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Multiple pathways of commodity crop expansion in tropical forest landscapes

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Abstract

Commodity crop expansion, for both global and domestic urban markets, follows multiple land change pathways entailing direct and indirect deforestation, and results in various social and environmental impacts. Here we compare six published case studies of rapid commodity crop expansion within forested tropical regions. Across cases, between 1.7% and 89.5% of new commodity cropland was sourced from forestlands. Four main factors controlled pathways of commodity crop expansion: (i) the availability of suitable forestland, which is determined by forest area, agroecological or accessibility constraints, and land use policies, (ii) economic and technical characteristics of agricultural systems, (iii) differences in constraints and strategies between small-scale and large-scale actors, and (iv) variable costs and benefits of forest clearing. When remaining forests were unsuitable for agriculture and/or policies restricted forest encroachment, a larger share of commodity crop expansion occurred by conversion of existing agricultural lands, and land use displacement was smaller. Expansion strategies of large-scale actors emerge from context-specific balances between the search for suitable lands; transaction costs or conflicts associated with expanding into forests or other state-owned lands versus smallholder lands; net benefits of forest clearing; and greater access to infrastructure in already-cleared lands. We propose five hypotheses to be tested in further studies: (i) land availability mediates expansion pathways and the likelihood that land use is displaced to distant, rather than to local places; (ii) use of already-cleared lands is favored when commodity crops require access to infrastructure; (iii) in proportion to total agricultural expansion, large-scale actors generate more clearing of mature forests than smallholders; (iv) property rights and land tenure security influence the actors participating in commodity crop expansion, the form of land use displacement, and livelihood outcomes; (v) intensive commodity crops may fail to spare land when inducing displacement. We conclude that understanding pathways of commodity crop expansion is essential to improve land use governance.

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Keywords: land use displacement, deforestation drivers, indirect land use change, agricultural intensification, land sparing, market integration

1. Introduction

Changes in rural landscapes are increasingly influenced by production for distant consumers [1, 2]. Global agricultural production is increasing mainly through yield increases [3] (figure 1). A share of these production gains also comes from cropland expansion, mainly into tropical forests [4]. Tropical deforestation is increasingly driven by commodity crops (e.g., coffee, palm oil, soybeans) destined for global and domestic urban markets [5]. Beyond expansion into forests, commodity croplands may also replace a variety of land uses and covers, including existing agricultural lands important for smallholder subsistence or local markets, and a range of other non-forest lands such as abandoned agriculture, fallows, low-intensity

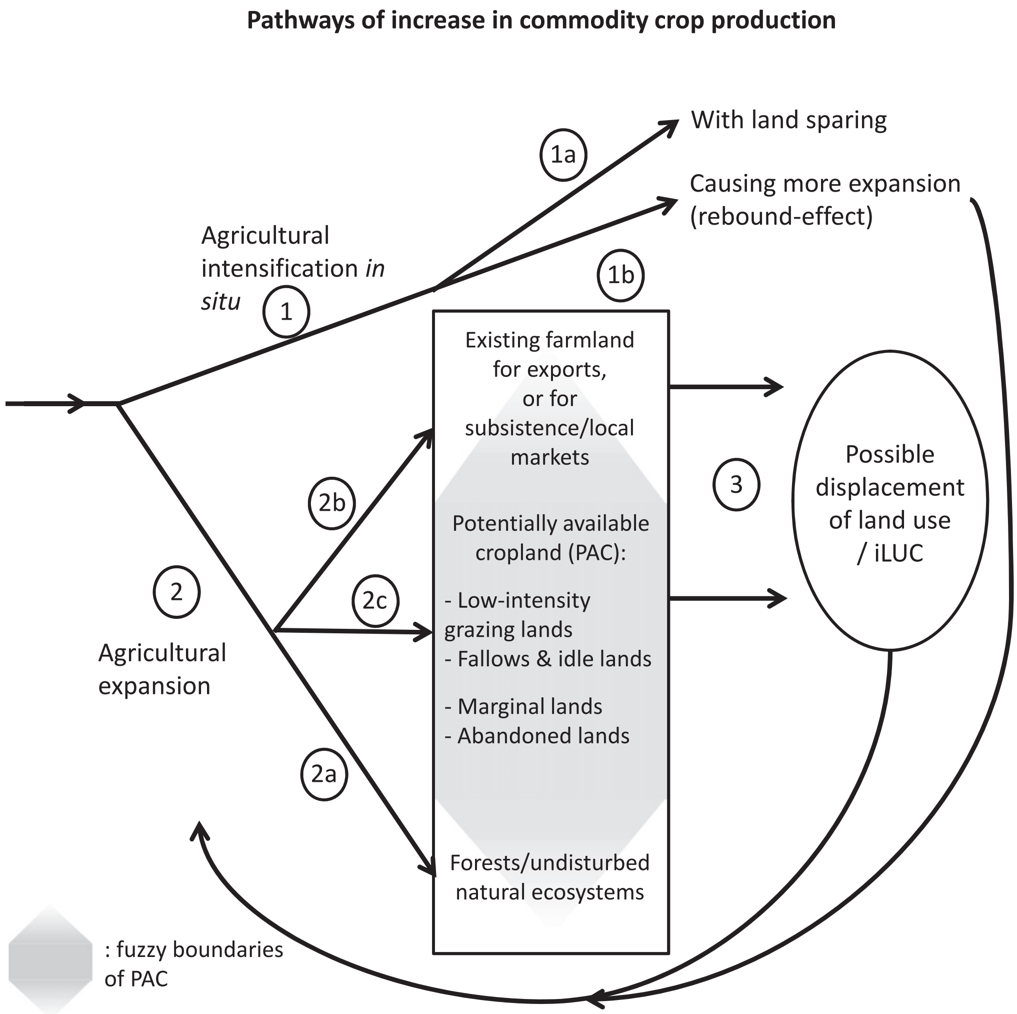

Figure 1. Pathways of increase in commodity crop production. Increases in commodity crop production can occur through four processes of land use change: intensification *in situ*, or expansion into forest, existing farmland for subsistence or local markets, or other potentially available cropland. These farm-level changes may trigger three distant or indirect effects: land sparing, rebound-effect (which can be seen as negative land sparing), and displacement/iLUC. Figure S1 presents a version of this figure valid for pathways of increase in agricultural production in general.

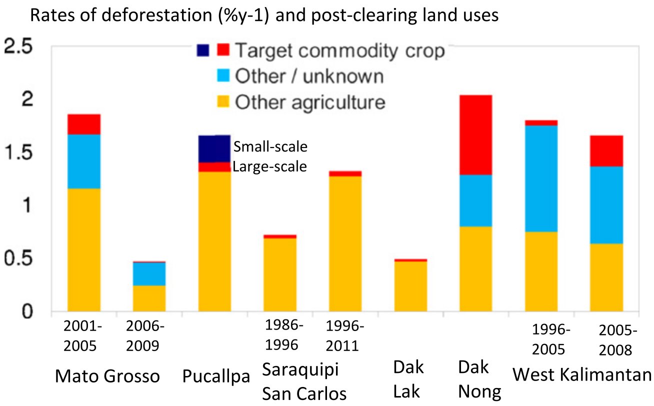

Figure 2. Gross deforestation rates (in %y-1 of total study landscape) and land uses following clearing across six study regions. Due to differences in baselines and boundaries, deforestation rates are not comparable across study cases, but highlight the direct and indirect effects of commodity crop expansion.

grazing lands, and so-called 'marginal' lands, which together constitute 'potentially available cropland' [6].

These various pathways of land use change (figure 1) produce distinctive environmental and social effects. Beyond the *in situ* or direct environmental effects of land use conversion [7], commodity crop expansion into existing agriculture can lead to a displacement of the former land use [8]. This process is also referred to as indirect land use change (iLUC) and is a strong concern for the effectiveness of bioenergy crops to reduce greenhouse gases emissions [9]. These displaced land uses may, in turn, encroach on forest margins, causing additional impacts [8]. Another form of land use displacement occurs when agricultural expansion in one area reduces incentives for agricultural production in other regions, leading to reduced expansion and/or land abandonment [8]. Furthermore, the 'land sparing' argument holds that intensification of agriculture (i.e., increasing output per unit of land) can spare land for conservation of natural ecosystems, thus reconciling nature conservation with agricultural demand [10; but see 11]. Absolute land sparing, resulting in net farmland contraction [12], can be distinguished from relative land sparing, in which only the per-capita land demand—or the rate of agricultural expansion compared to a counterfactual scenario—is reduced, while the total amount of agricultural land still increases [13]. But increasing yields in a given region may also stimulate further agricultural expansion; this rebound effect, driven by increasing local profitability of farming, occurs when producers face high price and income elasticity of demand [14].

Social effects of commodity crop expansion depend on the context and actors involved [15]. A broad distinction can be made between smallholders (i.e., small, family farms operating with limited capital, and labor-intensive techniques) and large-scale actors (i.e., large, privately-owned farms, government parastatals or agro-industrial operations, often engaged in capital-intensive agriculture) [16, 17]. When commodity crops expand into existing smallholder agricultural land, livelihoods implications depend on whether smallholders themselves switch crops or are replaced by other agricultural actors [18]. In the second case, commodity crop expansion may manifest itself as transnational 'land-grabbing' by sovereign wealth funds or agro-industrial corporations [19]. Livelihood outcomes differ with various forms of agrarian changes, including contract farming, wage labor in large-scale plantations, migration or off-farm work, and smallholder marginalization [20]. Commodity crop expansion into forests or potentially available cropland also brings social impacts, as local communities often use this land for various purposes, e.g. logging, grazing, or fallows [6]. Further, these rapidly-expanding crops are often non-staple products that contribute little to directly increasing food availability for the rural poor. They may provide important income and contribute to urban food availability, but also increasingly expose farmers to global market price volatility [21].

Our objective is to identify the factors that influence contemporary pathways of commodity-oriented agricultural expansion in tropical landscapes. We focus on whether this expansion occurs via conversion of forests (i.e., direct deforestation) versus existing agricultural lands (i.e., substitution), and whether substitution entails displacement of the former land use. We conducted a comparative analysis of six published case studies of commodity crop expansion in Latin America and Southeast Asia: (i) soy in Mato Grosso state in the Brazilian Amazon [22]; (ii) oil palm in Pucallpa in the Ucayali department in the Peruvian Amazon [23]; (iii) pineapple and banana in the Sarapiqui-San Carlos region in northeastern Costa Rica [24]; (iv) coffee in the Central Highlands of Vietnam (centered on Dak Lak province) [25]; (v) rubber in Vietnam (Dak Nong province) [26]; and (vi) oil palm in Ketapang district in West Kalimantan, Indonesia [27]. See SI Text and tables S1–S3 for a detailed description of the cases and results.

2. Methods

2.1. Study design

We synthesized the few recently published case studies of rapid commodity cropland expansion in tropical forest regions that present spatially-explicit land use/cover trajectory matrices. The small number of cases existing prevented a formal meta-analysis; rather, we compiled quantitative land use/cover trajectory variables, and assessed the influencing factors quantitatively and qualitatively. Analyses from the original papers were combined with expert knowledge from case study authors to explain recent dynamics of cropland expansion. Cases differ in geographic extent, boundary definitions, and methods. As is customary in meta-analyses in land change science, we relied on informed decisions by the original authors to define study areas characterized by homogeneous land change processes or areas which can be considered as a single land use system. We did not compare each factor individually across cases, but considered the whole configuration and interactions of variables in each land use system.

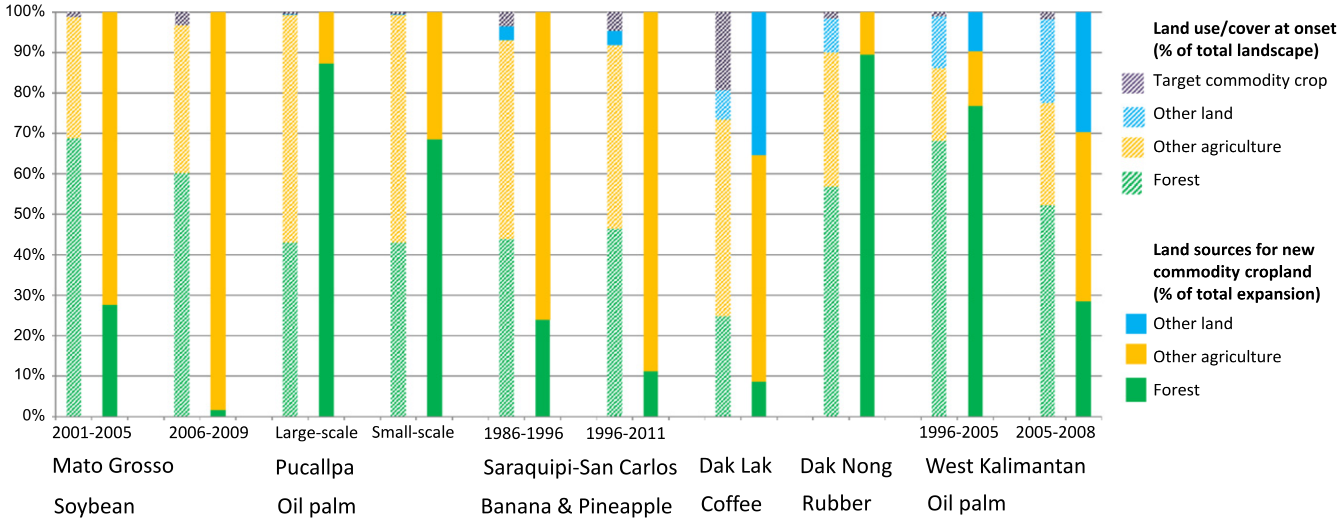

Figure 3. Potential pools and actual sources of land for commodity crop expansion. Dashed bars represent the percentages of different land uses/covers in the total landscape area at the start of the period. These constitute the potential pools for commodity crop expansion, notwithstanding biophysical, socio-economic or political barriers to expansion. Solid bars represent the actual shares of different land covers in land sources for expansion of the commodity crop over the period, in percent of total expansion.

2.2. Data and calculations

For each case, based on data from the original studies and additional sources, we first calculated indicators of land use/cover changes: (i) gross deforestation rate (figure 2); (ii) post-deforestation land use; (iii) gross and net area changes for the target commodity crop and other agricultural land uses; and (iv) land sources for commodity cropland (figure 3). Land use displacement implies causal links between commodity crop expansion in one place and land use change elsewhere. For each case, we thus discuss the underlying land change processes to assess whether land use displacement could have occurred over the study period. Then, based on the case studies, we identified the main factors that affected local crop expansion pathways (table 1), and measured them for each case using various sources and expert knowledge: (i) availability or scarcity of forests versus previously cleared land, measured as the proportion of different land covers at the start of each period, and rural population density and rate of change; (ii) biophysical, accessibility and technical constraints on expansion, including specific crop requirements; (iii) land use zoning, measured as the percentage of forested land covered by a zoning scheme strictly or partly restricting agricultural expansion (i.e., protected areas, indigenous lands, logging concessions, forestry lands zoned for various purposes), and a qualitative ranking of the enforcement of land use policies within these zones; (iv) land tenure and its security, and land markets; (v) types of agents—i.e. smallholders or large-scale actors—active in the various agricultural land uses; and (vi) agricultural intensification, measured as change in average yields of the target crop (see definitions and details in the SI text).

To evaluate the selection biases of the set of cases, we performed a representativeness analysis using the Global Collaborative Engine or GLOBE system, an online collaborative land change database ([28, 29]; http://globe.umbc.edu/). We compared the frequency distribution of global gridded variables relevant for our study in our set of cases, compared with all tropical lands. This comparison shows whether the set of case studies can be considered as resulting from a random sampling of locations within tropical lands, and which ranges of values or categories of the global variables are under- or overrepresented in the sample. Then, we performed the same analysis for the set of deforestation case studies present in GLOBE, using these same variables, compared with all tropical lands (details and results in the SI).

3. Case studies

3.1. Soy in Amazonian mato grosso, Brazil

From 2000–05, large-scale, intensive soy agriculture expanded rapidly in this forest frontier (500 915 km^2), mainly replacing low-productivity pastures, but also forests [30]. Pastures expanded into forests. From 2006–09, high deforestation rates decreased and gross agricultural expansion declined, with soy expanding almost exclusively into previously cleared lands [22]. During this period, agricultural markets conditions changed, and six implemented measures possibly influenced deforestation rates: expansion of the protected areas network; stronger enforcement of the Brazilian Forest Code which limits deforestation on private properties; creation of a land registry; restrictions on credit for illegal deforesters; satellite-based monitoring of deforestation; and two voluntary moratoria discouraging the sale of cattle and soybeans produced in newly-deforested areas [22, 31–35].

Table 1. Land use displacement and main factors affecting pathways of commodity crop expansion.

Case	Mato Grosso		Pucallpa		Saraquipi—San Carlos		Dak Lak	Dak Nong	West Kalimantan	
Period/actors	2001–05	2006–09	2000–10 L	2000–10 S	1986–96	1996–2011	2005–10	2004–08	1996–2005	2005–08
Displacement										
Local	**	*	*	*/**	?	?	**	*	?	?
Distant	?	?	*	?	**	**	*	*	?	?
Rural population										
Density (p/km2)	0.46	0.5	3.65	3.65	22.58	40.4	83.81	53.99	19.05	23.79
Change (%y-1)	1.69	1.69	−0.56	−0.56	4.93	1.16	2.06	3.67	2.77	1.58
Land use policies										
% strict/partial	~30/~70	~30/~70	0/0	0/0	~15	~100	41/52	27/67	73/0	75/0
Enforcement	*	***	*	*	*	**	**	*	*	*
Land tenure and markets										
Rights on agric./forest lands	*	**	*	*	**/***	***	**/*	**/*	*	*
Markets on agric./forest lands	**/**	***/**	*/*	*/*	**/**	***/***	**/*	**/*	*/*	*/*
Agricultural systems										
Actors for commodity crop/other agriculture	L/S&L	L/S&L	L/S	S/S	L/S&L	L/S&L	S/S	L/S	L/S	L/S
Yields change of comm. crop, %/y	−0.6	1.2	0.7	0.7	40.7/−1.8	−11	6.2	4.9	2.4	−0.9

Notes: Types of actors: S: smallholders, L: large holders. Displacement:?: Uncertain/unknown; * likely small; ** possibly large. Land use policies: % of forest land with strict/partial restrictions on agriculture. Enforcement of land use policies: *: poor; ** medium; ***: strong. Property rights: *: informal rights for most smallholders; ** formal rights of smallholders are not always enforced; ***: overall, good enforcement of property rights for most actors. Land markets: *: non-existent or poorly functioning; ** existing but not functioning perfectly; ***: functioning well. Yields for Costa Rica are given for pineapple/banana. Definitions and sources: see SI text.

3.2. Oil palm in Pucallpa, Peru

Since the mid-1990s, oil palm plantations have expanded in this landscape (2134 km^2) dominated by pastures and swidden cultivation [23]. Private companies developed large-scale plantations mainly on mature forest. Supported by public incentives but facing capital constraints, smallholders established small-scale plantations on diverse land covers, including mature forest, and secondary forest, pastures, and other mixed agriculture (including young fallows). None of the study area is under formal protection [36]. Property rights of smallholder land holdings are generally informal, but can also be registered officially [37]. A dense road network suggests that accessibility is not a strong constraint on expansion [38].

3.3. Banana and pineapple in Saraquipi-San Carlos, Costa Rica

Expansion of large-scale, export-oriented, intensive crop production, predominantly of bananas and pineapples, began in the 1990s in this landscape (6617 km^2) of forest and pasture [24]. From 1986 to 1996, deforestation was common in mature and secondary forests, and only ∼15% of the forests in the study area were officially protected as riparian or protected zones [39]. Since 1996, the Forest Law mandated a nation-wide ban on deforestation and expanded a fund for payments for environmental services, including tree planting and forest protection in specific areas [39]. Consequently, from 1996 to 2011 the loss of mature forests declined sharply, although clearing of unprotected secondary forests accelerated. After 1996, most new cropland was sourced from pastures. Banana expansion, which is constrained by access to roads, and the need for fertile soil and large capital investments, is concentrated in fertile river floodplains. By contrast, pineapple can grow on poor-quality soils and is mainly constrained by road access.

3.4. Coffee in Dak Lak and rubber in Dak Nong, Vietnam

Dak Lak study area (7478 km^2) experienced a coffee boom and major deforestation in the 1990s. Deforestation decreased in the early 2000s with the coffee bust, and then increased again from 2005 to 2010 as coffee prices slowly recovered [25]. Shifting cultivation was the main land use after forest clearing as well as the primary land source for coffee expansion [25]. Coffee expansion by well-capitalized smallholder migrants resulted in spatial displacement and marginalization of poor migrants and ethnic minorities, who resorted to shifting cultivation on increasingly marginal forestland. In Dak Nong (6513 km^2), rubber expansion by large-scale actors, especially former state forest enterprises, directly encroached into forests [26]. Zoning subdivides land into protection, special-use and production forests. On the latter, local administrations sometimes tolerate subsistence agriculture. Rubber expansion is authorized in 'poor quality' production forests, encouraging a sequence of forest logging, followed by clearing for rubber. Long-term certificates grant agricultural land rights to households, while most forestry lands remain under the control of forest enterprises.

3.5. Oil palm in West Kalimantan, Indonesia

In the Ketapang study region (12038 km^2), oil palm expansion began in the early 1990s, when logging concessions were converted to large-scale plantations, with support from state policies [27]. From 1996–2005, moderate oil palm expansion occurred mainly into logged and intact (hereafter referred to as 'secondary' and 'mature') forests. From 2005–08, land sources shifted; oil palm expanded rapidly onto swidden agricultural lands, while only 5.4% of expansion cleared mature forests. Strikingly, >90% of 1989–2008 deforestation resulted from intentional and drought-related fire, especially during the 1997–98 El Niño Southern Oscillation-associated drought. Forests are now concentrated within protected areas and peatlands, while rural communities and their swidden mosaics are concentrated on mineral soils. Until 2002, all lands were controlled by the central State. Today, specific land zones are controlled by district, provincial, and national agencies. Land use plans often bear little relation to field conditions: agrarian communities are frequently enclosed within the forest estate, where legally agriculture is restricted. Because formal land ownership comes with high transaction costs and rarely excludes state and private sector interests, most smallholders forgo land titles. Rural communities lack the capital to invest in the infrastructure required for palm oil processing, and must therefore sell fruit to company mills.

4. Comparison of the case studies

4.1. Direct conversion of forest versus agricultural lands

Across cases and periods, 1.7–89.5% of new commodity cropland was sourced from forestlands. The remaining 10.5–98.3% was sourced from existing agricultural or other lands (figure 3). We identified four types of factors that contribute to bias in commodity crop expansion towards forest or existing agriculture (figure 4).

First, a scarcity of suitable forestland, determined by a combination of forest area, biophysical or accessibility constraints, and land use policies, was associated with a higher share of conversion of existing agricultural land to commodity cropland. In Ketapang, few mature forests on mineral soils remained outside protected areas after ∼2005 [27]. This influenced the increased proportion of swidden lands sourced for oil palm plantations over this period. In contrast, the greater Kalimantan region harbors extensive mature forests vulnerable to oil palm expansion [40]. In Dak Lak, remaining forests concentrated on steep slopes and high elevation areas lacking water for coffee irrigation. Constraints on expansion change over time. Technological progress and road expansion may increase the pool of land available for commodity agriculture. In the second analytical period in Mato Grosso and Saraquipi-San Carlos, implementation of new land use policies constrained commodity crop expansion into already-

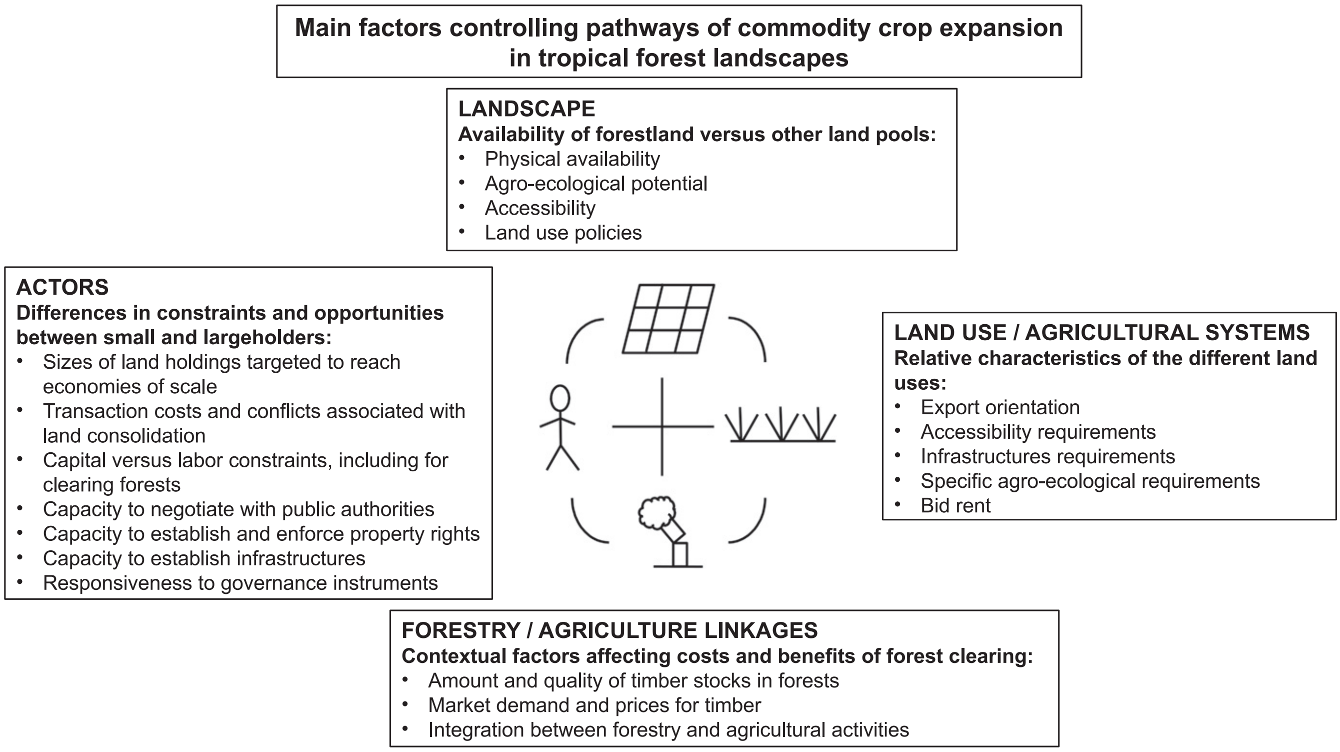

Figure 4. Main factors controlling pathways of commodity crop expansion in tropical forest landscapes. These factors are grouped in four categories, corresponding to characteristics of: the landscape, the land uses and agricultural systems, the agricultural actors, and the linkages between agriculture and forestry systems.

cleared lands or secondary regrowth (figure 3) [22, 24]. In Dak Lak, zoning for forest protection restricted coffee expansion [25]. By contrast, in Pucallpa, lack of legal constraints on forest clearing enabled disproportionate expansion of large-scale oil palm into forests. However, land use policies may also induce expansion to concentrate on forestlands: state policies supported expansion of rubber into degraded forests in Dak Nong [26], and of oil palm into logging concessions in West Kalimantan [41].

Economic and technical characteristics of agricultural systems also influence land cover sources for commodity crop expansion. In Mato Grosso, production of crops and cattle destined for exports outside the region, and the dynamic of land markets, have caused progression of the agricultural frontier to follow Von Thunen's location rent model at the regional scale, centered on the major export points and corridors [42, 43]. Lower-value cattle ranching occupied remote locations with scarce labor and low land rent, while higher-value soy advanced into high-rent already-cleared land, where supply chain infrastructure permitted agglomeration economies [44]. During the early 2000s, with highly favorable conditions for exports, soy fields 'leapfrogged' pastures at greater rate than before, and expanded directly into forests [30, 45]. Coffee expansion into shifting agriculture in Dak Lak followed the same Thunian pattern. In Saraquipi-San Carlos, post-ban commodity crop expansion was dominated by pineapple, which already expanded mainly into low-fertility land outside mature forests before the deforestation ban. Banana expansion, which occurred mainly into mature forests before the ban, decreased immediately after the ban but then recovered by targeting fertile pastures [24]. Different requirements in soils and market accessibility largely explain these trajectories. Intensification and changes in yields may also affect trajectories of expansion. But understanding the role of yield changes is complicated by the sensitivity of yields to climate fluctuations, and long time lag between crop establishment and first harvest. Rapid expansion of a crop can decrease mean yields temporarily, as in Mato Grosso and Indonesia.

Third, expansion behaviors of small-scale and large-scale actors differ due to different constraints and opportunities associated with farm size. Smallholders tend to use their already-cleared agricultural lands to develop commodity crops. In Pucallpa, smallholders, often planted oil palm in degraded pastures and secondary forests, with government support, thereby increasing the value of these lands. By contrast, large companies preferentially planted oil palm into state-owned forests, likely to minimize transaction costs and social conflicts associated with consolidating a large number of small plots from multiple smallholders [23]. In West Kalimantan, plantation development since 2007 has been skewed toward peatlands, despite higher costs of drainage and land preparation [27, 36]. It has been argued that avoiding disputes with local communities over land tenure rights could be a motivation explaining this trend, but there is not yet any conclusive evidence to support this hypothesis [46]. Large-scale operators can reduce transaction costs of establishing large landholdings by dealing with only one, often public, land provider, especially in regions with loose legal frameworks and limited recognition of customary rights on forestlands [47, 48]. Large companies can finance their own infrastructure (e.g., roads) beyond existing agricultural lands [16]. In Laos, only 20% of the land targeted by large-scale investment deals for agricultural projects was already cultivated [49].

Finally, costs and benefits of forest clearing differ across geographical contexts, further influencing the rent of different land pools. Conversion of already-cleared land generally requires lower capital investments. But higher quality soils under forests and benefits from timber harvest, especially from high-value dipterocarp forests in Asia, can favor forest clearing. In West Kalimantan, companies commonly finance plantations with profits from residual timber [27, 50]. This initial revenue pulse is particularly important for perennial crops, which become productive only after several years. The broader economic context modifies this incentive: in Indonesia, the overcapacity of wood-based industries required large amounts of timber, encouraging forest clearing for oil palm plantations during the first study period [41].

4.2. Displacement of land use

Displacement of existing agriculture replaced by commodity cropland can be local (i.e., within the study area) or distant (i.e., outside the study area through teleconnections).

Locally, within Amazonian Mato Grosso in the early 2000s, some deforestation might be attributed to pastures displaced by expanding soy fields, but this remains unquantified [43, 51]. After 2006, pasture expansion into forests declined nearly seven-fold despite increasing soy area, suggesting that local displacement became unlikely [22]. Land use policies discouraged deforestation, while the strength of the Brazilian Real decreased the cost competiveness of Brazilian soy production relative to US soy, and increases in variable production costs also reduced the profitability of soy [22, 45]. Cattle intensification was promoted by institutional changes and land use policies, and was suggested as a way to reduce displacement associated with conversion of pastures to cropland, but its role remains unclear. Between 1975 and 1996, across Brazilian Amazon municipalities, increased stocking rates were associated with pasture expansion, suggesting that intensification did not always reduce local expansion. Yet, the relation reversed in many states, including Mato Grosso, from 1996–2006 [52]. In Saraquipi-San Carlos, from 1996–2011, pasture area remained relatively constant, despite pastures being replaced by cropland. Assuming complete displacement, as much as 10–50% of deforestation by pasture can be related to cropland expansion in 1986–2005. Local displacement was likely reduced in 2005–10, as cropland expansion into pasture exceeded deforestation for pasture. In Dak Lak, local displacement of shifting cultivation, pushed by expansion of coffee and other market crops, was the main direct cause of deforestation. This displacement was enabled by incomplete enforcement of zoning, with local authorities recognizing the lack of alternatives for marginalized smallholders. In contrast, rubber in Dak Nong and large-scale oil palm in Pucallpa expanded almost exclusively into forests, with no discernable displacement of agriculture. Small-scale oil palm in Pucallpa spread preferentially into degraded pastures and secondary forests. While converting abandoned pastures is unlikely to drive displacement of land use, some cacao or annual croplands converted to oil palm may have been displaced further into forests. In West Kalimantan, there is little evidence of displacement of smallholder agriculture. Outside of protected areas, few forests remained on mineral soils, and biophysical and financial constraints on cultivating peatlands likely prevented displacement of swidden croplands into these lands. Beyond agricultural displacement, commodity crop expansion may lead to other forms of iLUC. For example, in West Kalimantan, although the causes of fires could not always be discerned, oil palm plantations are considered to be major contributors to regional fire prevalence.

Less evidence exists regarding land use displacement to or from distant places. In 2003–08, soy expansion in Mato Grosso influenced deforestation for cattle in the Amazonian frontier, providing evidence for distant displacement, but the marginal effect remains unquantified [43, 53]. Accelerating rates of Cerrado clearing after 2010, including in areas remote from Mato Grosso and the Amazon (on average ~7500 km^2 per year over 2010–12, versus ~3900 km^2 per year over 2004–10) ([54], www.lapig.iesa.ufg.br), could also be related to distant land use displacement, but no study has established a causal link. Further, soy and cattle expansion in the Amazon and Cerrado may partly result from their displacement by sugarcane expansion in southeast Brazil [55], and cattle intensification in the Center-West region may have partly compensated for pasture contraction in Mato Grosso [56]. A partial equilibrium model experiment suggests that policies supporting further cattle intensification and taxing extensive cattle ranching in Brazil could spare pasture land, concentrate cropland expansion on pastures, and reduce displacement of pastures into the Amazon [57]. In Pucallpa, local landlords sometimes consolidated oil palm plantations, resulting in previous landowners migrating, mostly to nearby cities like Pucallpa, creating a demand for agricultural products from local and distant sources. Loss of swidden land, as in West Kalimantan, may also be compensated by intensification, off-site seasonal employment, remittances, income generated from land sales to and employment by large-scale companies, and permanent migration, with various effects on land use displacement. In the long run, technological innovations allow for distant geographic displacement of crop booms, as for South American rubber in mainland Southeast Asia [15, 17], and Asian soy in the Cerrado and parts of the Amazon. Macroeconomic factors, including trade policies and currency exchange rates, are also important factors affecting the regional distribution of crop production.

Quantifying displacement is challenging. First, the absence of local displacement does not preclude the possibility of long distance displacement or iLUC, so that the area over which an analysis is conducted can determine whether displacement is detected or not. Fully measuring land use displacement would require accounting for land pools and transitions at a global scale. Beyond humid tropical forests, savanna and dry forests ecosystems like the Brazilian Cerrado may be disproportionately affected by iLUC due to weaker land use policies. Monitoring land use changes in these biomes may require different remote sensing approaches, and they are often ignored because of their comparatively lower carbon stocks. Displacement may not only involve shifting products to a different location, but also product substitutions in the supply chain. Further indirect effects could also be due to changes in consumption of displaced landowners [58]. Second, establishing firm causal links between substitution in one place and expansion in another place requires developing a plausible counterfactual for the state of land use absent either agricultural expansion or the diversion of agricultural output to other uses [59]. The same holds true for assessing land sparing, for which a counterfactual, absent agricultural intensification, is required. Simulation models greatly contribute to this goal, but empirical approaches are also needed to improve the design, calibration, validation and interpretation of simulations. Statistical approaches to build such counterfactuals, including statistical matching and synthetic control methods, are increasingly used in land systems science [60–62], and could be used for assessing land sparing or displacement. Statistical inferences about displacement and iLUC can also be made based on spatial regressions [53] and spatial analyses of land use change patterns [25]. Various analytical approaches, including fixed effects panel analyses or natural experiments, control for unobserved characteristics that may influence outcomes [59]. Empirical studies are also crucially needed to investigate the motivations and decision-making strategies of land users (e.g., households, large farms, and corporations), reconstruct the means by which regional demand for agricultural products is met, and track actors across space via land registries [8].

5. Discussion and conclusions

Commodity crop booms have a long history in the tropics [63, 64], but assessing patterns and drivers that control pathways of commodity crop expansion, following the approach proposed here, bears increasing significance for contemporary governance of several crucial issues related to land use [1, 2, 5]. Quantitative estimates and deeper understanding are urgently needed to improve assessments and projections of global commodity and bioenergy crop environmental impacts, including iLUCs. Global economic simulations of agriculture and food security issues would benefit from improved data on expansion pathways; e.g., to calibrate the land supply elasticities of different land pools [65, 66]. Understanding these land change dynamics is crucial for designing interventions for reducing greenhouse gases emissions from deforestation and forest degradation (REDD+) that minimize and internalize the cost of leakage—i.e., emissions caused by land use displaced by an intervention to reduce emissions.

Strategies to promote land sparing should account for the pathways to achieve intensification, and its multiple impacts

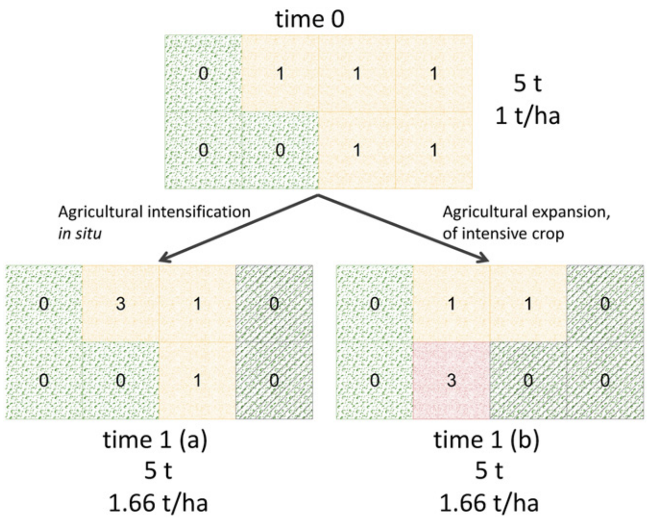

Figure 5. Gross land use/cover trajectories and net land sparing at the landscape scale. In this idealized landscape, green is forest, yellow is cropland. Numbers indicate annual agricultural production in tons over each 1 ha grid cell. We assume fixed demand (i.e., no rebound effect of increasing yields) on a tonnage basis over time. Compared with the situation in time 0, in scenario 1(a), *in situ* agricultural intensification spares two hectares for nature, which are removed from cultivation (dashed). In scenario 1(b), expansion of intensive agricultural production into mature forest (in red), combined with abandonment of 1 ha of lower-productivity agriculture, results in the same total area cultivated and production, thus the same net amount of land is available for nature. With aggregated agricultural data, the two scenarios cannot be distinguished, but in reality their effects on biodiversity and ecosystem services may differ widely. This reasoning holds whether the output is measured in units of mass, economic returns, calories or any other terms.

beyond the net measure of area spared. Returning to the framework in figure 1, land sparing is usually considered to take place by *in situ* increases of yields on existing croplands [10] (figure 5(a)). When considering agricultural production aggregated at a regional-to-global level, expansion of high-yielding commodity cropland into lower-productivity agricultural land can also result in net land sparing by increasing the aggregate output per unit area over the whole landscape (figure 5(b)). The net environmental impacts (e.g., carbon emissions, biodiversity losses) then depend on the land cover types replaced by agricultural expansion [23] and the dynamics of secondary land use changes—including displacement—triggered by such expansion. Taken together, these costs could outweigh the benefits of land spared for nature. Policy decisions and studies on land sparing and conservation may thus be misguided if based solely on data aggregated over large units that overlook spatially-explicit trajectories of land use/cover change at finer scales. Transformation of land use systems primarily aimed at subsistence or local markets towards more outward-oriented agriculture has important implications for local livelihoods. This process may reflect the consolidation and increased productivity of agricultural systems, but may also bring increased social inequality, conflicts, and contraction of labor demand [18, 67, 68]. Land use displacement may reflect marginalization of ethnic minorities or poor farmers [25].

Understanding the factors driving large-scale corporations to either intensify or expand, as well as conditions facilitating expansion into forests versus existing agriculture or other lands, would allow more proactive land use planning and governance of large-scale land transactions, and increase the effectiveness of supply-chain and demand-driven interventions [69].

We identified four main factors controlling pathways of commodity crop expansion: (i) the availability of suitable forestland, which is a combination of forest area, biophysical or accessibility constraints, and land use policies and enforcement, (ii) economic and technical characteristics of agricultural systems, (iii) differences in constraints and strategies between small-scale and large-scale actors, and (iv) variable costs and benefits of forest clearing. Conversion of existing agriculture and smaller land use displacement were more likely where forests with suitable biophysical conditions were scarce (e.g., Dak Lak, West Kalimantan in the second period), or where well-enforced land use policies and other measures restricted agricultural expansion (e.g., Mato Grosso and Saraquipi-San Carlos in the second period) [12]. Expansion strategies of large-scale agricultural actors emerge from context-specific balances between the search for suitable lands; transaction costs or conflicts associated with expanding into forests or other state-owned lands versus smallholder lands; net benefits of forest clearing; and greater access to infrastructure in already-cleared lands. To capture these factors, economic approaches based on land rent need to be complemented by a detailed account of political and institutional contexts. Enforcing land use policies to control deforestation, combined with intensifying agriculture as in Mato Grosso, can channel commodity crop expansion toward already-cleared lands and reduce local displacement. Finally, the effects of macroeconomic changes, including long-term demand increase and short-term price spikes, on pathways of expansion are not well understood. Self-sustaining crop booms can occur when profits from price spikes are used to finance further expansion and/or intensification.

Our set of case studies was not meant to be statistically representative of the average patterns of land change in tropical regions. Rather, we highlighted a diversity of possible pathways and controlling factors. For example, some of the cases (the second period in Mato Grosso and Saraquipi—San Carlos) illustrate strong policy interventions to conserve forests, while other cases (e.g., Pucallpa or Dak Nong) exemplify minimal land use policy influence. The representativeness analysis (see the supplementary information available at stacks.iop.org/ERL/9/074012/mmedia) showed that our set of cases display some of the well-known biases in tropical deforestation studies, including a lack of studies in Africa, and a focus on frontier regions with substantial remaining forest cover, intermediate levels of population density and protected area coverage. Our cases also mainly represent regions with relatively good market access and a high influence of external markets, as expected given the focus of this study on expansion of export-oriented crops. Although agricultural systems in Africa are still dominated by smallholders, and production for local markets is still widespread, export-oriented commodity crops (e.g., cocoa) have had a long presence [70], and large-scale plantations (e.g., oil palm) are also emerging [71]. Quantitative studies on land change pathways associated with commodity crop production in Africa remain a research priority. Land use change processes in areas with less dynamic expansion or a higher prevalence of other potentially available cropland may differ from those identified here.

Based on our findings, we propose a set of hypotheses highlighting interactions among the above-identified factors:

(i) **Land availability, particularly as determined by land use policies, biophysical attributes and accessibility of land, mediates expansion pathways and the likelihood that land use is displaced to distant, rather than to local places.** In line with theories of induced intensification and forest transition [72, 73], extensive agriculture replaced by more intensive cropland is less likely to be displaced locally when forest or potentially available cropland is scarce—due to land use policies, biophysical characteristics, or accessibility. Enforced land property rights reduce local displacement of less profitable land uses. Local land scarcity or strict land use policies may lead to distal displacement of extensive or less profitable land uses, particularly to frontier regions with ill-defined property rights.

(ii) **Use of already-cleared lands is favored when commodity crops require access to infrastructure.** In line with the bid rent theory [74], for commodity crops that are more dependent on access to existing infrastructure and markets for inputs, outputs and agglomeration economies, expansion into already-cleared lands or remnant forests near infrastructure is favored over remote forests and other land sources, especially when the expanding crop is more profitable than existing agriculture. Well-functioning land markets increase the likelihood that profitable land uses outcompete less profitable land uses on already-cleared lands.

(iii) **Large-scale actors generate more clearing of mature forests than smallholders, in proportion of their total expansion.** In contrast to the previous hypothesis, well-capitalized large-scale actors are more likely to expand into large areas of mature forests, especially where forests are extensive, owned by a single actor, unprotected, contain high quality soils and timber, and where transaction costs and social conflicts associated with consolidating non-forest land from smallholders are high. This hypothesis fits with the cases of West Kalimantan and Pucallpa, as well as with the comparison between large-scale rubber and small-scale coffee farms in the Vietnamese cases. But large-scale actors may also be more responsive to supply-chain and demand-driven interventions to conserve forests [69].

(iv) **Property rights and land tenure security influence the actors participating in commodity crop expansion, the form of land use displacement, and livelihood outcomes.** In contrast with the previous hypothesis, in places where returns to scale exist and smallholders have weak land tenure security, large-scale actors will dominate commodity crop expansion by consolidating existing agricultural lands. Displacement of smallholder agriculture is then likely, but may be mediated by policies, pull of labor force towards urban and off-farm economies, or use of local labor in large-scale plantations.

(v) **Intensive commodity crops may fail to spare land when inducing displacement.** For commodities with high price and income elasticity of demand, it has been already suggested that intensification, by increasing local profitability, may drive additional expansion of this crop and thus fail to spare land [14, 75]. Many land sparing studies consider only the outcome in terms of land demand for the crop that intensifies, or group all agricultural activities into one sector that intensifies homogeneously. In both cases, these studies do not consider the dynamics related to the changing intensity differential between different land uses. Here, we highlight that when expansion of intensive crops induces iLUC for other crops, the balance of land sparing and its environmental effects depends not only on the crop experiencing intensification, but also on indirect effects on other crops [57]. Pastures in Mato Grosso and shifting cultivation in Dak Lak were displaced by more intensive crops, which led to additional agricultural expansion and deforestation (although land use policies could contribute to control this displacement). Potential land sparing and land use displacement are intricately related and jointly emerge from pathways of agricultural expansion, in landscapes where intensification occurs by replacing a less intensive system by another, more intensive one. This may be more likely when intensification is induced by new market opportunities rather than by technological progress [76].

In any case of commodity crop expansion, these processes can have reinforcing or conflicting influences, and the outcome remains an empirical question. Quantitative studies measuring (i) land sources and transition matrices of land use/cover changes, (ii) the factors identified above, and (iii) displacement through causal investigations, should formally test these hypotheses over a more comprehensive set of cases. The framework proposed here to compare case studies of land change can shed light on processes of cropland expansion.

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