 to 2011. Native reforestation, after an initial pulse from 1986 to 1996, has fluctuated around a relatively constant overall area (figure 4), with widespread clearing and regrowth occurring across the landscape (5–10% turnover in regrowth per year; figure S4). Young native reforestation, lacking legal protection, had high rates of clearing indicative of clearing of natural regeneration rather

than young tree plantations (figure S5). Older reforestation >15 years in age had intermediate rates of clearing in comparison to mature forest (figure S5). Older reforestation may include native tree plantations, but visual inspection of aerial imagery revealed that tree plantations were rare in 1986 when the older native reforestation originated (>20 years).

Conversion of forest regrowth to cropland was largely one-way: we observed that cropland was one third as likely as pasture to revert to native reforestation over our time period. Just 4% of cropland areas were abandoned or converted to reforestation compared to 11.6% of pastures over our time period.

4. Discussion

These results suggest that the deforestation ban did not completely halt mature forest loss after 1996, but was associated with a ∼50% decline in the rate of mature forest conversion (figure 3). Although we cannot say with certainty that the land cover changes following the ban were caused by it, the ban and accompanying forest protection PES coincide with the rapid decline in mature forest loss after 1996. This reduction in deforestation occurred while regional population grew (2–8% yr^{-1}; [52, 53]) and export-oriented agricultural pressure increased. Whether the reduction would have occurred without the ban is not possible to know. However, Morse *et al* [37] found that 40% of interviewed farmers in 2004 reported that they would have cleared forest in the absence of forest protection policies, suggesting that the policies were effective in reducing deforestation rates. Gross deforestation rates elsewhere in Latin America were high from 2001 to 2010 (>5% a year, [54]). Net deforestation (reforestation–deforestation) in Latin America was steady during the 1990–2010 period, declining slightly in Central America (−1.49 for 1990–2000 to −1.13% for 2000–2010) and staying steady in South America (−0.45% to −0.41%) [55].

The deforestation ban may have promoted land-sparing by preventing forest clearing for export-oriented cropland; regional agricultural production rose while forest loss declined. From 1996 to 2011, the per cent of land area in pasture stayed relatively steady, while cropland tripled from 4.5% to 13.3% of total land area in the study region (figure 4). Despite the expansion in cropland, the proportion of cropland derived from mature forest conversion was 16.4% pre-ban and <3.1% post-ban (figure 6). The establishment of forest protection policies was associated with a switch by intensive agriculture between 'land-hungry' (forest-demanding) and 'land-sparing' (forest-avoiding) expansion.

It is possible that clearing patterns were affected by a strong preference for already-cleared areas by export-oriented cultivators and/or by the change from banana to pineapple dominance. The rapid expansion of pineapple post-ban may be attributable to a preference for pineapple to expand onto low-fertility and non-forest lands (figure 5, figure S6), but both pineapple and banana cultivators appeared to respond to the ban by decreasing their likelihood of expansion into mature forests (figure 5). The substantial clearing of mature forest for banana prior to the ban, despite available pasture (figures 5 and 6, figure S6), implies that export cultivators readily clear mature forest when soils are suitable or when required for establishing large-scale plantations. This phenomenon has been observed in numerous other tropical regions [10–12, 15, 56]. In this study region, extensive mature forest persists on flat, well-drained soils (figure S6); the extent of forest suitable for cropland is comparable to the area currently under banana and pineapple cultivation. Some clearing of mature forest for pineapple and banana occurred after 1996 and clearing of native reforestation for crops increased post-ban (figures 5 and 6), indicating that cropland expansion in forest habitats was common but re-directed by the ban away from mature forest.

Continued conversion of mature forest to pasture might result from cropland expansion displacing pasture to other areas. If we assume complete displacement of pasture to elsewhere in the study area, we estimate that at most 10–50% of deforestation to pasture resulted from cropland expansion in the years 1986–2005. After 2005, 100% displacement is possible because cropland expansion on pasture exceeded deforestation, which was at a historical low (figure 3). We cannot rule out the possibility that displacement of deforestation occurred inside and outside our region [31, 34]. Costa Rica has increasingly displaced wood consumption internationally since the late 1980s [34]; roughly three-quarters of post-ban wood imports came from temperate countries [34, 40].

Regrowth turnover and declining pasture area indicate that pressure on available land rose after 1996, but we did not observe the expected post-ban decline in the area of forest regrowth. This may result from the selective abandonment of pastures that are less suitable for crops and/or the success of reforestation PES. Natural regeneration of pasture in this landscape has historically been quite dynamic [57]. Young fallows have been cleared quickly since 1996, a pattern attributed to farmers' reluctance to allow land to approach the successional stage which meets the legal definition of forest [37, 58]. In this sense the 1996 Forest Law created a perverse incentive to clear regrowth [58]. In our study, valuable cropland was one third as likely as pasture to be allowed to revert to forest, which is consistent with forest transition theory on fertile soils [59]. But despite the inclusion of older secondary forests in the 1996 law, even older native reforestation had higher rates of clearing than mature forest (figure S5) [37, 39]. The short rotation and decline in pasture fallows, a 'land-sharing' production system, may have been exacerbated by the increased pressure on land engendered by policies favoring a 'land-sparing' expansion.

The high turnover rate of native reforestation and steady loss of legally protected forest after 1996 imply a continuing decline in biodiverse mature forest and a modest gain in net forest cover through forest regrowth, rather than rapid deforestation. Similarly, in China's Yunnan region, net forest cover stabilized and mature forest declined despite partial land-use restrictions [29]. Our results suggest that forest protection efforts in northern Costa Rica slowed mature forest loss and succeeded in re-directing expansion of

export-oriented cropland to areas outside mature forest. Our study parallels recent observations in Brazil, where a soy deforestation moratorium in Mato Grosso was associated with increased soy production and a drop in deforestation [35]. This indicates that it is possible for mandated forest protection outside parks to maintain forest cover without negatively affecting agricultural production. While we could not determine whether the deforestation ban or PES was primarily responsible in northern Costa Rica, their combined potential effect on deforestation over time was large (∼50%). In comparison, a recent study estimated that Costa Rican protected areas reduced deforestation by only 9% between 1960 and 1997 [18].

It should be noted, however, that intensive agriculture expanded into a number of natural habitats other than legally protected forests, including native reforestation (figure 6) and wetlands [71]. Future policies should be careful to delineate all habitats that merit legal protection. In addition, the expansion of crops in close proximity to forests may have negative ecological impacts in this critical corridor region, surrounding remnant forest patches with a harsh matrix that may lower forest connectivity and ecosystem health over the long-term [60–63]. Pineapple and banana production in Costa Rica depends on extremely high applications of fertilizer and toxic pesticides [47, 64]. In Costa Rica these agro-chemicals have degraded water quality and disrupted downstream ecosystems [47, 63], and contaminated montane forests with pesticides [65].

Potential generalities that merit further investigation emerge from this study. First, deforestation bans may result in more effective protection of mature forest than older forest regrowth; this may result from the relative ease of clearing and/or farmer bias against losing land to regrowth [37]. Second, cropland expansion may 'harden' pastoral tropical landscapes by reducing the likelihood of reforestation to connect forest remnants [66]. Finally, deforestation bans may be more effective in restricting clearing for large-scale intensive agriculture than for less intensive agriculture such as pasture. The export-oriented banana and pineapple producers in northern Costa Rica may be more sensitive to potential boycotts and the tarnishing of their brands than smaller domestic cattle producers [67–70]. The success of the soy deforestation moratorium in Brazil shows that large producers can and do respond to socio-political pressures [35]. If large export cultivators are indeed generally more responsive to bans on forest clearing, future implementation of bans should focus on a suite of mechanisms that incentivize large- and small-scale farmers to reduce deforestation. Comprehensive forest protection policies may be a potential tool to promote land-sparing in regions undergoing deforestation for intensive agriculture.

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