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Unexpected Interactions between Agricultural and Forest Sectors through International Trade: Wood Pallets and Agricultural Exports in Costa Rica

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Academic Editor: Ximena Rueda Fajardo
Received: 27 September 2016; Accepted: 16 December 2016; Published: 24 December 2016

Abstract: International market forces have played an increasingly important role in shaping land use dynamics through complex supply chains. In Costa Rica, the shift from a net loss to a net gain in forest cover was facilitated by forest plantations and the replacement of extensive cropland and pastures by export-oriented, high-yielding crops. However, agricultural intensification generated several feedbacks affecting forests. We analyzed the interactions between Costa Rica's agricultural and forestry sectors associated with the use of wood pallets for commodity exports over 1985–2013. Wood pallets for growing agricultural exports created a demand for domestic tree plantations. The annual land demand for tree plantations to produce these wood pallets increased by 669%, reaching 17,606 ha in 2013 and representing 28% of the increase in demand for cropland for agricultural exports over 1994–2013. Wood supplied from plantations failed to fully substitute for wood from natural forests, only allowing for a relative substitution and preventing a major sparing of these forests. The dominant use of wood from plantations for production of low-value pallets de-incentivized investments in sustainable plantations. We showed that, beyond the typical interactions between agriculture and forestry through direct competition for land, international trade generated unexpected feedback where agricultural activities and supply chains affected forestry by triggering new demand and profound changes in forestry management. Land systems behave as complex systems, calling for integrated approaches to study the outcomes of forest conservation, reforestation programs, and development of land-based businesses.

Keywords: forests; international trade; export-oriented agriculture; wood pallets; Costa Rica

1. Introduction

Agricultural activities have usually interacted with forests and the forestry sector at local, regional and national scales, in particular through competition for land. Forestry activities are often a precursor of agricultural expansion, as the opening of previously inaccessible and undisturbed forests through the construction or improvement of logging roads has facilitated the clearing of land for ranching or cultivation [1–3]. More than 80% of the agricultural expansion that occurred in tropical regions over 1980–2000 came at the expense of forests [4]. In 2000–2010, a large part of agricultural expansion in Latin America occurred in forests [5]. Inversely, the abandonment of agricultural lands

may lead to reforestation through natural regeneration and/or tree planting, a common phenomenon in Central America in recent decades [6–8]. Under certain conditions, agricultural intensification can help relieve pressure on forests by releasing land while maintaining the same level of production [9,10]. One of the main factors controlling land allocation between agriculture and forest is land rent, i.e., the potential profit that can be generated from a piece of land from different land uses, accounting for output prices and subtracting costs. Land rent depends on factors related to the land itself, such as its location and suitability for different uses, as well as external factors such as input costs and output prices [11].

With economic globalization and the increase in trade of agricultural and forest products, interactions between agriculture and forests have expanded and broadened across national boundaries and continents [12]. International market forces have played an increasingly important role in shaping land use dynamics through supply chains, which have become longer and more complex [13–15]. This may generate unexpected feedbacks, over which national policies have little control. For example, international trade may promote deforestation in some places at first, but then lead to reforestation in these places in subsequent time periods [2,16]. The growing interest in interactions between human and natural systems and in interconnections between the world's economies to explain land use dynamics has also prompted integrated perspectives to better capture the complexity of land systems [17,18].

According to the latest Global Forest Resources Assessments of the FAO [19–21], the decrease in the rate of net forest loss over the last decades can be attributed in large part to the expansion of planted forests. Tree plantations have become a major land use globally and have also taken an increasing share in the provision of wood products, accounting for 46.3% of the global supply of industrial roundwood in 2012 [22–24]. Given their faster growth and higher average productivity compared to natural forests, plantations have long been assumed to relieve logging pressure on tropical natural forests [25]. Drawing a parallel between forestry and agriculture, the potential conservation effect of plantation forestry is an example of land sparing [25]. Yet, there is conflicting evidence in the literature regarding the impacts of plantations on natural forests [26,27]. In some contexts, plantations may foster deforestation by directly competing for land with natural forests [28]. The development of high-yield timber plantations has the potential to reduce the timber price and thus the value of natural forests as a productive resource, which can favor their conversion into other land uses associated with higher rent (e.g., large-scale agriculture) [27]. Under specific market conditions, however, lower timber prices may decrease incentives to harvest and therefore limit the degradation of natural forests [26].

In Central America, Costa Rica experienced rampant deforestation until the mid-1980s, mainly due to the conversion of forests to pastures for cattle ranching [29–31]. A drop in international prices of bovine meat and in public support for agriculture coupled with the development of tourism led to the abandonment of pastures in the 1980s [32,33]. In parallel, forest policies and financial incentives were established to promote forest protection and restoration [34,35]. This resulted in a forest transition, i.e., a national-scale shift from net loss to net gain in forest cover [36], which was facilitated by a displacement of land use abroad, a spatial re-organization of agriculture within the country, and land use intensification [37]. Agricultural intensification, largely through the replacement of extensive cropland and pastures by export-oriented high-yielding crops, led to two feedbacks affecting forests. First, as sometimes observed for export crops with elastic demand on the global market [12,38], yield increase led to cropland expansion for bananas and pineapples (i.e., rebound effect) [37]. This study analyzes a second, more unexpected feedback, in which the exports of these crops created a demand for wood pallets that went unrecorded in trade statistics of forest-derived products and affected the forestry sector in terms of economics and land use.

The use of pallets accompanied the containerization of international freight transport [39]. Pallets have enabled a more efficient flow and storage of goods, reducing manual handling and the associated risk of damage to products. Although various alternatives to wood are developing, such as plastic, metal or paperboard pallets, wooden pallets still dominate the world market [40]. They are generally cheaper and easier to repair than their alternatives. Wooden pallets also offer high

resistance to heavy loads and ensures protection and hygiene in agro-food distribution thanks to its antibacterial properties [41]. With its growing exports of bananas, pineapples, and other products over the past three decades [42], Costa Rica's demand for pallets has increased, and so has the wood required to produce them. Depending on the quantity and source of this wood for pallets, the growth in agricultural exports may pose a threat to forest conservation and restoration successes in Costa Rica.

The objective of this study was to analyze the interactions between the agricultural and forestry sectors associated with the use of wood pallets for commodity exports in Costa Rica. We addressed the following questions: (1) How has the demand for wood pallets in Costa Rica evolved over the past three decades due to exports of agricultural products? (2) How has the country met this demand? (3) How have the growing commodity exports and the associated demand for pallets affected Costa Rica's forestry sector and land use? The goal of the study was not to calculate an overall land use footprint of agricultural exports over time, but rather to highlight and document the feedback from the fruit export industry on Costa Rica's forestry sector through the increase in pallet-dedicated plantations. Our results highlighted unexpected feedbacks driven by international trade and globalization on land use at the national scale (Figure 1). The study period extended from 1985, when Costa Rica initiated its pallets industry, until 2013, given the availability of trade data. Yet, given the lack of reliable time series of trade data for wood and pallets, many of our estimates only covered the period 1994–2013.

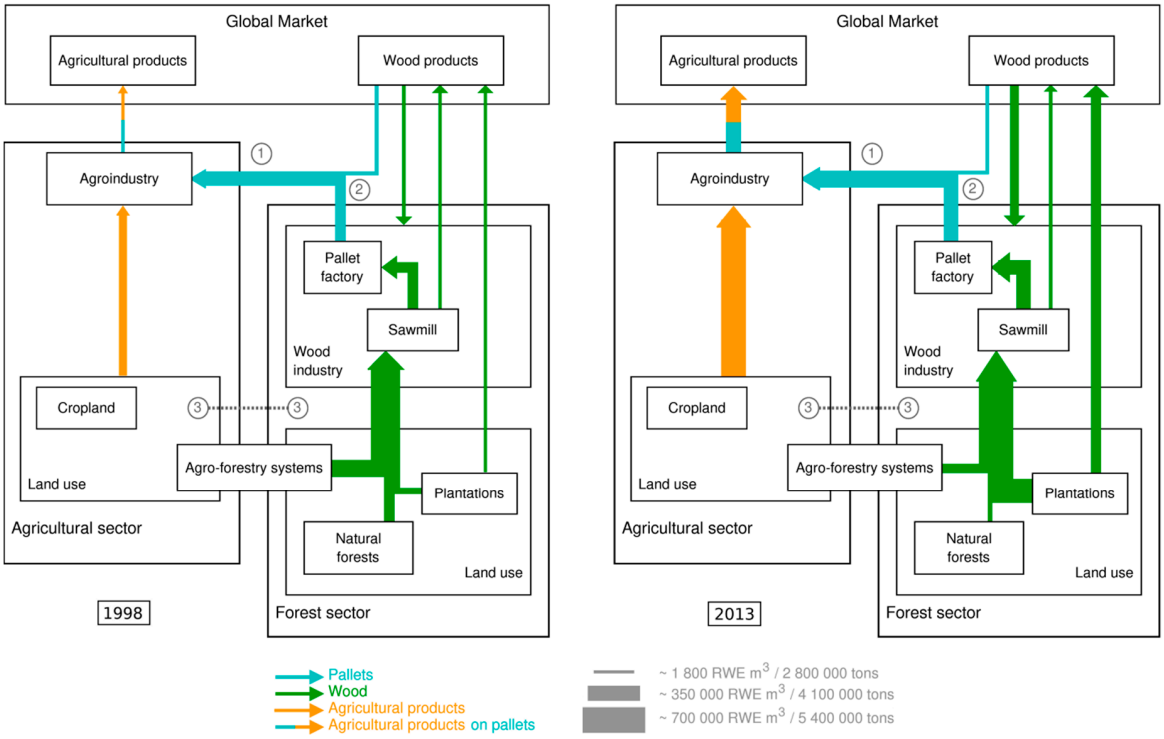

Figure 1. Main material flows between the forestry and agricultural sectors of Costa Rica, and the international market, resulting from the use of wood pallets to export the five main agricultural products exported on wood pallets over the past three decades (bananas, pineapples, melons, palm oil and cassava). The color of *arrows* represents the nature of the corresponding flows, while their width represents the size of the flows for the years 1998 and 2013. Flows of pallets are expressed in number of items (*blue*), flows of wood in roundwood equivalent cubic meters (*green*), and flows of agricultural products (on pallets or not) in tons (*orange*). *Numbers* in *grey* refer to the three questions addressed in this study.

2. Materials and Methods

The data used for this study were compiled from various sources, including semi-structured interviews realized in Costa Rica in November 2015. We interviewed: (i) representatives of nine companies producing and treating[1] wood pallets (out of a total of 80 companies authorized by the State Phytosanitary Service (SFE) of the Costa Rica's Ministry of Agriculture and Livestock (MAG) to treat packaging materials in October 2015); (ii) one representative of a company specialized in rental and maintenance of pallets; (iii) two members of the IUCN involved in forest governance and economy; (iv) one engineer from the Ministry of Agriculture and Livestock; and (v) a forest engineer who invested in a 150 ha forest plantation in the early 2000s. These interviews consisted of a series of open and closed questions adapted to each interlocutor and aimed to gather both quantitative and qualitative information on: (i) domestic production and trade of wood; (ii) domestic production and consumption, and trade of wood pallets; (iii) supply and value chains of wood pallets; (iv) establishment, management, and productivity of forest plantations; (v) use of wood pallets, including the volume and weight of agricultural products that can be loaded on one pallet. The total average annual production of pallets realized by the sample of nine companies accounted for 26% of domestic production for export of agricultural and industrial products, as estimated by the National Forest Office (ONF) for 2014 [43], see Appendix A for a summary of the parameters used in the analysis steps described below.

2.1. Evolution over Time of Demand for Wood Pallets due to Agricultural Exports

Our objective being to study interactions between Costa Rica's economic sectors as a result of international trade, we focused on the demand and production of wood pallets related to the export of agricultural and industrial products, hereafter referred to as "export-based demand". We neglected the wood pallets used for transport within the country, and those exported as such by Costa Rica. The latter category corresponded to maximum 18% of our estimated export-based demand over 1994–2013 (according to the methodology used to estimate the proportion accounted for by pallets imports; see Section 2.2). The annual export-based demand for wood pallets was estimated for 1985–2013 based on trade data concerning the main products exported on pallets compiled from Comtrade [44] and FAOSTAT [42], in combination with parameters derived from data published by the ONF [41,43,45–51]. The ONF reports provide an estimation of the total number of pallets produced in the country based on trade values and weights of the 50 most exported products, and the detailed number of pallets required for the 10–15 most pallet-demanding products in each year of 2006–2014. We selected all the products that have been included in this list for more than two years, and for which a detailed time series of trade data existed. For each of them, we estimated the average weight that can be loaded on one pallet based on data from the ONF reports and our interviews, and then divided the total export weights for each year in 1985–2013 by these estimates. Finally, we obtained our estimates of total annual export-based demand for pallets over 1985–2013 by extrapolating the pallets demand associated with our products' selection based on the average proportion accounted for by this selection in the total export-based production estimated by the ONF over 2006–2013 (i.e., 79.8%). Based on the ONF reports, we assumed that the products taken into account in our estimation were exclusively exported on wood pallets [41,43,45–51]. We tested for an increasing trend in our estimated demand for pallets over time using simple ordinary least squares (OLS) regression and heteroscedasticity and autocorrelation-consistent estimators of covariance [52].

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[1] Since 2002, all wood packaging material destined for export must be subjected to a heat treatment and certified according to the International Standards For Phytosanitary Measures (ISPM) N°15, adopted by the Interim Commission on Phytosanitary Measures (ICPM) [115].

2.2. How Costa Rica Has Met Its Demand for Wood Pallets over Time

According to the ONF estimates, Costa Rica has produced all the pallets it required to export its agricultural and industrial products since 2006. We verified this information by estimating the maximum number of pallets that Costa Rica could have imported. We compiled detailed import weights of the Comtrade category "wooden pallets, box pallets and load boards" from Comtrade and Procomer [53] for the period 1994–2013, assuming that this category consisted exclusively of pallets. The year 1996 was excluded due to aberrant value. The imported weights were converted into numbers of pallets based on the minimum, average and maximum weights of standard American and European pallets (respectively 14, 22, and 28 kg) [54–56]. We assumed that Costa Rica has imported American and European pallets in the same proportions since it has mainly used them to export tropical fruits, about half of which went to the U.S. and half to Europe over 1985–2013 [44]. We then compared the high estimate of pallets imports to our estimate of export-based demand in each year of 1994–2013. As the demand for wood pallets in Costa Rica is reported to be closely linked to the main export-oriented agricultural activities [57], we assumed that all the pallets imported by the country over the study period were used to export its agricultural and industrial products. We thus used the estimates of pallet imports based on the average weights of American and European pallets to deduce the annual domestic production of wood pallets as the difference between demand and imports. We tested for trends in pallet imports over time with simple OLS regressions [58].

We reconstructed the origin of the wood used for domestic production of pallets in Costa Rica by estimating the share of that wood coming from (i) domestic sources or imported from abroad, and for the domestic part, from (ii) plantations versus other domestic sources. We compiled data on annual imports of round- and sawnwood from Comtrade and Procomer for the period 1994–2013, and estimated the maximum proportion of our estimated domestic production of pallets that could have been produced using the imported wood in each year. To this end, we converted imports weights into cubic meters based on parameters from the literature [57,59,60], and multiplied them by the minimum requirements of round and sawn wood to produce one pallet obtained from our interviews (respectively 0.06 and 0.03 m^3/pallet, while the maximums are respectively 0.1 and 0.04 m^3/pallet). This estimation revealed that the pallet industry of Costa Rica had mainly relied on wood from domestic sources over 1994–2013. In the absence of data on the quantity of imported wood used for domestic production of pallets, and based on the literature and our interviews, we assumed that wood was preferentially obtained from tree plantations. Tree plantations were thus the unique source of wood for the pallet industry in the years where the total volume of wood supplied from plantations was greater than or equal to the wood requirement of this industry. For the other years, the unexplained supply of wood for the domestic pallet industry had to be met from imports and other domestic sources in unknown proportions. The wood requirements for the domestic production of pallets were estimated using the average factor of 0.084 m^3 of round wood by pallet, calculated on the basis of our interviews and weighted according to the share of each company in the total annual pallet production of the whole sample. We further computed low and high estimates of these wood requirements (using the minimum and maximum factors of 0.06 and 0.1 round m^3/pallet) to estimate the low and high proportions represented by the volume of wood from plantations used for domestic production of pallets in the total volume supplied from plantations in Costa Rica over 1994–2013. We then relied on our interviews to compute, for our sample of companies, the proportions of their total annual production of pallets that was realized with (i) domestic versus imported wood; (ii) wood coming from plantations versus other domestic sources; and (iii) different tree species.

Finally, to evaluate the profitability of using wood from natural forest for pallet production, compared to wood from plantations, we reconstructed the Costa Rican pallet's supply and value chains based on data collected from our sample of pallet companies. We considered four different steps from the acquisition of the raw material to the sale of finished products: (i) sawing of round wood into slats; (ii) assembly of pallets from slats and nails; (iii) heat treatment of pallets; and (iv) commercialization of treated pallets. This allowed estimating the minimum, average and

maximum fixed costs of converting sawnwood into finished pallets. Considering a unitary price for a new pallet ranging from $7 to $20, based on our interviews, we determined the range of prices that a company could pay for one cubic meter of sawnwood to make a nil profit. We then compared this range to the prices published by the ONF for sawnwood of different species over the period 2008–2015 [61–66], grouping the species into three categories: softwood from plantations, semi-hard wood from natural forests, and hardwood (excluding the most expensive Almond and Medlar species) from natural forests.

2.3. Effects on Costa Rica's Forestry Sector and Land Use

To quantify the hypothetical area of natural forest that would have been spared if the use of plantations for pallet production would have substituted for extraction in natural forests, we estimated the area of natural forest that would have been required each year of 1994–2013 to supply Costa Rica's domestic industry of pallets in the absence of planted forests. We considered the sawnwood requirements derived from our interviews (0.03–0.04 m^3/pallet), a productivity of 15–20 m^3/ha over a cutting cycle of 15 years as prescribed by the national standards for sustainable forest management [67,68], and a conversion efficiency of roundwood into sawnwood of 50%–70% (respectively equivalent and higher than the average for wood from plantations) [57]. We compared our high and low estimates for natural forest with those for plantations, computed with a productivity of 150–300 m^3/ha over a rotation length of 12 years [69,70]. We also compared our estimates of the natural forest area that would have been impacted by pallet production with the country's forest cover, including primary and secondary natural forests but excluding mangroves and tree plantations, for 1997, 2000, 2005 and 2012 [71–74]. These dates were selected based on the availability of reliable detailed data on national forest cover.

Then, to assess the impact of the growing exports of commodities by Costa Rica on its land use, we estimated the annual land demand associated with the production and export of bananas, pineapples, melons, palm oil and cassava, including the cropland used for production as well as the area of forest required to produce pallets used for exports. These are the main export-oriented products that were exported on pallets (together they represented 80% of our estimates of total demand for pallets over 1985–2103) and whose cultivated area expanded between 1985 and 2013. The evolution of this cultivated area has been reconstructed based on data from FAOSTAT and Estado de la Nación [75], combining both databases to fill gaps and correct outliers. Concerning the forest component, it can be divided into three subcomponents: (i) the area of forest outside Costa Rica that was used to produce the pallets imported by the country; (ii) the area of forest plantations harvested in Costa Rica to supply the domestic pallet industry; and (iii) the area of forest embodied in the other sources of wood included in the unexplained supply, which corresponds to forests abroad that supplied the wood imported by Costa Rica for its pallet industry and/or to local natural forests and agro-forestry systems used for this industry. As the objective of the analysis was to highlight and document the increasing and leading role played by domestic forest plantations in Costa Rica's pallet industry and given the lack of data on the latter sources, we focused exclusively on the first two subcomponents. We assumed that the pallets imported by Costa Rica were used in the same proportions for all the different products over 1994–2013, so that around 80% of total pallet imports were used for our selection of products in each year of the period. First, to estimate the forest area embodied in these imported pallets, we considered that 21% of all the pallets in circulation throughout the world in 2009 were newly produced pallets (the rest being recycled pallets) and that the number of reusable pallets has increased by 2.5% each year over the past two decades [76]. Applying these two parameters to the Costa Rica's imports, we obtained the number of new pallets imported in each year over 1994–2013. We then converted these numbers of pallets into volume of wood based on a weighted average requirement of sawnwood of 0.034 m^3/pallet obtained from our interviews. Assuming that all the imported pallets had been produced with wood from plantations, we estimated the area of forest plantation required to produce this wood using an average mean annual increment for the different countries of

imports' origins (compiled from Comtrade) based on FAO [77], Brown [70] and Del Lungo et al. [78]. Second, we estimated the area of Costa Rican plantations that was used to produce the pallets' demand not met by imports based on the weighted average roundwood requirement of 0.084 m^3/pallet and a productivity of 20 m^3/ha/yr. This is the average productivity of the most frequently planted species in Costa Rica, *Gmelina arborea* (beechwood), as measured in the southern part of the country [79,80]. We finally computed the accumulated increase/decrease in land demand compared to the year 1994 (in hectare times year) for the three components, in total and separately. Integrating changes through time allowed for smoothing inter-annual fluctuations of land demand and for attenuating the influence of the precise years defining the start and end of the study period on the results.

3. Results

3.1. Evolution over Time of Demand for Wood Pallets due to Agricultural Exports

According to our interviews, Costa Rica began using wood pallets to export its fruits in the early 1980s. Before that, boxes of products, mainly bananas, were directly placed in the holds of ships, in a practice known as break-bulk. Our reconstruction of the annual demand for pallets coming from the export of agricultural and industrial products shows an increasing trend over the past three decades, from 1,262,708 pallets in 1985 to 5,754,658 in 2013 ($p < 0.0001$) (Figure 2). This increase resulted mainly from the growing export of bananas until 1998, and of pineapples since then. Together, bananas and pineapples accounted for 72% of the total demand for pallets to export agricultural and industrial products over 1985–2013. According to the ONF, industrial products such as glass containers and iron/steel bars represented around 13% of total export-based demand over 2007–2014.

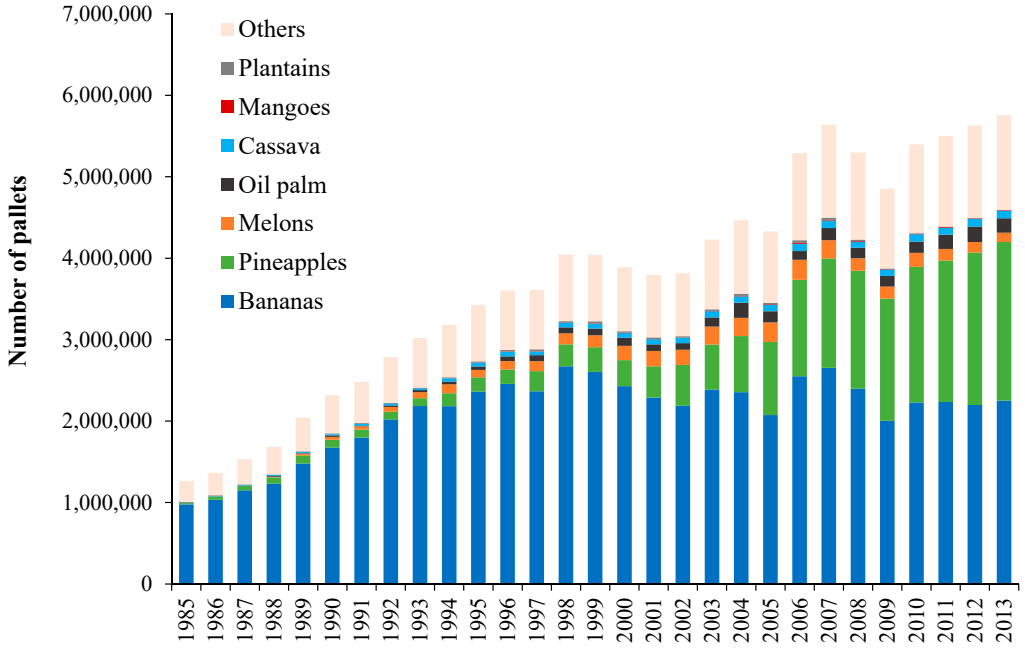

Figure 2. Estimates of annual demand for wood pallets by Costa Rica to export its agricultural and industrial products. The category "Others" includes industrial and other agricultural products.

3.2. How Costa Rica Has Met Its Demand for Wood Pallets Over Time

Interviews revealed that at least since the early 1990s, demand for wood pallets has been mainly met by domestic production in Costa Rica. Indeed, we calculated that imported pallets may have accounted for a maximum of 10% of total export-based demand over 1994–2013 (with a maximum annual contribution of 23.7% in 1997 and a minimum of 2% in 2007) (Figure 3). This proportion shows a decreasing trend over 1997–2007 ($p < 0.01$), and a slight increasing trend over 2007–2012 ($p < 0.05$).

Before the 1990s, Costa Rica is reported to have imported most of the pallets it needed, notably from the U.S. In the late 1980s, the U.S. pallets were the second largest item by value of total Costa Rican wood imports [81].

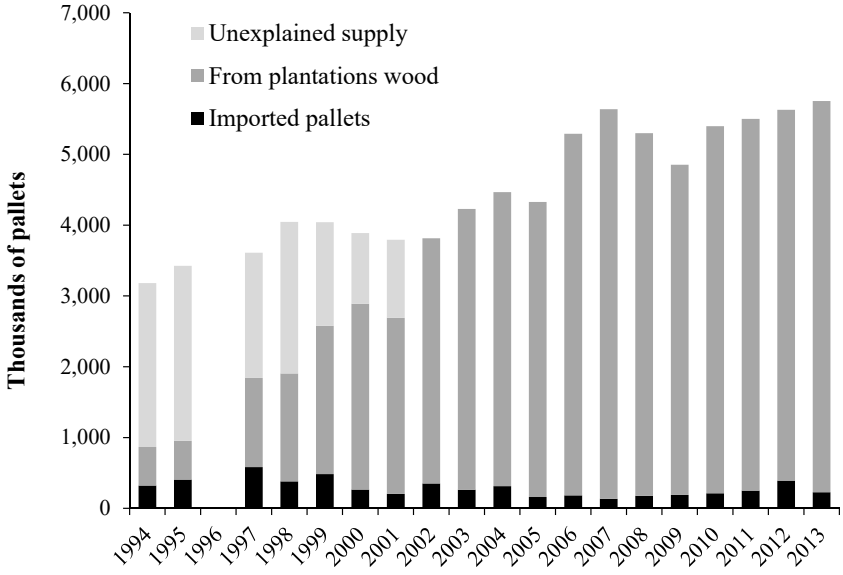

Figure 3. Best guess estimates of the contribution of the different sources of pallets and wood to the total export-based demand, expressed in number of pallets. The unexplained supply corresponds to the wood requirement of the domestic pallet industry that could not have been met by wood supplied from plantations, and thus came from natural forests, agro-forestry systems, and other wood imports.

Seven of the nine interviewed companies that produce and sell new wood pallets (accounting together for 89% of total production of the sample, plus the rental company) relied exclusively on wood coming from Costa Rica (Figure 4). Using a low and high wood requirement to produce one pallet, the total volume of round- and sawnwood imported over 1994–2013 would have covered only 31%–33% of total wood used for domestic production of the export-based demand for pallets.

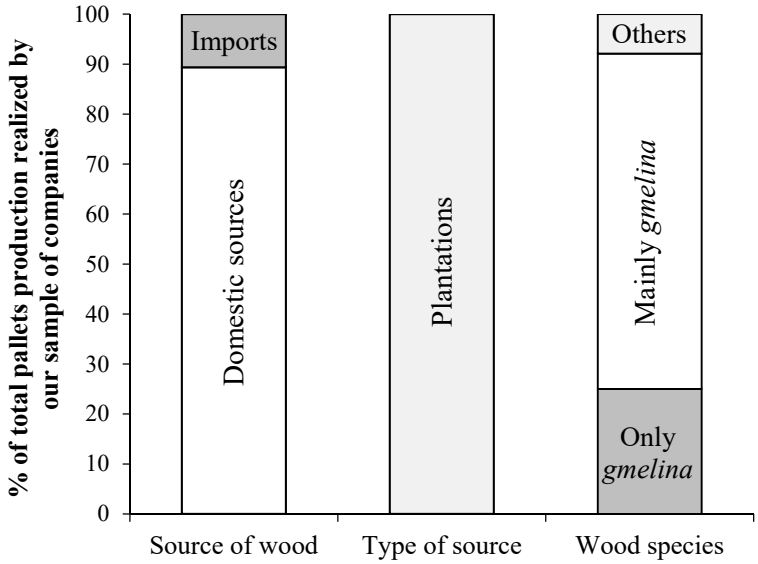

Figure 4. Proportion of the different sources and species of wood used by the nine interviewed companies that produce and sell new wood pallets, expressed as the proportion of total production accounted for by this sample of companies.

All the pallet companies interviewed declared using only wood from forest plantations (Figure 4). Most of them (9/10 when considering also the rental company) used mainly *Gmelina arborea*. At least 8/9 companies (accounting for 97% of total production by the sample) relied on monoculture on privately owned land (their own plantations for 6 companies accounting for 88% of the total sample's production). Wood from three- or four-year-old *Gmelina* plantations trees can already be used for the production of pallets. Five of the six companies that managed their own plantations (accounting for 82% of sample's production) applied a maximum total cycle of less than 8 years (with several thinnings), while the average rotation length of *Gmelina* in Costa Rica is normally 12–14 years [69]. Whereas in the 1990s pallets were made of imported wood and domestic wood coming from natural forests and agro-forestry systems, since 2002 the volume of wood supplied from plantations has been sufficient to meet the requirements of the pallet industry of Costa Rica (Figure 3). Based on the literature and our interviews, we considered that domestic plantations were thus the unique source of wood for this industry after 2001, so that the unexplained supply component disappears during the subsequent period. According to ONF, the domestic production of pallets absorbed 60.5% of the total wood supply from plantations over 2005–2014. Considering our low and high estimates of the volume of wood required to produce one pallet, respectively 45% and 71% of the total supply from plantations has been consumed by the Costa Rican pallet industry over 1994–2013.

We estimated that a Costa Rican company could afford to pay between $214 and $398 for one cubic meter of sawnwood to produce and sell pallets at 2015 market prices without making any profit or loss. This price range overlaps prices for all the species from forest plantations that have been commonly used for pallet production in Costa Rica. Although this range intersects the price ranges of both semi-hard and hardwood species from natural forests (respectively $342–575 and $334–802 per m^3 in 2015), the average prices of sawnwood from natural forests (excluding the most expensive Almond and Medlar hardwood) were higher than $480 in 2015, thus exceeding the value that pallet producing companies can afford for wood to be profitable on the pallet market. We therefore assumed that the Costa Rican pallet industry has not relied on wood from natural forests since 2002.

3.3. Effects on Costa Rica's Forestry Sector and Land Use

The first tree plantations of Costa Rica were established in the late 1970s based on an income tax deduction [67,82]. Since then, the rate of planting evolved in three distinct phases. The first was a phase of experimentation and learning that extended over 1978–1987, with an average of about 2000 ha annually planted. The second phase occurred over 1988–1996 when new incentives were added to the income tax deduction. The process became more accessible for small and medium owners and the average rate of planting surpassed 9000 ha/year. The last phase began in 1997 with the replacement of the previous incentives by a more restrictive national Payments for Ecosystem Services (PES) program [83,84] (see [85,86] for a thorough description of the program). This phase was marked by a decreasing trend in the reforestation rate, with an average of less than 4000 ha sown per year since 2000.

In the hypothetical scenario where the wood demand of the Costa Rican pallet industry could not have been met by forest plantations, we calculated the natural forest land area that would have been required to produce the same amount of wood as that coming from plantations between 1994 and 2013. Based on the range of sawnwood requirements derived from our interviews, and considering that natural forests are nine to 25 times less productive than *Gmelina* plantations in Costa Rica, but that sawing efficiency can be higher for wood from natural forest [57,79], the production of wood pallets from Costa Rica's natural forests instead of plantations over 1994–2013 would have required an area seven to 31 times larger. The area annually required would have represented an increasing proportion of the country's natural forest cover, i.e., 8%–12% between 1997 and 2013 (Figure 5).

The growing export of commodities resulted in an increasing demand for both agricultural and forest land. Bananas, pineapples, melons, palm oil and cassava were the main export-oriented products that were exported on pallets and whose cultivation area expanded between 1985 and 2013.

The aggregated cultivated area of these five commodities doubled, while the area of plantations required in Costa Rica to produce the associated pallets increased by 669% between 1994 and 2013, from 2289 ha to 17,606 ha (Figure 6). In terms of area, the decreasing imports of pallets compensated for only 1% of the cumulated agricultural expansion over 1994–2013, while the use of domestic plantations for pallet production added a land demand equivalent to 28% of that expansion (Table 1).

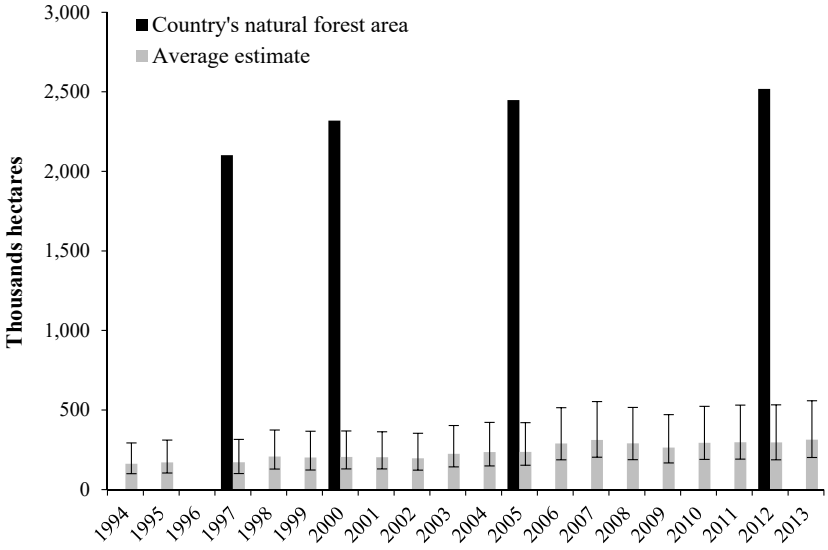

Figure 5. Estimates of the area of natural forest that would have been required annually to meet the total wood demand of the pallets industry in Costa Rica over 1994–2013, compared to the actual country's area of natural forest. Grey bars represent our best guess estimates, based on a productivity of 1 m^3/ha/yr, an average requirement of sawnwood by pallet of 0.034 m^3, and a sawing efficiency of 60%. Errors bars are associated to the ranges of forest productivity (1–1.3 m^3/ha/yr), sawnwood requirement (0.03–0.04 m^3/pallet), and sawing efficiency (50%–70%).

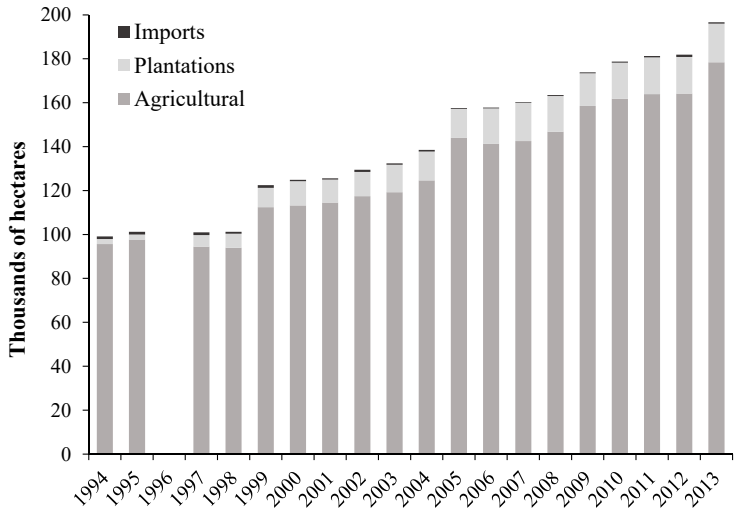

Figure 6. Evolution of the land demand associated with the cultivation and export of bananas, pineapples, palm oil, melons, and cassava in Costa Rica over 1994–2013, highlighting the contribution of three components. The agricultural and plantations components refer respectively to cropland expansion and the increasing area of plantations that has been required to produce the wood pallets used for crops exports in Costa Rica. The imports component corresponds to the area of forest plantations that was required abroad to produce the pallets imported by Costa Rica. The land demand associated with the unexplained supply over the period 1994-2001 has been ignored.

Table 1. Estimates of three components of the land demand associated with the cultivation and export of bananas, pineapples, palm oil, melons, and cassava in Costa Rica. The three components are integrated over 1994–2013 and thus expressed in terms of accumulated area of expansion/contraction over this period (in hectare times year).

Components of the Land Demand	Agricultural	Plantations	Imports
Accumulated expansion/contraction (ha.yr)	667 008	185 060	−7 585
% of the agricultural component	100	27.7	−1.14

4. Discussion

4.1. Growing Demand for Wood Pallets Met from Domestic Forest Plantations

The growing export of agricultural and industrial products has led to a 4.6-fold increase in demand for wood pallets in Costa Rica between 1985 and 2013. Bananas, pineapples, melons, palm oil and cassava have accounted for more than 79% of total export-based demand for pallets in this period. Costa Rica started by importing these pallets, but rapidly developed its own pallet industry in the 1980s. Until the early 2000s, domestically-produced pallets were mainly made of semi-hardwood from natural forests and agro-forestry systems. Following the implementation of more stringent management standards for natural forests in 1999 and the suspension of the PES contracts for the sustainable management of these forests in 2002, plantations became the main source of raw material for the wood industry of the country [48,67]. More than half of the total domestic supply of wood has come from plantations since 2003, and this proportion has continuously increased over the following decade [57,68]. Due to the higher efficiency and profitability they enable, plantations also became the only source of wood for the Costa Rica's domestic pallets industry. Since the 1990s, this industry has met at least 90% of the country's export-based demand for wood pallets (Figure 1). Note that a portion of the domestic wood used by the Costa Rican pallet industry over the study period might have been harvested illegally. However, since we focused on the evolution of the plantation sector, and illegal logging has mostly affected natural forests and agro-forestry systems in the country [87], the portion of wood illegally cut in these forests is not of our concern.

4.2. Use of Plantations for Pallet Production: Competition with Natural Forests or Land Sparing?

The ambivalent effects of establishing forest plantations as a substitute source of wood to natural forests has been widely discussed [25–27]. In the absence of plantations, Costa Rica would have further relied on imports of pallets or wood, or on wood from its natural forests and agroforestry systems. The use of forest plantations for pallet production in Costa Rica had two advantages from economic and ecological perspectives. Firstly, the development of the pallet industry has generated economic activity (from $42 million in 2006 to $61.63 million in 2013) and more than 2000 direct jobs since 2006, including harvest, transport and sawing of roundwood, in addition to the assembly and treatment of pallets [41,43,45–51]. Secondly, the major reliance of this pallet industry on wood from plantations has avoided additional land use displacement abroad through wood imports, both during the 1980–1990 period and the larger forest transition period over which the country turned into being a net exporter of land use [37].

However, planted forests—from which more than half of the wood supply has been used by the Costa Rican pallet industry since the 2000s—have also competed for land with natural forests in Costa Rica. The establishment of plantations has been estimated to be directly responsible for 10% of the deforestation over 1987–2013 [88]. The clearance of native tropical forests for monoculture tree plantations was reported to have large impacts on biodiversity, carbon sequestration, and water cycle in other Latin American countries [23,89,90]. In addition, plantations established on previous pastureland may have contributed indirectly to deforestation by displacing pastures. A similar dynamic

has already been discussed for cropland expansion over pastures [91]. Conversion of forest to pasture corresponded to 70% of the deforestation over 1987–2013 [88], and was in particular responsible for the clearing of mature forests [91]. Plantations' establishment on former pastures may also have prevented the regeneration of more environmentally valuable natural forests, although regeneration would have depended on several factors such as distance to sources of propagules or intensity of site degradation. By contrast, plantations may have favored or accelerated the regeneration or afforestation of native species in some places, notably by attracting agents of seed dispersal and improving local soil and microclimatic conditions [92–94]. It has been estimated that 10% of total natural regeneration in Costa Rica has occurred on previous plantations over 1987–2013 [88].

The primary motivation for introducing tree plantations in Costa Rica in the late 1970s was to mitigate deforestation by creating an alternative source of wood than natural forests [95,96]. Two of the most important prerequisites highlighted in the literature [25,97] to achieve this objective were not completely met in Costa Rica. First, logging was not the main cause of deforestation, but instead it was agriculture. While the country's forest cover has increased since the late 1980s, natural forests have still been converted to agricultural use and real estate, especially in private forests [35,98,99]. Secondly, wood from plantations has not been an effective substitute for wood from natural forests, and thus failed to capture the already existing markets supplied by native timber. The *Gmelina* tree species was chosen for its rapid growth and good adaptability to most sites, but without much knowledge about its wood properties and potential uses in the wood industry [68,100]. In the early 1990s, when the first thinning was made, the demand for *Gmelina* wood was inexistent on the traditional domestic market [69]. This wood was thus supplied to a market demanding wood quantity but not quality: the pallet industry for banana exports [57,69,101]. Later, *Gmelina* wood was entered into other markets, like those of construction and furniture, but this incursion has been slow and limited due to the lack of equipment and experience to properly process *Gmelina*, and to continuing demand for species from natural forests with higher resistance values. Overall, the plantations' wood allowed for a relative substitution—i.e., it fulfilled the new and growing demand for pallets—but did not allow for an absolute substitution—i.e., decreasing the absolute demand for wood from natural forests. Costa Rica's plantations thus contrast with other cases in which forest plantations reduced the value of—and subsequently the demand for—products from natural forests, potentially sparing land and reducing deforestation and degradation [26,102].

On the whole, using wood from plantations for pallet production has not strongly contributed to sparing Costa Rica's natural forests. However, the competition of the country's plantations with natural forests is only a mild source of concern. The establishment rate of plantations in Costa Rica has decreased since the mid-1990s at a pace that neither ensures their sustainability, nor attracts investments in this activity [103]. The main reasons for this decrease, as reported by various authors [96,103], include: (i) a lack of financial support and incentives to establish and manage plantations, combined with administrative hurdles and red tape; (ii) the absence of a strategy for the industrialization of wood supplied from plantations which, combined with the competition among pallets producers to offer low-priced pallets, has kept low prices for wood from plantations; (iii) the competition with cheaper imported wood, notably from Chile due to free trade agreements; and (iv) the competition for land with tourism or agricultural activities—like export-crops cultivation—that are less regulated and generate higher income in a shorter-term.

4.3. Unexpected Feedbacks of International Trade on Costa Rica's Land Use and Forestry Sector

The agricultural intensification that occurred through the replacement of extensive pastures and cropland by more intensive export-oriented cultivation has contributed to a certain extent to the forest transition of Costa Rica [37,96]. However, the shift to a more export-based agriculture brought unintended effects on the country's land use. First, it led to an increasing demand for agricultural land, mostly for bananas and pineapples in the most agro-environmentally suitable provinces, which are also characterized by the largest proportion of mature forests and the highest

ecological value [37]. While this expansion occurred mainly by conversion of traditional cropland and pastures, it also directly caused deforestation. Other studies have also shown that, while shifting cultivation and cattle ranching were traditionally the main causes of forest loss in Latin America, the region recently experienced a rise in large-scale agribusiness for international markets as key agents of deforestation [16,104–106]. Secondly, through the use of wood pallets, the development of export-oriented cultivation has resulted in a growing demand for forestry land, mostly for short-rotation plantations. Over 1994–2013, the cumulative increase in demand for domestic tree plantations for the export of the main export-oriented crops grown in Costa Rica corresponded to 28% of the associated cropland expansion.

The effects on the forest sector of this demand for wood pallets for export-oriented agriculture were multiple. On the one hand, it contributed to the depletion of the country's legal sources of wood. The wood demand for pallets production has continuously increased, while the establishment rate of plantations has decreased over the same period. Moreover, the large consumption of wood for pallet production led to an over-exploitation of plantations, mostly due to inappropriate silvicultural practices [57,68,107]. The need for logs of small diameter and often the pressing need for cash have encouraged early harvesting and the operation of crown thinning by the upper part of the trees [47]. This prevented the production of large-diameter wood with higher value and it significantly affected the future productivity of plantations [68,107]. On the other hand, the development of the domestic pallet industry has de-incentivized new tree plantations. Actually, the strong competition on the pallet market resulting from the growing production based on wood from plantations and the pressure exerted on pallet prices by the big agro-exporters established in Costa Rica, like Chiquita and Dole, resulted in very low profitability of investments in forest plantations by small producers, which had to absorb the costs of management, extraction, transport and sawmilling with decreasing subsidies [50]. The forestry system of Costa Rica appears locked into a techno-institutional configuration resulting from interactions between technological, institutional and socio-economic forces [108,109], as described in other contexts such as the energy and fishery sectors [110,111].

Export-oriented agriculture, despite its net land sparing effect [37], turned out to be a strong contender for both natural forest and sustainably managed plantations. The level of agricultural rents is a key determinant of the impacts of forest plantations on the conservation of natural forests [25]. In Costa Rica's case, the higher profits that can be derived from large-scale export-oriented agriculture compared to tree planting increased the opportunity cost of reforestation, as it can also do with regard to nature conservation [112]. This has been shown in other countries of Latin America, such as for soybean cultivation versus plantations in Uruguay [113]. Considering the low financial returns of plantations, it is not surprising that large areas of forest plantations established in Costa Rica over the 1990s were since then harvested and converted to cropland or real estate projects instead of being replanted [114]. Due to limited financial resources, the PES program has not been able to compete with cash crops like pineapples or bananas [98,115]. Incentive programs to reforest and protect forests should take into account increasing yields and land rents of other land-based activities to achieve full efficiency [116]. These results highlight the increased complexity of land systems resulting from the international trade in land-based products, and support the call for a framework integrating ecological, social and economic components of coupled human-natural systems [117].

4.4. Sustainability of Domestic Wood Production at Risk

As a result of the plantations dwindling in Costa Rica, the growing total demand for wood—mainly fueled by the packaging and construction sectors—has increasingly exceeded the domestic supply since the 2000s [83,118]. This raises concerns about the sustainability of wood production in the country [67,100,115]. On the one hand, natural forests have increasingly suffered from illegal logging due to the higher price of their wood compared to the wood from plantations, and the strict policies that make their management costly and difficult [83]. Beyond direct environmental impacts, this may discourage domestic and foreign investment in sustainable forestry

activities, and negatively affect rural economies mostly responsible for wood production and industrialization [83]. Illegal harvest has also distorted markets and contributed to lower roundwood prices [50].

On the other hand, Costa Rica has become increasingly dependent on wood imports, mainly in the form of sawnwood from Chile [42,67]. Given the lower price of Chilean wood compared to Costa Rican wood suitable for pallets production [119], it has become increasingly interesting to import wood from Chile rather than invest in new plantations in Costa Rica. With its highly advanced plantation industry mainly based on the high-yielding *Pinus radiata* species, Chile presents a comparative advantage for wood production against Costa Rica [70,97,120]. Yet, Chile's exotic tree plantations have largely expanded at the expense of native temperate forests and their high biodiversity over the past decades [89,121]. Moreover, while Chile's plantations have succeeded in capturing the domestic markets for construction lumber, pulp and paper, and mass-market furniture, they did not relieve the pressure for the exploitation of natural forests [97]. Thus, contrarily to Costa Rica, the key challenge in Chile has not been the establishment and management of forest plantations for wood production, but rather the protection of the ecologically valuable but economically marginal natural forests [122].

5. Conclusions

Costa Rica's forest transition has been widely recognized as a success story. The shift from a net decrease to a net increase in the national forest area was made possible, on one hand, by the intensification of agricultural and forestry land uses and, on the other hand, by high-yielding export-oriented cultivation and new tree plantations. To a certain extent, both have allowed for net land sparing. However, as a result of international trade, the development of a more intensive export-oriented agriculture led to unexpected feedback to the forestry sector and the land use dynamics of the country. Since the 1980s, products destined for export like bananas and pineapples have been loaded on wood pallets that are not accounted for in global trade statistics as they are considered as being consumed within a domestic industry. We estimated a 356% increase in Costa Rica's demand for wood pallets to export its agricultural and industrial products between 1985 and 2013. The country developed its pallets industry over the 1990s and mainly relied on its tree plantations to produce more than 90% of its wood pallets' needs over 1994–2013. Consequently, the growing exports of agricultural products by Costa Rica led to an increasing demand not only for agricultural land, but also for tree plantations. Between 1994 and 2013, the demand for the country's plantations for pallets used to export the main agricultural products exported on pallets by Costa Rica increased by 669% and accounted for 28% of the cumulative agricultural expansion associated with these products.

The growing demand for wood supplied from plantations could have fostered the planting of trees in the country and further contributed to spare natural forests. Instead, wood from plantations failed to capture the traditional market supplied by wood from natural forests, whose prices remain higher and the perceived quality better compared to wood from plantations, thus failing to induce a significant sparing of natural forests. Overall, the plantations' wood allowed for a relative substitution—i.e., it fulfilled the new and growing demand for pallets—but did not allow for an absolute substitution—i.e., decreasing the absolute demand for wood from natural forests. The major use of plantations' wood for pallet production and the lack of alternative outlets further contributed to de-incentivizing the establishment of new plantations, whose rate of expansion significantly decreased since the mid-1990s. The lack of planning and strategy for the industrialization of wood from plantations led to the promotion of its competitive use for production of low-value pallets, which kept the price of this wood down. Combined with a lack of financial and administrative support for the establishment and management of plantations, low prices of plantations' wood has made the investment in tree cultivation uncompetitive with the far more profitable export-oriented agriculture. As the establishment of new plantations has decreased while domestic demand for wood has continuously increased, Costa Rica has faced a growing wood shortage since the 2000s. This has

resulted in a rise of illegal logging of natural forests and an increasing dependence on wood imports from Chile, where the system of wood production is efficient, but not necessarily environmentally sustainable. The growth in agricultural exports thus brings specific threats to forest conservation and restoration success in Costa Rica.

Interactions between agriculture and forestry often occur through competition for land. Here, we demonstrated another form of interaction where changes in agricultural activities and supply chains triggered new demand and profound changes in the forestry sector. The present study highlighted how local institutional and economic factors may interplay with international markets to determine the multi-scale outcomes of sectoral decisions and activities in a country and to generate unintended feedback in other land uses and economic sectors. The case of Costa Rica exemplified the increasing role of large-scale, industrial agriculture in shaping national land use dynamics. It also demonstrated how land systems behave as complex systems with dynamic feedbacks, thus highlighting the importance of adopting an integrated approach—including interactions between agricultural and forestry sectors, national land use, and international trade—when dealing with forest conservation, reforestation and development of land-based businesses.

Acknowledgments: This work was financially supported by the Belgian National Fund for Scientific Research (F.R.S.-FNRS).

Author Contributions: I.J., P.M. and E.F.L. conceived and designed the study; I.J. and J.C.Z.P. conducted field work; I.J. analyzed the data; I.J., P.M. and E.F.L. wrote the paper.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Summary of the parameters used in the different steps of the analysis.

Parameter			Value	Unit	Source
Average weight to be loaded on one pallet		Bananas	0.86	tons/pallet	[41,43,45–51], interviews
		Plantains	1.06		
		Pineapples	1.01		
		Melons	1.01		
		Cassava	1.01		
		Mangoes	1.05		
		Oil palm	0.96		
Weight of European and American pallets		Minimum	14	kg	[54–56]
		Average	22		
		Maximum	28		
Factors to convert weight into volume	Roundwood	No coniferous	1.31	m^3/ton	[57,59,60]
		Coniferous	1.43		
	Sawnwood	No coniferous	1.43		
		Coniferous	1.82		
Roundwood requirements for pallet production		Minimum	0.06	m^3/pallet	Interviews
		Weighted average	0.084		
		Maximum	0.1		
Sawnwood requirements for pallet production		Minimum	0.03		
		Weighted average	0.034		
		Maximum	0.04		

Table A1. *Cont.*

Parameter			Value	Unit	Source
Fixed costs of converting sawnwood into finished pallets	Assembly	Minimum	0.08	$/pallet	Interviews
		Average	2.88		
		Maximum	3.34		
	Heat treatment	Minimum	0.50		
		Average	0.73		
		Maximum	0.75		
	Commercialization	Minimum	0.00		
		Average	1.12		
		Maximum	2.55		
Price of new pallets		Minimum	7		
		Maximum	20		
Productivity of Costa Rican forests	Natural forests	Minimum	1	m^3/ha/yr	[67,68]
		Maximum	1.3		
	Forest plantations	Minimum	12		[69,70,79,80]
		Average	20		
		Maximum	25		
Conversion efficiency of roundwood into sawnwood	From natural forests	Minimum	50	%	[57]
		Average	60		
		Maximum	70		
	From tree plantations	Minimum	40		
		Maximum	50		
Area of primary and secondary forests (excluding mangroves and tree plantations)		1997	2,101,979	ha	[71–74]
		2000	2,318,500		
		2005	2,447,690		
		2012	2,518,423		
Percentage of newly produced pallets in the World (2009)			21	%	[76]
Annual increase of reusable pallets in the World (since 1994)			2.5	%	
Average mean annual increment of forest plantations		USA and Europe	9	m^3/ha/yr	[70,77,78]
		Central America	12		
		Ecuador, Colombia, Venezuela	15		
		Brazil	20		
		Argentina	22		
		Chile	24		

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