International trade, and land use intensification and spatial reorganization explain Costa Rica's forest transition

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CORRIGENDUM

Corrigendum: International trade, and land use intensification and spatial reorganization explain Costa Rica's forest transition (2016 *Environ. Res. Lett.* 11 035005)

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In figure 3(a), the part of the legend explaining the difference between solid and hatched bars was missing. In figure 5, the second time interval should be 1987–2000 (not 1986–2000). The two figures with their complete and correct legend are shown below.

In table 1, the formatting of numbers was changed to facilitate reading. The layout was also modified to highlight that total land demand/released is the sum of the three terms of accumulated land demand (RF, CS, EP), and the sum of the three terms of accumulated land released (IP, IT, RD). The modified table is shown below.

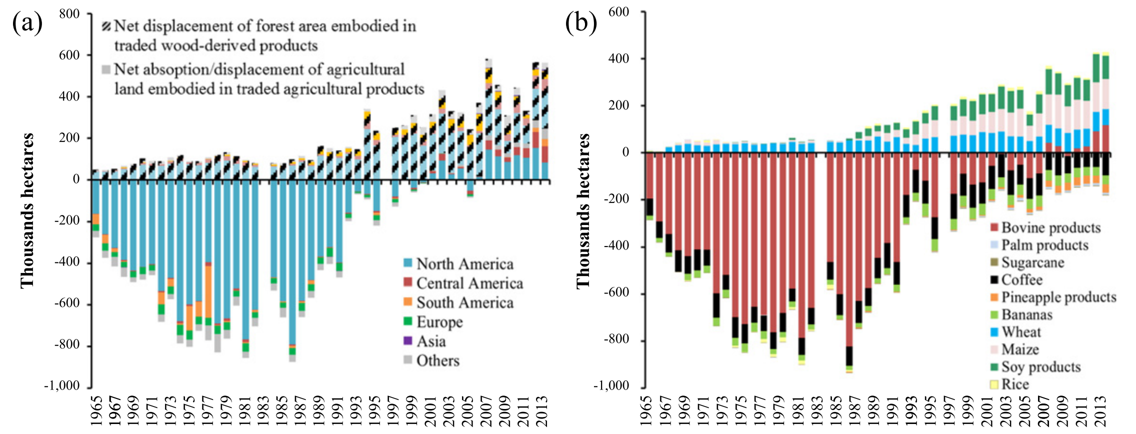

Figure 3. Net land use displacement (land embodied in imports minus land embodied in exports) associated with trade of (a) both agricultural and wood products and, (b) the selected agricultural products, over 1965–2013. The countries represented on the figure (a) account together for more than 85% of total land use displacement in most years of the study period. *Others* include countries from the different regions.

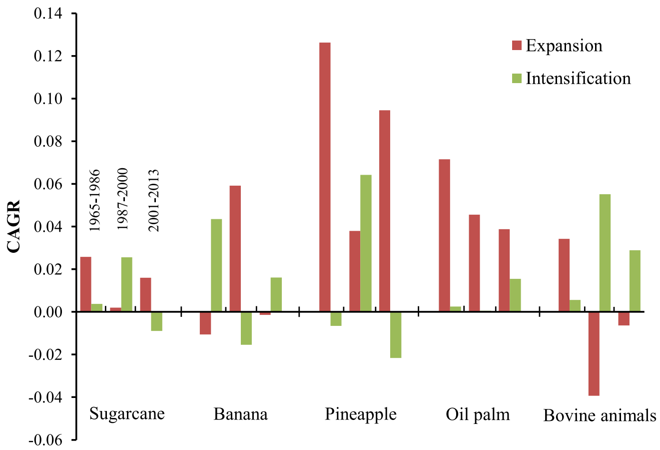

Figure 5. Compound annual growth rate (CAGR) of expansion (*red*) and intensification (*green*) for the selected crops whose production increased and bovine animals (for exports, and for meat and milk production) over three time intervals corresponding to the period preceding the forest transition in Costa Rica (1965–1986), the transition period (1987–2000), and the period following it (2001–2013).

Table 1. Estimates of the terms of equation (1).

	Accumulated land demand for			Total land demand/released	Accumulated land released through		
	RF	CS	EP		IP	IT	RD
Accumulated area (ha.yr)	14 427 636	21 471 024	9 266 965	45 165 625	10 977 361	34 188 264	
% of total land demand/released	31.94	47.54	20.52	100	24.30	75.70	

RF: net reforestation.
CS: growing consumption of agricultural products.
EP: growing exports of agricultural products.
IP: growing imports of agricultural products.
IT: intensification of agriculture.
RD: redistribution of agricultural land.

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Keywords: forest transition, trade, land use, displacement, environmental impacts, agricultural intensification

Supplementary material for this article is available online

Abstract

While tropical deforestation remains widespread, some countries experienced a forest transition—a shift from net deforestation to net reforestation. Costa Rica had one of the highest deforestation rates in the 1980s and is now considered as a model of environmental sustainability, despite being a major producer of bananas and pineapples. We tested three land use processes that are thought to facilitate forest transitions. First, forest transitions may be accompanied by land use displacement through international trade of land-based products, which may undermine the global-scale environmental benefits of national forest protection. Second, reforestation is often associated with land use intensification in agriculture and forestry, allowing for land sparing. Third, this intensification may partly result from a geographical redistribution of land use at the sub-national scale to better match land use with land suitability. These hypotheses were verified for Costa Rica's forest transition. We also tested whether forest increased mainly in regions with a low ecological value and agriculture expanded in regions with a high ecological value. Intensification and land use redistribution accounted for 76% of land spared during the forest transition, with 32% of this spared area corresponding to net reforestation. Decreasing meat exports led to a contraction of pastures, freeing an area equivalent to 80% of the reforested area. The forest transition in Costa Rica was environmentally beneficial at the global scale, with the reforested area over 1989–2013 corresponding to 130% of the land use displaced abroad through imports of agricultural products. However, expansion of export-oriented cropland caused deforestation in the most ecologically valuable regions of Costa Rica. Moreover, wood extraction from forest plantations increased to produce the pallets needed to export fruits. This highlights the importance of a multi-scale analysis when evaluating causes and impacts of national-scale forest transitions.

1. Introduction

Tropical deforestation is a major threat to sustainability, prevalent in many regions [1]. Yet, some countries have reversed the declining trend in their forest cover [2, 3]. Costa Rica, which is known for its ecological richness [4], experienced a forest transition—a national-scale shift from shrinking to expanding forests [5]—over the past three decades [6]. Having one of the highest deforestation rates worldwide in the mid 1980s [7], the country is now viewed as a model of sustainable forest management [4]. It has also become a leader in the export of tropical fruits [8].

Three land use processes have been proposed to explain recent forest transitions in the tropics. First, forest transitions are often accompanied by changes in international trade patterns of land-based products, causing a displacement of land use, i.e. 'a geographical shift of land use from one place to another' [9, p 7]. This displacement may reduce the global-scale

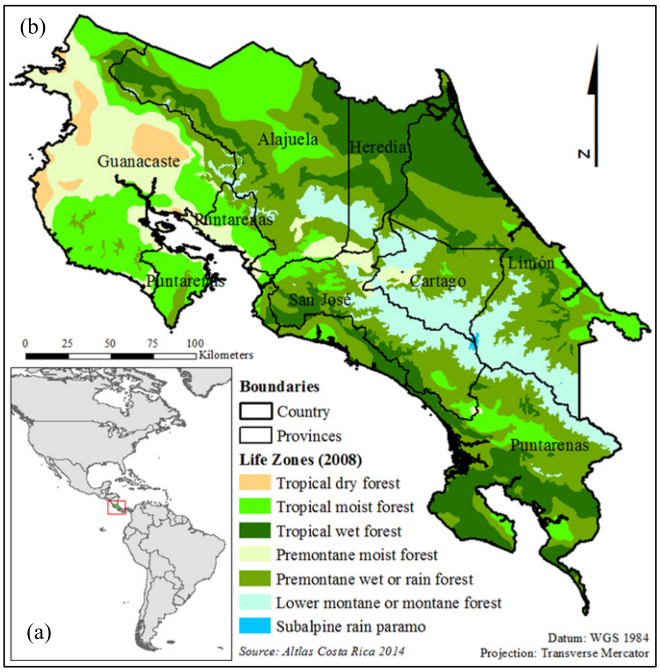

Figure 1. (a) Location of Costa Rica within Central America. (b) Map of Costa Rica highlighting its 2008 life zones, and the boundaries of its seven provinces.

environmental benefits from national-scale forest recovery [10–12]. Second, reforestation may be associated with land use intensification, with technological improvements and greater inputs use increasing agricultural yields. A positive relationship between yields increase and cropland contraction has been observed for some countries [13, 14]. Land released from agriculture may then be available for reforestation. However, intensification does not always lead to land sparing, depending on local political, technological and economic circumstances [15, 16]. Third, this intensification may wholly or partly result from an agricultural adjustment to land capability [17]. Through a learning process, agriculture is progressively concentrated on the most suitable land, allowing to maintain constant production from a smaller area. These mechanisms are summarized by a land demand and supply equation:

$$\mathrm{RF} + \mathrm{CS} + \mathrm{EP} = \mathrm{IP} + \mathrm{IT} + \mathrm{RD} \qquad (1)$$

with the left term corresponding to the additional land demand for: net reforestation (RF), growth in domestic consumption (CS), and growth in exports of land-based commodities (EP); and the right term representing the land spared or released by: growth in imports of land-based commodities (IP), land use intensification (IT), and national-scale geographical redistribution of land use (RD).

Forest cover changes in Costa Rica have been well documented [7, 18–23]. The turnaround in forest cover occurred in the late 1980s, thanks to economic and political factors [24]. A drop in international prices of bovine meat, the development of tourism and a transition from a rural to a more urban society led to the abandonment of pastures, on which forest have regenerated or been planted [21]. Public support for agriculture, including cattle ranching, diminished while financial incentives and land use policies promoted forest protection and restoration [4, 7, 20]. Starting with the creation of the protected areas (PAs) system in the late 1970s, policies evolved from tax and direct subsidies for large landowners to more democratic incentives in the late 1980s, and finally to the Payment for Ecosystem Services program in the late 1990s. Previous studies have linked the forest transition with agricultural dynamics [25–27] and with international trade in agricultural and forest products [2], but have not connected these two aspects. Yet, assessing the ecological impacts of international land use displacement requires linking international trade with land use dynamics, as these impacts may vary within a country given spatial variations in agro-ecological suitability and natural resource endowment [28].

The objectives of this study are to: (i) understand the relations between land use changes since 1965, international trade in agricultural and wood products, and forest protection policies of Costa Rica, and (ii) assess environmental outcomes of these interactions at international and sub-national scales. We tested three hypotheses for Costa Rica (figure 1), for the period 1965–2013:

Hypothesis 1. As Costa Rica was protecting its forests, (a) it increased its imports of wood products while decreasing its exports of agricultural products, and (b) consequently, it transitioned from being a net exporter to a net importer of land use embodied in its trade of land-based products.

Hypothesis 2. Land use intensity increased during Costa Rica's forest transition as: (a) wood supply shifted from natural forests to short-rotation plantations, (b) agricultural yields increased, and (c) extensive pastures were abandoned in favor of either reforestation or high-yielding crops.

Hypothesis 3. (a) Costa Rica's forest transition has been associated with a geographical redistribution of land use within the country, with land abandonment in regions with low agro-environmental suitability and agricultural expansion in high suitability regions. Given the widely reported—though complex—positive relationship between vegetation productivity and species diversity [29, 30], a corollary is that (b) forest increase took place in the regions with a low ecological value, and agricultural expansion and intensification in the regions with a high ecological value.

We then evaluated whether Costa Rica's forest transition and its associated land use displacement abroad led overall to ecological benefits at the sub-national and global scales.

We followed these steps: Analysis of trade in agricultural and forest products by Costa Rica (hypothesis 1(a)); estimation of the land use displacement associated with this trade (1b); reconstruction of the national production of wood (2a) and agricultural products (2b); analysis of land use dynamics at national and provincial scales (2c); comparison of the agro-environmental suitability and ecological value of the seven provinces (3(a), (b)); and comparison of the land used abroad by Costa Rica with the land used on its territory for domestic production. See supplementary material for more details.

2. Materials and method

We compiled data from various sources (tables S1–3). To test the first hypothesis, we selected ten agricultural products (wheat, maize, soy products, rice, bovine products, coffee, sugarcane, bananas, pineapples products, and oil palm products) and two wood-derived products (roundwood, and paper, paperboard and manufactures thereof), which contributed most to changes in trade in agricultural and forestry products. Pallets used to export agricultural products are not reported in trade records but were also included as they represent large quantities of roundwood. The years 1983 and 1996 were excluded due to aberrant values. We compiled annual traded quantities of the selected products (excluding pallets) for the main trade partners of Costa Rica for the period 1965–2013. We then estimated the net land use displacement associated with trade of the 13 products by converting traded quantities to the agricultural or forest area that was required for their production, based on annual yields in the exporting country. We tested for trends in trade exchanges and land use displacement using simple ordinary least squares (OLS) regressions and heteroscedasticity and autocorrelation consistent estimators of covariance [31].

To test the second hypothesis, we distributed the roundwood production between their sources—natural forest, plantations, and agricultural land—for 1998–2013. For the agricultural products whose production increased, we calculated the compound annual growth rate of agricultural expansion and intensification for periods before, during and after the forest transition (1965–1986, 1987–2000, 2001–2013). We tested for expansion/intensification trends for every product over each period with simple OLS regressions, and for the heterogeneity between regressions for successive periods with Chow test [32]. We reconstructed the areas covered by forest, pasture and the selected crops for eight dates between 1960–2012 at the national scale, and for two periods (1982–1986, 2012–2014) at the provincial scale.

The third hypothesis was tested by comparing provinces in terms of: (a) soil and terrain suitability for rainfed agriculture, length of growing period, net primary production, and suitability for bananas and oil palm cultivation, as proxies of agro-environmental suitability; and (b) proportion of PAs and indigenous reserves (IRs), average density of extinct, endangered and threatened species (for birds, amphibians, reptiles and mammals), proportion of different forest types, and total biomass carbon stored in forests, as proxies for the ecological value of provinces. Multiple OLS regressions were used to test the association between changes in provincial forest area and: (i) changes in provincial area of pasture and export crops, (ii) agro-environmental suitability, and (iii) ecological value of each province. Only the most significant results are reported.

Based on the above results and the literature, we discuss environmental outcomes of Costa Rica's forest transition at global and sub-national scales by comparing qualitatively systems of wood and agricultural production in Costa Rica with those of its main trading partners.

Finally, we estimated the different terms of equation (1) to quantify: (i) trade-offs between local and global environmental outcomes, i.e., between the area reforested in Costa Rica and the additional area displaced abroad for increasing agricultural imports, and (ii) trade-offs related to the allocation of the land area spared in Costa Rica between reforestation, domestic consumption and agricultural exports.

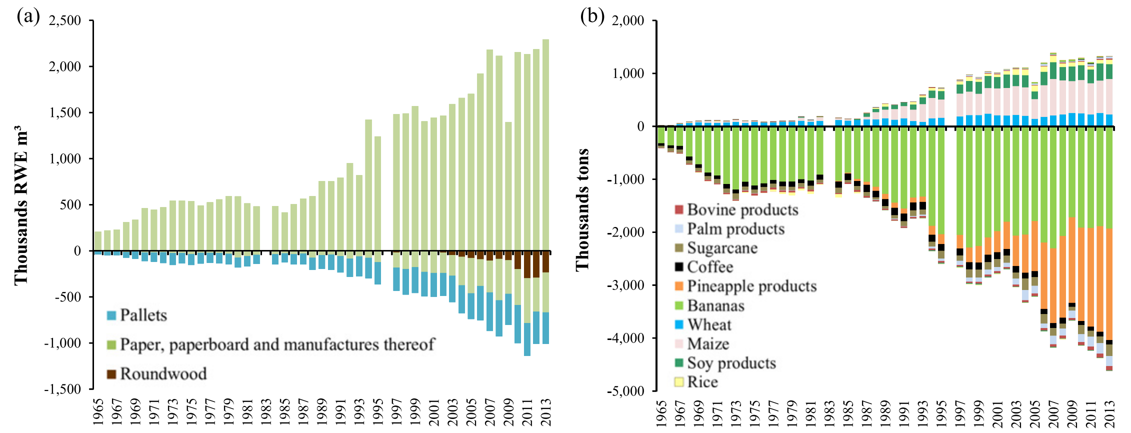

Figure 2. Annual imported and exported quantities of (a) the three selected categories of wood-derived products in RWE volume, and (b) the ten selected categories of agricultural products in tons, between 1965 and 2013. *Positive bars* correspond to imports, while *negative bars* represent exports.

3. Results

3.1. International trade of agricultural and wood products (hypothesis 1(a))

Costa Rica has increasingly imported products derived from paper and paperboard ($P < 0.0001$, table S4) (figure 2(a)), mainly from the US, Canada, and Mexico. Exports of wood products have also increased over the last decade ($P < 0.0001$). While their importance in value is negligible, pallets used to export agricultural products represent the main export in volume over the whole period (over 50% of the total RWE volume exported). From 1965 to 2013, the number of pallets exported was multiplied by twelve ($P < 0.0001$) and the volume of roundwood required to produce them by ten.

Imports of maize and soy products have increased almost continuously since the late 1980s (figure 2(b)) ($P < 0.0001$ over 1965–2013, table S4). Imports of bovine products have also increased since the early 1980s, but with smaller volume traded and growth rate compared to exports ($P < 0.0001$ for imports and exports over 1965–2013). More than 88% of wheat, maize, soy products and rice were imported from the US, while bovine products came mainly from Nicaragua (37%) and Panama (24%). The US was the main importer of Costa Rican bovine products (48%), ahead of Central American countries (37%). The main products exported by Costa Rica were bananas (67% of total agricultural exports in tons), pineapples (18%), coffee (5%), sugarcane (5%), and palm products (2%) (significant increase, $P < 0.0001$, for all products except coffee). Exports of bananas, pineapples and coffee went almost exclusively to the US (respectively 52%, 48%, and 30%) and the European Union (respectively 33%, 37% and 34%). The US was also the main importer of sugarcane (67%). Most oil palm products were exported to Mexico (75%) and Central America (18%).

3.2. Displacement of land-use through trade (hypothesis 1(b))

The net displacement associated with the trade of wood-derived products is positive throughout the study period, with an increasing trend from the mid 1980s to 2007 (significant increase over 1965–2013, $P < 0.0001$, table S5) (figure 3(a)). Forest use was mainly displaced to the US (>50% in most years), and to Canada (7%) and Mexico (6%).

By contrast, trade in agricultural products has led to a net absorption of land use by Costa Rica until 2000, especially through exports of bovine products (accounting for 75% of total land embodied in agricultural exports) (figure 3(b)). This land use was mainly absorbed from the US (74% of total agricultural land use absorption over 1965–2013). The agricultural land area absorbed by Costa Rica increased until the early 1980s ($P < 0.001$, table S5), then decreased after 1986 ($P < 0.0001$) to become smaller than the use of forest area displaced abroad in 1993, and switched to net displacement in 2001. As a result, the net displacement associated with both forest and agricultural products has been positive since 1993, with an increasing trend over the last two decades ($P < 0.0001$).

3.3. Production of wood and agricultural products in Costa Rica (hypotheses 2(a) and (b))

Total production and sources of roundwood in Costa Rica have varied during the study period (figure 4). Forest plantations have supplied an increasing fraction of total roundwood produced domestically. The fraction coming from natural forests has been small since 1999 and decreased in the last decade.

Production of sugarcane, bananas, pineapples, oil palm fruits and bovine products has increased largely over the study period, while maize and coffee production has declined since respectively the late 1980s and the early 1990s. The respective contributions of expansion and intensification to the increase in agricultural

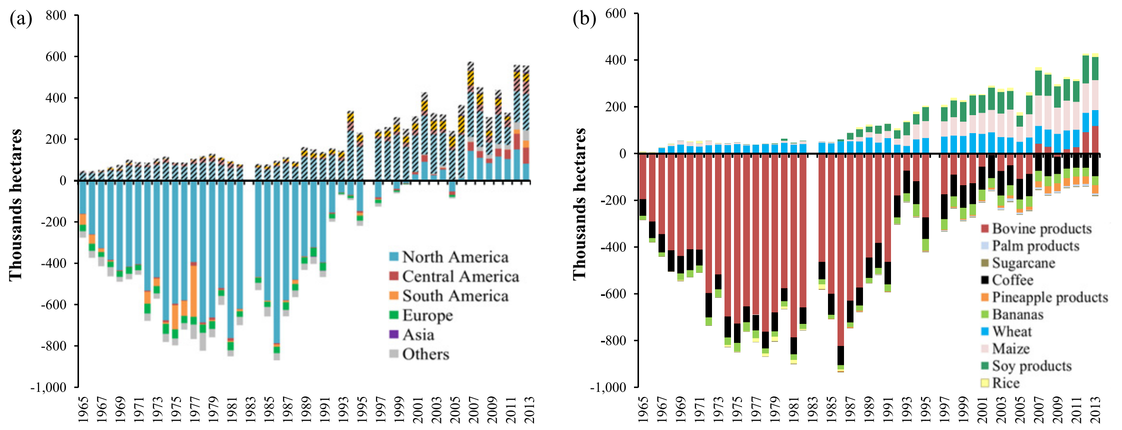

Figure 3. Net land use displacement (land embodied in imports minus land embodied in exports) associated with trade of (a) both agricultural and wood products and, (b) the selected agricultural products, over 1965–2013. The countries represented on the figure (a) account together for more than 85% of total land use displacement in most years of the study period. *Others* include countries from the different regions.

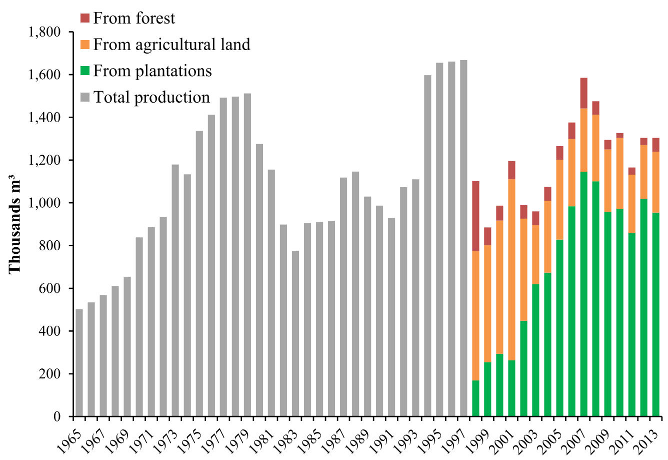

Figure 4. Volume of roundwood annually produced in Costa Rica between 1965 and 2013, not including firewood, with the share of total production supplied from different sources for the period 1999–2013.

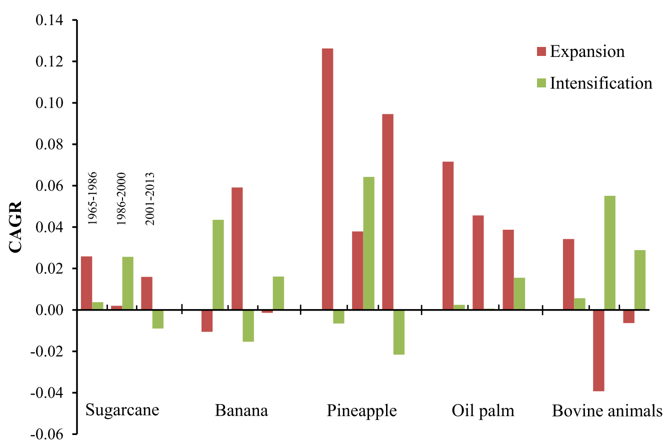

Figure 5. Compound annual growth rate (CAGR) of expansion (*red*) and intensification (*green*) for the selected crops whose production increased and bovine animals (for exports, and for meat and milk production) over three time intervals corresponding to the period preceding the forest transition in Costa Rica (1965–1986), the transition period (1987–2000), and the period following it (2001–2013).

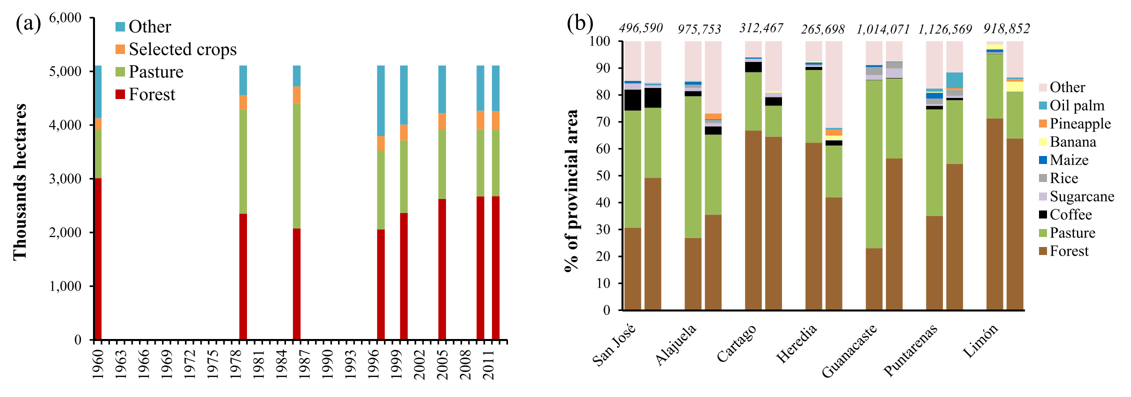

Figure 6. Distribution of the land cover/use of (a) the total territory of Costa Rica (511 0000 ha) in eight years, and (b) the seven provinces around 1984 and 2013. Figures in *italic* correspond to the total provincial area in hectares.

production varied through time and for the different crops (figure 5, table S6). Cattle rearing increased mainly through pastures expansion before the transition (significant increase in pasture area over 1965–1986, $P < 0.0001$; non-significant trend in yield), while there was significant contraction in pastures and intensification in ranching after 1987 ($P < 0.0001$). For the export crops, a phase of intensification was typically followed by expansion (significant intensification over 1965–1986 ($P < 0.0001$) and expansion over 1987–2000 ($P < 0.001$) for banana, and significant intensification over 1987–2000 ($P < 0.05$) and expansion over 2001–2013 ($P < 0.0001$) for sugarcane and pineapple).

3.4. Land-use dynamics at national and provincial scales (hypothesis 2(c))

Forests and pastures have accounted for more than 70% of the country's area over the study period (figure 6(a)). From the 1960s to the late 1980s, pastures expanded at the expense of forests. This trend reversed from the 1990s to the mid 2000s, when forest and pasture areas have stabilized. Cultivated areas experienced smaller changes (figure S.1). Cropland expansion was mostly associated with sugarcane and coffee in 1961–1986, and with bananas, pineapples and oil palms after 1995.

At the provincial scale, the contraction of pastures since the late 1980s occurred across all provinces (figure 6(b)). Forest cover increased everywhere except in Heredia, Cartago and Limón. Total area harvested with the selected crops expanded in all the provinces, except in San José and Cartago. Each of these crops is concentrated in a couple of provinces with, in several cases, large changes in cultivated areas in these provinces. Change in forest cover area was most significantly, and negatively, associated with change in pastureland and pineapple area ($R^2 = 0.88$, $P < 0.05$, table S7).

3.5. Agro-environmental suitability and ecological value of provinces (hypothesis 3(a) and (b))

Soil and terrain are most suitable for agriculture in Heredia, Alajuela, Limón and Guanacaste (figure 7(a)). By contrast, 80% of the total area of San José and Cartago (the two most mountainous provinces) are marginal or not suitable at all. The growing period is the longest in Limón and Cartago, and the shortest in the northwestern provinces of Alajuela and Guanacaste (figure 7(b)). Puntarenas, San José and Heredia have also a large portion of their territory with a growing period longer than 300 days. Net primary production is highest in the Atlantic provinces (Heredia and Limón) and lowest in Guanacaste (figure 7(c)). Heredia, Puntarenas, Limón and Alajuela are most suitable for banana and oil palm. (figures 7(d) and (e)). Increase in forest area was significantly and negatively associated with the proportion of the province area with a growing period longer than 300 days and with a moderate to high suitability for banana ($R^2 = 0.83$, $P < 0.05$, table S7).

In 2012, Limón, Heredia, Cartago, and Alajuela had the largest proportion of mature forest (67%–83%) (figure 7(f)). With Puntarenas, these provinces had more than half of their forest area resulting from natural successions over >75 years. Mature forests were mainly found in mountains and PAs. Over 26% of Costa Rica is covered by PAs, some of it intersecting with one or several of the 24 legally recognized indigenous refuges (IRs) covering over 6% of the country. Cartago, Heredia and Limón have the largest proportion of PAs (about 40%), while Limón, Cartago and Puntarenas have the largest proportion of IRs (10%–15%) (figure 7(g)). The Caribbean provinces have the highest density of extinct, endangered and threatened species, taking together mammals, birds, amphibians and reptiles (figure 7(h)). By contrast, Guanacaste and San José have few PAs and IRs, which corresponds to their lower amount of mature forests, vulnerable ecosystems and endangered organisms. Guanacaste, which concentrates most of the deciduous trees of the

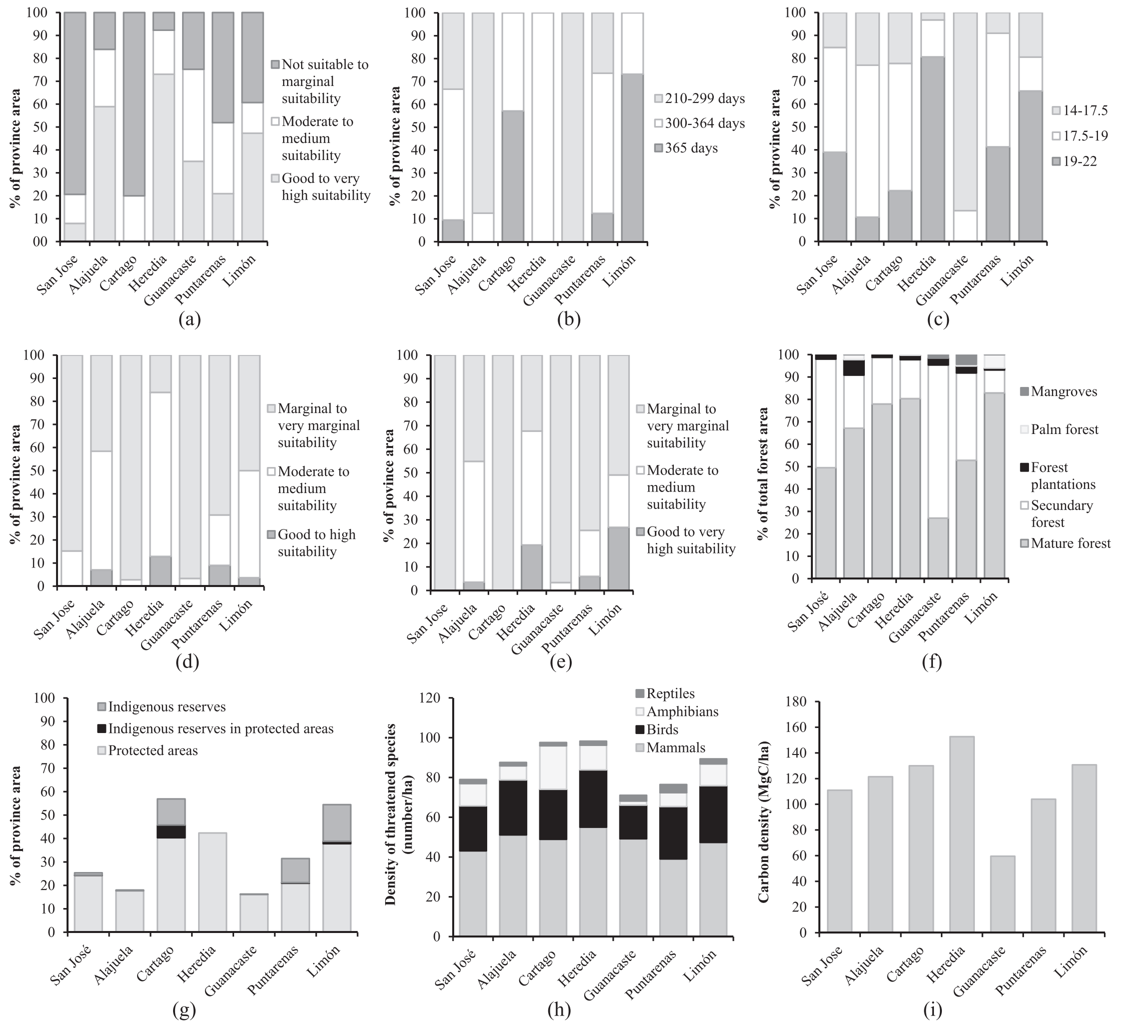

Figure 7. Comparison of the seven provinces in terms of (a) proportion of the different classes of soil and terrain suitability for rainfed agriculture, (b) proportion of the different classes of reference length of growing period, (c) proportion of the different classes of net primary production, (d) proportion of the different classes of suitability for banana cultivation, (e) proportion of the different classes of suitability for oil palm cultivation, (f) proportion of the different types of forest, (g) proportion of protected areas and indigenous reserves, (h) density of extinct, endangered and threatened species, and (i) density of carbon stored in forests (above and below ground).

country, included the largest area of secondary forests. Plantations accounted for the largest proportion of forests in Alajuela (7%), Guanacaste (3%) and Puntarenas (3%). The dry and montane forests of the Pacific region and central highlands had a lower carbon density than the moist forests of the Caribbean provinces (figure 7(i)). Forest area change was significantly, and negatively, associated with the density of extinct, endangered and threatened species, and forest carbon density ($R^2 = 0.93, P < 0.01$, table S7).

3.6. Land supply and land use trade-offs

Costa Rica's land release occurred mainly through land use intensification, including land use redistribution on most suitable lands (76% of the land supply), rather than by land use displacement (table 1). Yet, Costa Rica has simultaneously increased its imports of agricultural and wood products, leading to a net displacement of its land use abroad. Moreover, the decrease in meat exports led to a contraction of pastures that freed an area equivalent to 80% of the reforestation. Of the total land area spared in Costa Rica during its forest transition—through imports of land-based commodities, and intensification and redistribution of land use—almost half (48%) was used to meet the growth in domestic consumption, and 32% for reforestation. The remaining 20% served to produce the increasing exports of land-based products, accounting for the decrease in meat exports.

4. Discussion

4.1. Forest transition and land use displacement through trade

In contrast to other recent forest transition countries [2, 12], Costa Rica continued to absorb more land use than it displaced until the mid 1990s, mainly through exports of bovine meat. As these exports have declined since the mid 1980s while imports of paper and

Table 1. Estimates of the terms of equation (1).

	Accumulated land demand for				Accumulated land released through		
	RF	CS	EP	Total land demand/released	IP	IT	RD
Accumulated area (ha yr)	144 276 36	214 710 24	926 6965	451 656 25	109 773 61	341 882 64	
% of total land demand/released	31.94	47.54	20.52	100	24.30	75.70	

RF: Net reforestation.
CS: Growing consumption of agricultural products.
EP: Growing exports of agricultural products.
IP: Growing imports of agricultural products.
IT: Intensification of agriculture.
RD: Redistribution of agricultural land.

paperboard products increased, net land use absorption decreased and turned into net displacement in 1993. This supports our first hypothesis. The positive association between net land use displacement and forest cover increase had already been shown to be statistically significant [2]. The shift from being a net importer to a net exporter of land use would have occurred more markedly if Costa Rica had not exported pallets with its agricultural products.

Before 2001, Costa Rica has mainly absorbed agricultural land use (especially pastures) and mainly displaced forest use abroad. Until the early 2000s, wood production in Costa Rica was sufficient to meet its domestic demand [33]. Since then, the country has increasingly depended on imports to meet a rising demand for wood, which has been fueled by the growth of population and tourism, and by rising agricultural exports requiring wood packaging [34, 35]. As pastures were replaced by forests, whose exploitation has been increasingly regulated [36], Costa Rica has used more forestland abroad to meet its domestic demand, while exporting less meat, and importing more wheat, maize, soy products, and rice since the mid 1980s, and bovine products since the mid 2000s. Rice being central to the Costa Ricans' diet [37], its imports have increased with population growth [38]. Wheat, maize and soybean have primarily served to feed animals [39]. While bovine meat production decreased, milk and chicken production has increased since the early 1980s. Soybean was also imported to produce oil for the local and Central American markets [40]. Cropland embodied in the growing exports of bananas, pineapples and oil palm products has not outweighted the land embodied in decreasing bovine products exports and in feed crops imports, so that net agricultural land use absorption switched to net displacement in 2001.

4.2. Forest transition and land use intensification

Domestic wood production did not decrease with the forest transition in Costa Rica, and agricultural production has increased almost continuously since 1965. This has been possible through an increase in land use intensity, both in forestry and cattle rearing, which confirms part of our second hypothesis. Wood has been increasingly supplied from agricultural land and short-rotation plantations (mainly of *Gmelina* species) after the mid 1990s, when policies constrained extraction of wood from natural forests [35, 36]. Since 2002, requirements for obtaining harvest permits were made more stringent and the granting was restricted in the agroforestry systems. Wood supply from agricultural land thus decreased and plantations, though accounting for less than 10% of the total forest cover, became the main source of industrial wood.

Agriculture intensification occurred, firstly, through the conversion of extensive cropland and pastures to large-scale, export-oriented high-yielding crops (bananas, pineapples, oil palms) and, secondly, through the intensification of cattle rearing on pastures. The high profitability of milk over beef production after the mid 1970s encouraged dual purposes herds [41], which used pastures more intensively than single beef production [42]. Yields increases also explain the growth in production of sugarcane and pineapples during the forest transition. Yet, for these crops, as for bananas earlier, intensification was followed by expansion in the subsequent period, in what could be a rebound-effect typical of export-oriented crops with elastic demand in the global markets [15, 16].

4.3. Land use redistribution at sub-national scale

National-scale land use trends mask sub-national scale heterogeneity. In general, reforestation occurred at the expense of pastures and traditional crops (coffee, sugarcane, maize, rice). In area, the contraction of pastures is equivalent to about 80% of the reforestation. However, forest area decreased in the high agro-environmental suitability provinces of Heredia and Limón, and in Cartago (mountainous and thus hardly suitable on average), where banana has most expanded since the 1980s. Alajuela, Puntarenas, Limón and Heredia experienced the largest expansion of pineapples [43]. While the pressure from cattle ranching on forest decreased, that of banana and pineapples cultivation increased in those provinces [44]. After oil palm was introduced on the Pacific coast in the 1940s, it expanded by replacing bananas in the parts of Puntarenas that are most suited for oil palm, reaching Limón in the early 2010s [45–47]. While the expansion of export-oriented crops largely occurred by conversion of cropland and pastures [43, 48], it also directly caused deforestation [25, 49]. By contrast, the largest reforestation occurred in Guanacaste and San José, which have a lower agro-environmental suitability. These two provinces concentrated over 70% of the traditional crops in 2013. Land use has thus been spatially redistributed within Costa Rica, with reforestation in former pastures taking place on the Pacific side and central highlands, which are least suitable for agriculture, and deforestation for export crops on the more suitable Atlantic facade [3]. The regions with the greatest forest increase also have the lowest ecological value, while forests decreased in the regions with the highest value. Our third hypothesis is thus confirmed.

4.4. Ecological outcomes of forest transition at international and sub-national scales

Whether the net land use displacement associated with the forest transition in Costa Rica has been environmentally beneficial at the global scale depends on the trade-offs between land use impacts in Costa Rica and in countries of origin of its imports. Costa Rica has mainly displaced land use to the US (which represents 89% of the total displacement from imports of cereals and soy products, and 52% of the displacement from imports of paper and paperboard products). The bulk of cereal and soy production came from regions with a long agricultural history [50–52] and an intensive production system [53]. On average, maize and rice yields were respectively four and two times higher in the US than in Costa Rica over 1965–2013 [8]. Forest products were mostly extracted from well-managed natural temperate forests, plantations accounting for only 9% of total US forest land (13% of total timberland) [54]. The US forest area has been stable for a century, with a slight upward trend since the late 1980s [55]. The stock growth has exceeded removals for both soft and hardwoods since 1952, with no over-exploitation of forests. In Costa Rica, the efficiency of silvicultural techniques remains low and environmental damages of logging important compared to temperate forestry in the US [33, 35]. Considering these differences in management and the biological richness of Costa Rica's tropical forests, land use displacement to the US has alleviated global environmental pressure. Moreover, following equation (1) (table 1), the total land area reforested in Costa Rica over 1989–2013 corresponds to 130% of the additional land area used abroad for the growing imports of agricultural products. However, Costa Rica is increasingly displacing land use to Latin American countries through its imports of paper and paperboard, and bovine products, leading to a more uncertain environmental outcome recently.

In Costa Rica, reforestation rates have significantly decreased since the 2000s [21]. Meanwhile, productive plantations have been over-exploited to supply the growing construction and packaging sectors, and to export teak to Asian countries [35, 56]. This has led to increasing pressure on natural forests, including through illegal logging [35, 57]. The growing demand for wood pallets has compromised the initial purpose of forest plantations to meet domestic demand [21]. Over 2006–2013, 60% of the roundwood supplied from plantations was used to make pallets, mainly to export bananas and pineapples [56]. The growth in imports of wood products was also mostly associated with packaging products, also in part for agricultural exports. The forest protection policies are doubly undermined by investments in agriculture: through competition for productive land and the demand for wood products for packaging of export-oriented crops.

5. Conclusion

The case of Costa Rica illustrates the potential to undergo a forest transition while maintaining domestic production of wood and increasing exports of agricultural products. However, as Costa Rica has turned to an export-based agriculture, it has replaced traditional crops by more intensive cultivation, displacing more land use through cereal imports than it has absorbed through fruits and palm oil exports. The allocation of the land released by land use intensification and displacement to reforestation and agricultural production for domestic and export markets reflects a *de facto* trade-off between land use priorities, which was influenced by multiple factors, including policies and international markets trends. Costa Rica's forest transition led overall to global environmental benefits as land use was mostly displaced from rich tropical forest ecosystems to temperate ecosystems in the US, which has efficient production systems. At the national scale, environmental benefits are mixed as regions with a high agro-environmental suitability also tend to have the highest ecological value. Forest increased mainly where pastures and traditional crops were abandoned, and export-oriented crops have expanded in provinces where mature rainforests are the most abundant, with high carbon stocks and biodiversity. Export-oriented cultivation threatens forests through its demand for cropland and for wood for packaging. The early yield increases for these crops was associated with further expansion rather than land sparing after the forest transition. International market forces induce boom-and-bust cycles, having driven deforestation in Costa Rica before the 1980s and net reforestation after that. More recently, emerging oil palm expansion may further threaten the forest transition.

Sub-national scale analyzes are thus crucial when evaluating national-scale forest transitions and land use policies. Trade-offs between local and global outcomes of forest transitions raise political issues about inequities in distributing environmental pressures.

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