Supplementary Information Text

This SI text presents first a detailed description of the data and methods used to compile comparable land use/cover trajectories and controlling factors for the case studies, and second a detailed description of each case study.

Materials and Methods

Study design. Given the small number of cases, a meta-analysis based on formal analytical methods was not possible; rather, we compiled several quantitative land use/cover trajectory variables as well as associated factors across cases. Using these quantitative figures, coupled with rich qualitative knowledge of the cases by several of the main authors of these studies, we discuss commonalities and divergences, and draw insights regarding the role of the specific factors identified above. Cases differ in terms of geographic extent, criteria used to define study area boundaries, and methods used to analyze land change pathways. We relied on informed decisions from the original authors to define case study areas characterized by processes of land change that are broadly homogeneous or for which the study area can be considered as one land use system. Drawing on Letourneau et al. [*1*], we define land use systems as "distinct landscape patterns of human interactions with the environment (…) characterized by a specific combination of land cover, land use (including livestock), population pressure and accessibility". Scale and boundaries of each system are defined by the authors in each study. This is the approach implicitly used in meta-analyses in land change science [*2*], and corresponds to the traditional geographer's approach to deal with the Modifiable Areal Unit Problem [*3*]. Given the focus on trajectories of land use change and sources of new commodity cropland, we do not discuss factors that determine the aggregate demand for crops, such as population and income changes, diets and specific consumer demand. Tab. S1 presents a summary of the basic characteristics of the case studies.

Land use/cover trajectories data. For each case, using mainly data from the original studies listed above but also incorporating supplemental sources where necessary, we first calculated indicators of land use / cover trajectories (Tab. S2): (i) gross deforestation rate, expressed in percent of total landscape area per year; (ii) land use following deforestation; (iii) gross and net area changes for the target commodity crop and other agricultural land uses; and (iv) land sources for commodity cropland– i.e. the percentage of land for the target commodity crop sourced from mature forest, secondary forest, existing agricultural lands, or land with other or unknown use. Deforestation figures are not directly comparable across cases due to differences in baseline conditions and boundaries of the study areas. To facilitate comparisons in terms of study periods and thematic content of land use/cover classes, data from some of these papers were revised and may differ slightly from the figures originally published. Deforestation rates, gross and net changes in pasture area and post-clearing share of pastures for Pucallpa were calculated based on the Alternatives to Slash and Burn

(ASB) maps for Pucallpa benchmark area [*4*,*5*].

Definitions of the variables used are as follows:

- “Land use following clearing”, is measured as the proportion of cleared land (% of total gross deforested area) subsequently occupied by the target commodity crop, other agricultural land uses, and other or unknown uses, as measured at the next remote sensing time step. "Other or unknown uses" following clearing vary across cases, being small deforestation patches (<25 ha) in Mato Grosso, burned / bare land without use in Dak Nong, or all non-forested peatlands and burned, bare and built classes on mineral soils in West Kalimantan.

- "Secondary forest" refer to previously logged forest in Kalimantan, and to fallows or regrowth over ~3-5 years in other regions.

- Land sources with "other cover and/or unknown use" correspond to other natural vegetation, bare lands with uncertain land use, and, in West Kalimantan, all non-forested peatlands and burned, bare and built classes on mineral soils.

Measuring land use displacement requires making causal links between commodity crop expansion in one place and land use change elsewhere. This cannot be done using only land use/cover change data, especially for distant displacement as these study cases are open systems. Land use displacement was thus not quantified, but is discussed for each case based on the combined analyses of land use/cover changes and underlying processes.

Detailed results on land use/cover trajectories are in Tab. S2.

Controlling factors. The following main factors associated with pathways of commodity crop expansion were measured from various sources and qualitative expert knowledge:

1) The pools of land potentially available for cropland expansion at the start of each period – i.e., the percentage of land covered by forest, existing agricultural lands, and other or unknown land uses – , not considering land suitability, accessibility and policy constraints.

2) The main biophysical, infrastructure, and accessibility constraints affecting cropland expansion into these pools of land.

3) Population variables, i.e.: rural population density at the start of the study period, in people per km^2, rate of change in rural population density, in % y^{-1}, and rural population density over already cleared land.

4) The percentage of forested land area covered by a land use zoning scheme fully or partly restricting agricultural expansion through various forms of protected areas, indigenous lands with restrictions on agriculture, and classification as forestry lands or allocation to logging concessions, and qualitative ranking of the enforcement of land use policies.

5) Land tenure, i.e. "the set of institutions and policies that determine locally how the land and its resources are accessed, who can hold and use these resources, for how long and under what conditions", and its security, defined as the "assurance that land-based property rights will be upheld by society" [*6*]. Land markets can be broadly defined as "markets in which to exchange rights to land" [*7*].

6) Characteristics of the agricultural systems, including the types of agents primarily active in the target crop and the other agricultural land use systems – i.e. mainly smallholders or large-scale actors, and change in yields of the target crop, in % y^{-1}, representing a widely used indicator of agricultural intensification.

All numbers are calculated for the initial year of the period, using linear interpolation of data for available years if necessary. Sources include: for Mato Grosso: IBGE agricultural statistics and population censuses 2000 and 2010; for Peru: agricultural statistics and population censuses 1993 and 2007; for Costa Rica: Instituto Nacional de Estadística y Censos de Costa Rica 1984, 2000, and 2011, and FAOSTAT for yields (respectively pineapple then banana in the table); for Vietnam: Rural, agricultural and fishery censuses 2001, 2006, statistical yearbooks, forestry land zoning maps from Dak Lak and Dak Nong provinces; for Indonesia: population censuses 1990, 2000, and 2010; Kabupaten Ketapang and Kabupaten Pontianak Population Projections 1981-2002; West Kalimantan RTRWP, 2004; Indonesian Ministry of Forestry TGHK 1992; Indonesian Ministry of Agriculture Production Data through 2010.

Some factors are assessed with quantitative indicators or qualitative rankings (Tab. S3), while others are directly discussed in the text. Validation of the qualitative assessments was achieved through cross-checking by several authors. Given large differences in the local context and data definitions across cases, the quantitative indicators were not directly compared, but used to discuss the importance of these factors in each context. Considering that most of these factors work by interacting with the others, comparative analysis was performed not by comparing each factor individually across study cases, but by comparing, across cases, the whole configuration and interactions of variables in each land use system.

Understanding the role of yield changes is complicated by the sensitivity of yields to fluctuations in climate, and the time lag between crop establishment and first harvest, which can reach >5 years for oil palm and ~3 years for soy. Rapid expansion of a crop can thus temporarily decrease mean yields, as in Mato Grosso and Indonesia. Data on yields were thus not much used in the discussion, but were presented because this indicator is among the factors traditionally considered in land change science as influential for explaining land use change. Detailed results on controlling factors are in Tab. S3.

Detailed description of the case studies

Soy in Mato Grosso, Brazil. This study focuses on the shifting dynamics of soybean cultivation at the forest frontier in southeastern Amazonia during the 2000s. From 2000-2005, large-scale, intensive soy agriculture expanded rapidly in the region, primarily replacing low-productivity pastures but also directly into forested areas [*8*]. Meanwhile, low-productivity cattle ranching continued to move into forested areas. Deforestation rates skyrocketed during this period, then decreased precipitously from 2006-2009, likely in response to a contraction in global commodity markets and policy incentives aimed at curbing deforestation. During this latter period, gross expansion of soy declined by 50% relative to the first period, and occurred almost exclusively into pastures and other previously cleared lands, with minimal expansion into forests [*9-11*]. Net soy expansion decreased even more strongly. Gross expansion of pastures strongly declined in the second period, so that total pasture area decreased. Over both periods, pastures constituted the main land use following deforestation. Today, agriculture continues to intensify, with ranching becoming more productive and croplands moving towards double-cropping methods where a second late-season commodity crop (e.g. corn or cotton) is planted following the soybean harvest [*12*].

Land use policies were strongly reinforced between the first and second period. Over 8,600 km^2 of Mato Grosso's forest is legally designated as indigenous reserves, as well as state and federal protected areas. In 2010, this corresponded to 17.1% of the total land area, and approximately 30% of the remaining forest area. Pairwise comparison of point showed that these protected areas effectively reduced deforestation [*13*]. In addition to these protected areas – which strictly prohibit forest conversion for agricultural production – the Brazilian Forest Code partially restricts deforestation on private properties, including in riparian areas and uplands. Within the Amazon forest biome, the Forest Code restricts clear-cutting of forests to a maximum of 20% of large private properties and prohibits the use of riparian forest areas for production activities [*14*]. Over the course of the study period, there was a concerted effort to clarify land tenure in Mato Grosso through the creation of a land registry. In the latter half of the decade, a suite of policy measures were enacted aimed at reducing deforestation. These included restrictions on credit for illegal deforesters; satellite-based monitoring and enforcement of deforestation; and two voluntary moratoria, declared by cattle and soybean exporters, restricting the sale of cattle and soybeans produced in newly-deforested areas [*9*, *14-16*). Several of these measures were shown to be effective in reducing deforestation rates, including increasing enforcement efforts of the Brazilian environmental police [*17*], deforestation monitoring by remote sensing [*18*], and credit constraints in municipalities that did not comply with environmental regulations [*19*]. Large national and multinational corporations are the primary producers in the region, with property sizes ranging from a thousand to tens of thousands of hectares. Remaining small properties are being consolidated – via contract farming, property sales, or leases – into large-scale production areas, focused on export-oriented, mechanized production of commodity crops. Biophysical factors constrain the expansion of these mechanized crop production systems, which favor flat, well-drained soils, and require sufficient seasonal rainfall to support rainfed agriculture. Given the high level of inputs required for intensive production (e.g. seeds, fertilizers, pesticides, and heavy machinery) and limited regional storage capacity, expansion of commodity crops is somewhat constrained by access to roads, though in many cases agricultural production is sufficiently profitable to spur new road-building.

Oil Palm in Pucallpa, Peru. The study area near the city of Pucallpa is located in one of the most active deforestation hotspots in the Peruvian Amazon [*20*]. Pastures and shifting cultivation currently dominate the agricultural landscape, but oil palm plantations have actively expanded since the mid-1990s. Large-scale oil palm expansion (over 20-25 ha, typically of 250-2000 ha) is typically associated with private companies with enough resources to optimize production. In contrast, small-scale plantations, typically of 5-10 ha but possibly reaching up to 20 ha, are cultivated by smallholders with capital constraints preventing them to manage plantations at optimal levels. As a result, small-scale oil palm plantations generally achieve lower yields than large-scale plantations [*21-23*]. Smallholders often used their degraded pastures and fallows or secondary forests to plant oil palm, thereby increasing the value of their already-cleared lands, with lower conversion costs compared to mature forests. This was initially supported by incentives from governmental programs, including the USAID-funded anti-drug program Programa Desarrollo Alternativo (PDA). Some small-scale oil palm plantations with financial support from external funders, including PDA, achieve higher yields compared to other smallholders. Soil characteristics, related to differences in the types of land over which small- and large-scale plantations expand, might also play a role in yield differences [*22*]. In this study, oil palm plantations in 2010 were mapped, and sources of land for oil palm were calculated by overlaying new (<10 years old) plantation areas with a 2000 land cover map [*24,25*]. Large-scale oil palm expanded mainly (74.8%) on mature forest, while land sources for small-scale oil palm expansion were more diverse, with 30.2% being mature forest, 38.2% being secondary forest (mainly regeneration after pasture abandonment or fallowing), and 31.6% being pastures and other mixed agricultural land uses, including fallows younger than 3 years. Total expansion of small-scale oil palm was larger than of large-scale oil palm, but pastures and mixed agriculture remained the most rapidly expanding land use, as well as the largest land use following clearing, while oil palm accounted for 20.7% of newly cleared land.

Rural population density declined between 2000 and 2010. Demographic data, showing rural population decline and urban population growth, indicate that most of these migrants moved to nearby cities like Pucallpa, while maintaining complex relations with their rural place of origin [*26*]. Forest zoning in the Peruvian Amazon consists of protected areas and indigenous reserves (where agriculture is allowed), which effectively reduced deforestation and logging pressure on forests [*5,20*]. However, none of these protected land zones was present in the study area. Property rights on land holdings are generally informal and managed within communities, although properties can also be registered officially [*5*]. The study area is characterized by a dense road network [*27*] so accessibility is not expected to be a big constraint for expansion. In contrast the presence of seasonally flooded areas can be a limitation for expansion in some specific locations given the low tolerance of oil palm to flooding.

Banana and pineapple in Saraquipi-San Carlos, Costa Rica. The Sarapiqui-San Carlos study region is located in the Caribbean lowlands of northeastern Costa Rica, encompassing the Sarapiqui, Grecia, and San

Carlos cantons (sub-provinces). Despite undergoing widespread deforestation since opening as an agricultural frontier in the 1960s, this landscape has high remnant forest cover (>44%) [*28,29*]. Low-productivity cattle pasture dominates the agricultural landscape, but expansion of large-scale, export-oriented, intensive crop production began in the 1990s [*30,31*], predominantly of bananas and pineapples. Expansion of these commodity crops has been rapid, with pineapple and banana area respectively tripling and doubling over the last ten years. In 1996, Costa Rica enacted the Forest Law, which mandated a complete nation-wide ban on deforestation and the expansion of a payments for environmental services (PSA) fund for tree plantation establishment and forest protection in specified areas [*31,32*]. Prior to the 1996 Forest Law, forest clearing was allowed with appropriate permits, illegal deforestation was common, and only ~15% of the forests in the study area were officially protected in riparian or protected zones (Steed 2003). Over the course of the study period, enforcement of the deforestation ban affected clearing decisions by landowners [*29*] and there was a strong demand for enrollment in PSA programs [*32*].

This study [*33*] tracked patterns of cropland expansion and deforestation prior to (1986-1996) and after the enactment of the forest protection policies (1996-2011). Prior to these policies, deforestation rates in mature (>30 years in age) and secondary (<30 years in age) forests were both high, although rates of reforestation exceeded deforestation in remote areas due to land abandonment or establishment of plantation forests. After the new policies, rates of mature forest loss declined sharply, but unprotected secondary forests were cleared at higher rates. Indeed, following the legal definition of forest (at least 70% cover over 2 ha by 60 diverse tree species >15 cm DBH), the majority of secondary regeneration less than 8–12 years in age is not protected from clearing. Today, increasing regional population, the availability of relatively low-cost labor, and improving access to the capital, San Jose, is driving the expansion of urban zones and intensive pineapple and banana plantations [*35*]. Across both time periods, the main land use following forest clearing was pasture, with banana and pineapple covering only 4.7 and 3.5% of the cleared land over the first and second periods, respectively. Clearing of mature forest for cropland declined dramatically after 1996: 21% of cropland was derived from mature forest prior to the deforestation ban, compared to 1.9% after the ban. Consequently, an increasing share of land for banana and pineapple plantations was sourced from pastures and other agricultural lands over the second period.

Land tenure and private property rights were strong during this time period for actively managed properties, with steady declines in the area of absentee-owned cattle ranches being taken over by landless smallholders [*28,34*]. Roads expanded and improved in quality over time, often in response to expanding cropland cultivation, and the region is linked by highways to nearby markets in the capital, San Jose (1-2 hours) and a deepwater port, Limon (4-5 hours). Large-scale actors are leading pineapple and banana expansion. Banana expansion has been constrained by access to roads, the availability of fertile soil, and the high capital investment required for drainage canals, continued pesticide applications, and packaging facilities [*35*]. Its expansion is regionally concentrated in the flat, swampy coastal lowlands in fertile river floodplains. By contrast, pineapple is able to grow on poor-quality soils [*33*], and its expansion has been constrained more by access to highways and the availability of flat terrain; it is expanding along existing roads, with paved roads trailing the expansion front. Pineapple yields rose by 310% in 1989 as new methods were introduced to the country [*36,37*]. In the last two decades, yields of both Costa Rican pineapples and bananas were high (ranking in the top 5 countries globally) [*37*] but have declined in the last decade, likely due to large rapid expansion into low-quality lands.

Coffee and Rubber in Dak Lak and Dak Nong, Vietnam. The two study areas in Vietnam are located in the Central Highlands, the country's major deforestation frontier. Both areas are characterized by an extensive agricultural matrix of smallholders combining various land uses – including shifting cultivation, perennial plantation crops such as coffee, pepper, and fruit trees, and irrigated rice –, as well as the main forest remnants in the country, located mostly on steep slopes. The central part of Dak Lak province, over which the first study area is centered, is the major coffee-growing area in Vietnam. Coffee plantations require several years of growth before being adequately identified in remote sensing observations. Thus, sources of land where new perennial plantations were detected in the period 2005-2010 were analyzed with land cover data of 2000. With a coffee boom in the 1990s, this area was the major deforestation front in Vietnam. Along with the coffee bust in the early 2000s and then a slow recovery, the deforestation rate decreased in the early 2000s and then increased again over 2005-2010. Shifting cultivation subsequently occupied 96.1% of the deforested lands. In turn, shifting cultivation lands were the main source of land (56.1%) for coffee expansion. Coffee expansion by well-capitalized Kinh smallholders – the majority ethnic group in Vietnam – resulted in displacement of poor households of ethnic minorities, who resorted to shifting cultivation on increasingly marginal land [*38*]. Coffee expansion is limited by steep slopes and rocky soils in mountains and water requirements to irrigate to compensate for the short wet season. A second study area in Vietnam, covering the neighboring Dak Nong province, highlighted rubber expansion into forests by large-scale actors (including former state forest enterprises) [*39*]. Rapid deforestation (2.04% y^{-1}) was followed in equal shares by rubber and by other land uses, mainly shifting cultivation, and most of the expansion of rubber (89.5%) encroached directly into forests. Requiring temperatures above 18°C, rubber expansion in the Central Highlands is limited to the Southern provinces including Dak Nong.

Land zoning in Vietnam defines forestry land as land covered by forest or planned for forestry uses, subdivided into the categories of protection, special-use and production [*40*]. In both study areas, almost all remaining forests are covered by this land zoning scheme, with respectively 41% and 67% in the two study areas being classified as production forest where local administrations sometimes tolerate agricultural uses. In the Central Highlands, rubber is considered as a strategic crop, for which specific rules authorize its expansion over "poor quality" production forests – i.e. with timber stock below 110 m^3 [*39*]. These policies encourage a dynamic of forest degradation by logging, followed by deforestation for rubber. Long-term certificates granting rights for use of agricultural lands were distributed to households during the 1980s and early 1990s. With the Land Law of 1993, people gained rights to sell, lease, inherit and mortgage their allocated lands, thus effectively creating markets for land. Forestry land was similarly allocated to households in several regions of the country, but in the Central Highlands most forestry lands remained under the control of the state or large forest enterprises.

Oil Palm in West Kalimantan, Indonesia. The West Kalimantan study region is located in Ketapang and Kayong Utara Districts, on the West coast of Indonesian Borneo (Kalimantan). Most of the human population lives on mineral soils, which occupy ~50% of the study region; the remainder of this focal region is under peatlands. As a result of rapid oil palm plantation expansion, extensive logging since the mid-1980s, and wildfires during El Niño Southern Oscillation (ENSO)-associated droughts, this region has experienced some of the highest deforestation rates in Indonesia [*41-47*]. Logged and intact forests are now concentrated within protected areas and peatlands. Rural communities maintain swidden agricultural lands, including ~1 ha rain-fed rice fields as well as secondary rice fallows mixed with rubber and fruit tree agroforests [*48*]. Unlike the Dak Nong case study, where large-scale actors dominate the rubber business, West Kalimantan rubber gardens are small (~1-10 ha per household) and managed primarily by smallholders.

Here, we report land cover change in the study region measured in two eras: From 1996-2005, a period with moderate oil palm expansion and a severe 1997-1998 ENSO-related drought, and from 2005-2008, years characterized by rapid plantation expansion. Starting in the early 1990s, logging concessions containing previously logged forests and often enclosing villages and their mixed agroforest lands were converted to large-scale (~10,000 ha) oil palm plantations, with support from state policies. By 2008, sixteen companies had established oil palm on 6% of regional lands outside protected areas [*46*]. From 1989-2008, 93% of the deforestation in this study region resulted from fire, including drought-related wildfire as well as intentional burning to clear land. From 1996 through 2005, the primary sources of oil palm plantation land were intact forests (44.1%, hereafter referred to as "mature" forests), and previously logged forests (32.8%, hereafter referred to as "secondary" forests). Only 13.5% of oil palm plantations were sourced from swidden agricultural lands, including mixed fallows and agroforests. From 2005 to 2008, the sources of new oil palm land shifted, with swidden agricultural lands becoming the primary source (41.9%), and only 5.4% sourced from mature forests. Yet by 2005, the start of the second study period, little remaining forest in this focal study region was available to be cleared; only 16% of lands outside of protected areas contained mature forest. In contrast, the greater Kalimantan region harbors extensive mature forest area vulnerable to oil palm expansion [*44,47*]. The proportional increase in oil palm's share of post-clearing land use from 3% to 18% in the first and second study periods, respectively, reflects both increased gross rates of plantation establishment and extensive deforestation (totaling 9% of the study area) during the 1997-98 ENSO event with associated drought and wildfires. These ENSO-associated fires cleared a considerable land area that was later converted to oil palm plantation in a non-deforestation land transition.

Until decentralization policies were implemented in 2002, lands were controlled by the centralized State [*49*]. Specific land types, defined in 1997 by provincial development and land use plans (Rencana Tata

Ruang Wilayah Propinsi – RTRWP), are now controlled by district, provincial, and/or federal agencies. Yet, these land use plans often bear little relation to field conditions and practices. For example, deforestation rates in Indonesian protected areas are not significantly different from deforestation in areas zoned for timber production [*50*]. Moreover, while agriculture is technically restricted in the forest estate, resident agrarian communities are enclosed within logging and plantation leases. Thus, smallholder agriculture – primarily by long-term residents – occurs throughout all land zones. Although smallholders may apply for land titles, transaction costs are very high and titles rarely exclude State and private sector interests. In this case study region, agricultural lands are often held without formal titles, with usufruct land rights being negotiated among households within a community. In contrast, oil palm companies purchase land leases for ~30 years. High-quality palm oil requires processing within 24-48 hours of harvest. Thus, extensive road networks are necessary to facilitate harvest and transport to mills. Road maintenance and mill construction require significant capital unavailable to a typical smallholder or rural community.

Representativeness analysis with GLOBE

We performed a representativeness analysis using the GLOBE system [*51,52*; http://globe.umbc.edu/]. "GLOBE (Global Collaboration Engine) is an online collaborative environment (…) to share, compare and integrate local and regional studies with global data to assess the global relevance of their work." Because the GLOBE system is still under development, the display of the representativeness analysis (Fig. S2) is a subset of the full capabilities planned for the tool.

First, we compared the frequency distribution of global gridded variables relevant for our study in our set of cases, compared with all tropical lands. All numerical variables were stratified into five equal frequency bins. This comparison shows whether the set of case studies can be considered as resulting from a random sampling of locations within tropical lands. If the sample was indeed random, for numerical variables, the five bins would be represented in equal proportions in the sample, and for categorical variables, each category would be represented in the sample in proportion of the actual share of tropical lands within this category. This comparison thus highlights bins or categories which are over- or underrepresented 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. This allowed comparing our set of cases with the set of deforestation studies recorded in GLOBE. All analyses were performed on tropical biomes, as defined using the following units in Olson's biomes map [*53*]: Tropical and Subtropical Dry Broadleaf Forests; Tropical and Subtropical Grasslands, Savannas and Shrublands; Tropical and Subtropical Moist Broadleaf Forests; Flooded Grasslands and Savannas. The following global variables were used: a. Olson's biomes; b. World regions; c; Percentage of tree cover in 2001 [*54,55*]; d. Percentage of land in protected area (WDPA); e. Market Access Index and f. Market Influence Index [*56*]; g. Combined Land Suitability class

[*57*]; h. Population density in 2005 [*58*].

A summary of the results is presented in Fig. S2. Compared to a hypothetical random sample of tropical locations, our set of case studies is significantly biased towards Southeast Asia and Central America, as is the case for the whole set of tropical deforestation studies in land change science (Fig. S2b). Tropical savannas and African regions are underrepresented both in our sample and in deforestation studies in general, except for Western Africa (Fig. S2a). Compared with tropical regions in general, our set of case studies is concentrated within the class of areas with relatively high percentage of forest cover (35-65% in the equal frequency distribution of tropical lands) (Fig. S2c). This bias is similar to deforestation studies in general, and probably reflects a focus on frontier regions where forest cover is still abundant but rates of conversion are high. The distribution of our studies across protected areas is similar to deforestation studies in general, with an overrepresentation of studies in areas where protected areas cover a small to medium fraction of the landscape (up to ~80%), but are not absent (Fig. S2d). Again, this is consistent with a focus on newer and established frontier regions, which are neither so remote and wild that no form of protection is necessary, nor already-settled regions with high protection coverage (old frontiers). By contrast, our set of case studies is biased towards areas with relatively high market access and influence compared to the bulk of tropical regions, and compared to studies of deforestation in general (Fig. 2e,f). This reflects the focus of this study on regions with large and rapid expansion of commodity crops for export markets. Regarding population density, our set of case studies is spread over areas with relatively low, medium and high population density, with a bias toward regions with relatively high population. In sum, our set of case studies display some of the well-known selection biases in tropical deforestation studies (including a lack of studies in Africa, and a focus on frontier regions with substantial forest cover remaining, and intermediate levels of population density and protected area coverage), and reflects mainly the dynamics in areas with relatively good market access and high influence of external markets.

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Tab. S1: General description of the study cases

Case	Mato Grosso	Pucallpa	Sarapiqui-San Carlos	Dak Lak	Dak Nong	West Kalimantan
Country	Brazil	Peru	Costa Rica	Vietnam	Vietnam	Indonesia
Study periods	(i) 2001-2005; (ii) 2006-2009	2000-2010	(i) 1986-1996; (ii) 1996-2011	2005-2010	2004-2008	(i) 1996-2005; (ii) 2005-2008
Geographic extent (km2)	500,915	2,134	6,617	7,478	6,513	12,038
Level of political organization	Subset of state	Subset of department	Subset of two provinces	Subset of two provinces	Province	Subset of two districts
Criteria to select the study area and define the boundaries	Active front of deforestation and soy expansion; limits: forested part of Mato Grosso (excluding Cerrado)	Active deforestation front with large- and small-scale oil palm; limits: Ucayali and Aguaytia rivers	Active deforestation front; limits: 20 km buffer around San Juan-La Selva Biological Corridor	Coffee basin and surrounding forested areas; limits: ASTER footprints	Active deforestation front; limits: province boundaries	Early front of oil palm development; limits: Landsat footprint
Target expanding commodity crop	Soybean	(i) Large-scale and (ii) small-scale oil palm	Pineapple and banana	Coffee	Rubber	Oil palm
Other agricultural land uses	Mainly pastures	Pastures, shifting cultivation, coffee, cacao	Pastures, other crops (heart-of-palm, sugarcane, rice)	Shifting cultivation (rice, cassava and others), other perennial crops	Shifting cultivation (rice, cassava and others), other perennial crops	Swidden cultivation (rice), other perennial crops dominated by rubber and fruit agroforestry
Remote sensing data used in the original study	Landsat TM; MODIS	Landsat and ALOS/PALSAR	Landsat TM and ETM+	Landsat TM and ASTER	Landsat TM	Landsat TM and ETM+; Quickbird
Summary of methods for land use/cover and land use/cover change detection	Landsat TM for detecting deforestation; decision tree, based on MODIS Enhanced Vegetation Index (EVI) phenology, for post-deforestation land use	Land cover classification using random forest for 2010 and decision tree for 2000, and visual discrimination between high and low-yield oil palm plantations	Land cover classification of Landsat time series using random forest for each image date, post-classification change detection	Combination of post-classification change detection and Normalized Difference Vegetation Index (NDVI) differencing	Unknown	Object-oriented nearest-neighbor classification of CLASlite data and manual delineation, post-classification change detection
Main source	Macedo et al. 2012	Gutiérrez-Vélez et al. 2011, Gutiérrez-Vélez and DeFries 2013	Fagan et al. 2013	Meyfroidt et al. 2013	Hoang et al. 2010	Carlson et al. 2012

Tab. S2: Land use/cover changes in the study areas

Case	Mato Grosso		Pucallpa		Sarapiqui - San Carlos		Dak Lak	Dak Nong	West Kalimantan	
Period or type of actors	2001-2005	2006-2009	2000-2010, large-scale	2000-2010, small-scale	1986-1996	1996-2011	2005-2010	2004-2008	1996-2005	2005-2008
Deforestation (total, all causes)										
Gross deforestation, in %y^{-1} of total landscape	1.86	0.47	1.66	1.66	0.72	1.32	0.49	2.04	1.80	1.66
Land use at next remote sensing time step following clearing (% of gross total deforested area)										
Target commodity crop	10.1	2.2	5.3	15.4	4.7	3.5	3.7	37.0	2.7	17.6
Other agricultural land uses	62.0	51.4	79.3	79.3	95.3	96.5	96.3	39.1	41.7	38.5
Other or unknown uses	27.8	46.4	0.0	0.0	0.0	0.0	0.0	23.9	55.6	43.9
Gross and net land use changes (%y^{-1} over total landscape)										
Gross change in target commodity crop (%y^{-1})	0.85	0.62	0.10	0.37	0.24	0.72	0.30	0.84	0.06	1.02
Net change in target commodity crop (%y^{-1})	0.45	0.18	0.10	0.37	0.08	0.74	0.30	5.42	0.06	1.02
Gross change in other agricultural land uses (%y^{-1})	1.16	0.24	1.31	1.31	5.50	11.70	0.78	0.80	1.38	1.55
Net change in other agricultural land uses (%y^{-1})	0.66	-0.37	1.14	1.14	-0.25	0.33	0.37	-4.70	0.82	-0.12
Sources of new target commodity cropland (%)										
Forest	27.7	1.7	87.4	68.4	23.8	11.2	8.6	89.5	76.9	28.5
of which, mature forest	?	?	74.8	30.2	21.9	1.9	?	?	44.1	5.4
of which, secondary forest	?	?	12.6	38.2	1.9	9.3	?	?	32.8	23.1
Existing agricultural lands	72.3	98.3	12.6	31.6	76.2	88.8	56.1	10.5	13.5	41.9
Land with other cover and/or unknown use	0.0	0.0	0.0	0.0	0.0	0.0	35.3	0.0	9.6	29.6
Displacement (* likely small; ** possibly large)										
Local	**	*	*	**	?	?	**	*	?	?
Distant	?	?	*	?	**	**	*	*	?	?

Notes: ? indicates uncertain/unknown information. “Gross deforestation” measures the area of forest being converted to another land cover, in percent of the total landscape area per year. "Other or unknown uses" following clearing vary across cases, being small deforestation patches (<25 ha) in Mato Grosso, burned/bare land without use in Dak Nong, or all non-forested peatlands and burned, bare and built classes on mineral soils in West Kalimantan. "Secondary forest" refers to previously logged forest in Kalimantan, and to fallows or regrowth over ~3-5 years in other regions. Land sources with "other cover and/or unknown use" correspond to other natural vegetation, bare lands with uncertain land use, and, in West Kalimantan, all non-forested peatlands and burned, bare and built classes on mineral soils. Sources: recalculated based on primary data from Macedo et al. 2012, Gutiérrez-Vélez et al. 2011, Alternatives to Slash and Burn (ASB) maps for Pucallpa benchmark area (White et al. 2005, Velarde et al. 2010), Fagan et al. 2013, Meyfroidt et al. 2013, Hoang et al. 2010, and Carlson et al. 2012.

Tab. S3: Factors associated with pathways of commodity crop expansion

Case	Mato Grosso		Pucallpa		Sarapiqui -San Carlos		Dak Lak	Dak Nong	West Kalimantan	
Period or type of actors	2001-2005	2006-2009	2000-2010, large-scale	2000-2010, small-scale	1986-1996	1996-2011	2005-2010	2004-2008	1996-2005	2005-2008
Proportions of land use/cover in the landscape at onset										
% forest cover	68.8	60.3	43.1	43.1	44.0	46.4	24.7	56.9	68.2	52.2
% of land covered by other agricultural land uses	30.0	36.5	56.3	56.3	49.1	45.5	48.7	33.1	18.0	25.4
% of land with other/unknown uses	0.0	0.0	0.1	0.1	3.5	3.5	7.2	8.6	12.8	20.9
% of land with target commodity crop	1.2	3.2	0.5	0.5	3.5	4.5	19.4	1.5	1.0	1.6
Population density and changes										
Rural population density (p/km^2)	0.46	0.50	3.65	3.65	22.58	40.40	83.81	53.99	19.05	23.79
Rate of change of population density (%y^{-1})	1.69	1.69	-0.56	-0.56	4.93	1.16	2.06	3.67	2.77	1.58
Rural population density over cleared land in p/km^2)	1.22	1.09	5.94	5.94	40.29	75.42	277.83	125.25	59.97	49.75
Land use policies										
% of forested land with land use zoning strictly restricting agricultural expansion	~30	~30	0	0	0	0	41	27	73	75
% of forested land with land use zoning partly restricting agricultural expansion	~70	~70	0	0	~15	~100	52	67	0	0
Enforcement of land use policies (*: poor; ** medium; ***: strong)	*	***	*	*	*	**	**	*	*	*
Land tenure										
Clear and effective property rights on land (*: informal rights for most smallholders; **: smallholders may have formal rights but not always enforced; ***: overall, good enforcement of property rights for most actors)										
on agricultural lands	*	**	*	*	**	***	**	**	*	*
on forestlands	**	***	*	*	***	***	*	*	*	*
Existence of land markets (*: non-existent or poorly functioning; **: existing but not functioning perfectly; ***: functioning well)										
on agricultural lands	**	***	*	*	**	***	**	**	*	*
on forestlands	**	**	*	*	**	***	*	*	*	*
Agricultural systems										
Types of actors (SH: smallholders, LH: large holders):										
For the target expanding commodity crop	LH	LH	LH	SH	LH	LH	SH	LH	LH	LH
For the other agricultural land uses	SH / LH	SH / LH	SH	SH	SH / LH	SH / LH	SH	SH	SH	SH
Productivity increases (Average yields change of the target commodity crop, in %y^{-1} over the period)	-0.6	1.2	0.7	0.7	40.7 / -1.8	-2.2 / 0.2	6.2	4.9	2.4	-0.9

Notes: All numbers are calculated for the initial year of the period. Sources: Mato Grosso: IBGE agricultural statistics and population censuses 2000 and 2010; Peru: agricultural statistics and population censuses 1993 and 2007; Costa Rica: Instituto Nacional de Estadística y Censos de Costa Rica 1984, 2000, and 2011, and FAOSTAT for yields (respectively pineapple then banana in the table); Vietnam: rural, agricultural and fishery censuses 2001, 2006, statistical yearbooks, forestry land zoning maps from Dak Lak and Dak Nong provinces; Indonesia: population censuses 1990, 2000, and 2010; Kabupaten Ketapang and Kabupaten Pontianak Population Projections 1981-2002; West Kalimantan RTRWP, 2004; Indonesian Ministry of Forestry TGHK 1992; Indonesian Ministry of Agriculture Production Data through 2010.

Fig S1: Pathways of increase in agricultural production. This is a generalized version of Fig. 1. This increase can occur through four processes of land use change: intensification in situ or expansion into forest or undisturbed natural vegetation, 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.

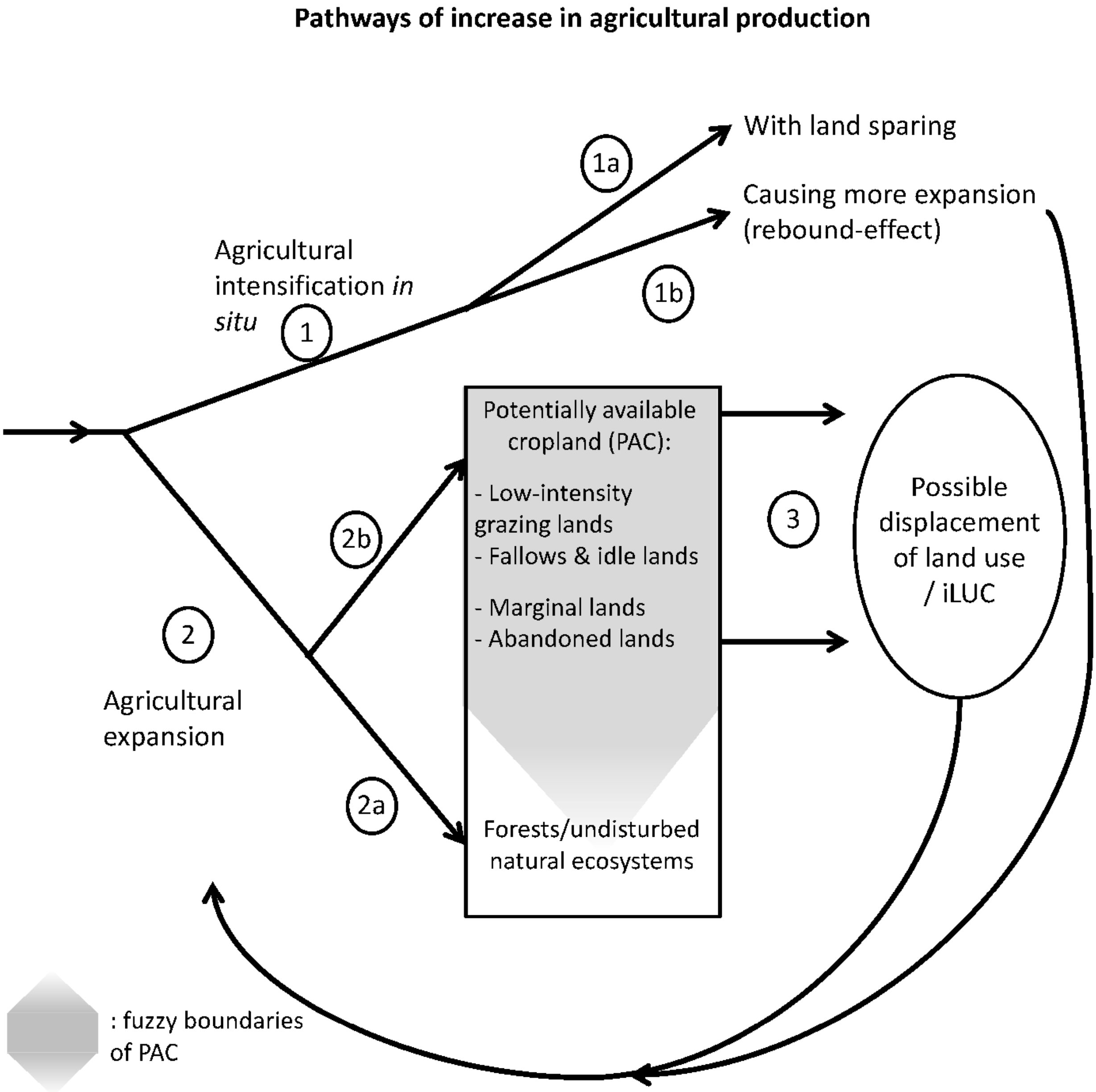

Fig S2: Summary of the representativeness analysis with GLOBE. For each variable, the left panel shows the pattern observed in our set of case studies (points) overlaid on bars presenting GLOBE data for tropical lands (either a categorical distribution of tropical lands, or equal frequency stratification). The right panel displays the pattern observed for the set of deforestation case studies in GLOBE (points) for the same variables. a. Olson's biomes (1: Tropical Moist, 2: Tropical Dry, 7: Tropical Savannas); b. World regions (5: Central America, 7: Eastern Africa, 13: Middle Africa, 18: South America, 19: Southeast Asia, 23: Western Africa); c; Percentage of tree cover in 2001; d. Percentage of land in protected area (WDPA); e. Market Access Index and f. Market Influence Index (0-1, with 1 = higher market access and influence); g. Combined Land Suitability class (2-9, larger value = lower suitability); h. Population density in 2005.