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Research, part of a Special Feature on Land Acquisitions, Well-being, and Environment

Carbon emissions from land acquisitions in Laos

Sonja Bauernschuster [1], *Melanie Pichler* [2], *Vong Nanhthavong* [3,4], *Rasso Bernhard* [1], *Michael Epprecht* [3] and *Simone Gingrich* [1]

ABSTRACT. Large-scale land acquisitions repeatedly fall short of their acclaimed socioeconomic benefits and are associated with unintended social, economic, and ecological costs. In Laos, the government has started to question its own "Turning Land into Capital" policy, and reviews land acquisitions or concessions with regard to their socioeconomic impacts. Empirical investigations of environmental impacts of land concessions, however, remain underrepresented. We link the nation-wide concession development between 2001 and 2017 with associated land use changes and quantify related land use change-induced emissions. Results show that land acquisitions for agriculture, forestry, and mining affect mainly forests and land previously used for shifting cultivation and permanent agriculture; e.g., rice paddies. Consequently, land conversions caused by concessions resulted in net carbon emissions of 4.9 Mt CO_2e yr-1 on average in 2001–2017, which amounted to 34% of total emissions from land conversions. Even tree plantations that are meant to serve as net carbon sinks caused net emissions, but those data are the least robust. The relatively low carbon emission intensity of shifting cultivation compared to the high carbon emission intensity of concessions challenges the dominant narrative of shifting cultivation as a causal factor for forest degradation. Political means of fostering sustainable development include the reduction of land acquisitions because of their emissions intensity, and minimization of emissions and social conflict induced by granted concessions, for example, by allocating land with low carbon densities and obtaining consent of local land users.

Key Words: *climate impact; concessions; emissions of land use; green growth; tree plantations*

INTRODUCTION

Since 2000, the scale and pace of the global land rush have been unprecedented (Liao et al. 2021), with particular ramifications on agrarian and environmental transformations in Southeast Asia (Corbera et al. 2017, Schoenberger et al. 2017, Ingalls et al. 2018). Laos is one example where investments from neighboring countries and beyond resulted in a "massive boom in large-scale land concessions"[1] (Baird 2011:15) in agriculture, forestry, hydropower, and mining (Hett et al. 2020). Since 2000, the Government of Laos has granted concessionaires access to 4% of the domestic territory, expecting infrastructure development and government revenues in return (Hett et al. 2020). This policy of "Turning Land into Capital" (Baird 2011, Kenney-Lazar et al. 2018) aimed at closing yield gaps, increasing food and energy security, improving off-farm employment opportunities, and enhancing local and international market access for agricultural, timber, and mining products (GoL 2004, 2006). At the same time, land acquisitions for tree plantations and agricultural products were expected to increase the productivity of national land use, allowing for land sparing of so-called marginal land, and thus contributing to climate change mitigation (Baird 2011, Fairhead et al. 2012, Davis et al. 2015b, Liao et al. 2021). We investigate the impact of concession development on biomass carbon (C) emissions in Laos since 2000, including agricultural and tree plantations as well as mining concessions, and discuss policy implications in view of sustainable land use.

In Laos, a country endowed with vast natural resources, the commodification of land is considered an attractive opportunity for economic growth and poverty alleviation to escape least-development status (GoL 2006, Lu and Schönweger 2019). Recently, the Government of Laos has started to address environmental concerns in its development plans, which has given rise to green growth strategies, with tree plantation development and sustainable agricultural intensification as main pillars (GoL 2018). In order to efficiently use natural resources, modernize land use practices, and combat poverty, the Government of Laos now preferably grants land concessions on land labeled as degraded land or potential forest (GoL 2007, Baird 2014, MRLG 2019). In the northern province of Luang Namtha, for example, tens of thousands of hectares of Chinese rubber plantations were approved as an instrument to replace shifting cultivation (and eradicate opium production) during the rubber boom decade of the 2000s (Shi 2008, Baird 2010). In the fertile Bolaven Plateau in the southern province of Champasak, in turn, large-scale coffee plantations, bauxite mining, and hydropower dams partially replaced the allegedly less efficient smallholder coffee farming (Delang et al. 2013).

Investors readily pick up the legitimization framework for "green grabs" (Fairhead et al. 2012:237) in the case of tree plantations (Scheidel and Work 2018, Liao et al. 2021), and are in general attracted by Laos's allegedly "untapped resource frontier" (Barney 2009:147), low cost of land, and weak land governance (Baird 2010, Lu and Schönweger 2019). Concessions, however, have often fallen short of meeting both the government's and investors' expectations. Some have never materialized (Schönweger and Messerli 2015, Lu and Schönweger 2019, Baird 2020), while some compete with local people's needs for arable land and other natural resources, thereby challenging local livelihoods and reinforcing trade-offs between food sovereignty, income, and livelihood resilience (Baird 2010, Nanhthavong et al. 2020).

A considerable number of researchers have investigated socioeconomic impacts of land acquisitions in recent years (Hall 2013, Friis and Nielsen 2017, Malkamäki et al. 2018, Müller et al. 2021). Emerging evidence also links land acquisitions to environmental impacts such as deforestation (Davis et al. 2015a, 2020), soil degradation (Shete et al. 2016), pressure on the local water balance (Breu et al. 2016), and chemical pollution (Friis and Nielsen 2016). However, there is less research on climate-

[1]University of Natural Resources and Life Sciences, Vienna, Department of Economics and Social Sciences (WiSo), Institute of Social Ecology (SEC), [2]Institute of Social Ecology, University of Natural Resources and Life Sciences, Vienna, Austria, [3]Centre for Development and Environment (CDE), University of Bern, [4]Institute of Geography, University of Bern

related impacts of the land rush (Liao et al. 2021). Liao et al. (2021) conducted the first study on global carbon (C) emissions related to land acquisitions for agricultural purposes, which showed negative climate effects but also potential savings if acquisitions occur only in areas with low carbon stocks. Furthermore, several case studies have quantified carbon stock (changes) in certain tree plantations in the tropics, and have suggested a range of carbon impacts can occur depending on plantation type, age, management, and vegetation prior to land conversion (e.g., Forrester et al. 2006, Du et al. 2015, Bruun et al. 2018, Guillaume et al. 2018). Less research on climate-related impacts of agricultural and mining concessions has been published (Hergoualc'h and Verchot 2011, Hergoualc'h et al. 2012, Bordonal et al. 2017). We contribute to this line of research by establishing the first nation-wide accounting of biomass carbon emissions caused by the implementation of land concessions in Laos, including tree plantations, agriculture, and mining.

Based on a recent inventory of land concessions in Laos and spatially explicit information on land cover, we assess all aboveground and belowground biomass carbon fluxes (emissions and sinks, excluding soil organic carbon) that have resulted from concession-related land use changes in Laos in 2001–2017. By comparing these carbon fluxes to national carbon fluxes from land use change, we are able to elucidate the role of concession development in the overall climate impact of Laos's land use. In addition, we identify which concession types are most critical and which previous land uses (and land users) are most affected by land acquisitions. We reflect on our results in view of their policy implications, aiming to stimulate a more nuanced discussion on concession granting and development in Laos and other countries, considering its effects on the global climate, as well as on local livelihoods.

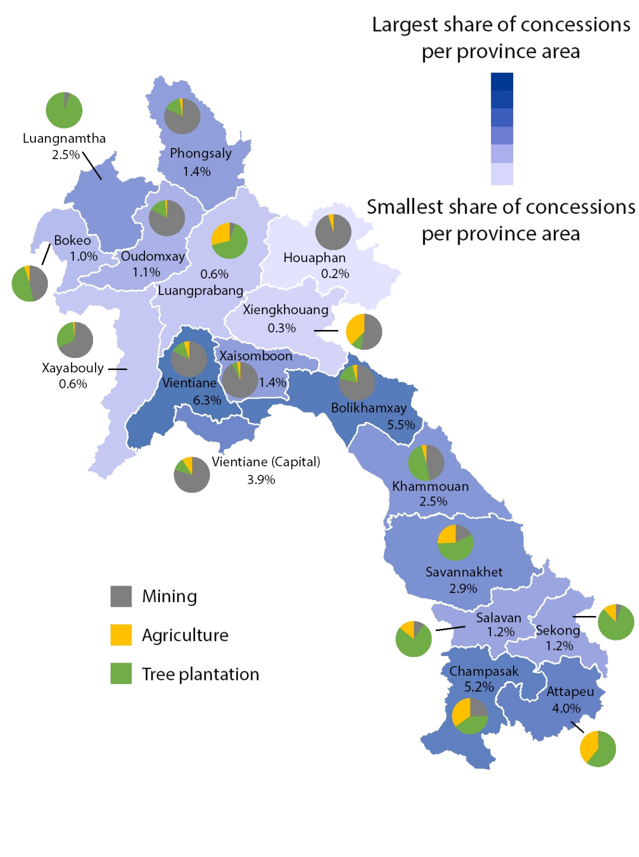
From Turning Land into Capital to green growth

Compared to other Southeast Asian countries, land acquisitions in Laos have a relatively short history. Since the early 2000s, the Government of Laos has promoted land acquisitions through creating favorable conditions for Foreign Direct Investment in the course of the Turning Land into Capital policy (Kenney-Lazar et al. 2018:iv). Although the Government of Laos has never officially used the term in regulations or laws, in practice, the policy is aimed at commodifying natural resources, mainly for hydropower, infrastructure development, and mining, as well as agricultural and tree plantations, in return for state revenues and infrastructure and service provisioning (e.g., [rail]roads, health centers) (Ingalls et al. 2018:104, Kenney-Lazar et al. 2018).

The Lao Ministries of Natural Resources and Environment, Agriculture and Forestry, Planning and Investment, and Energy and Mines recently completed the most comprehensive inventory of land leases and concessions in Laos to date (Hett et al. 2020). An analysis of the inventory data shows that of the 1 million hectares of land that have been granted as concessions for development in the primary sector, more than half has been granted for agricultural (mainly sugarcane, cassava, cattle and buffalo, coffee, and jatropha) and industrial tree plantations (mainly rubber, eucalyptus, and agarwood), followed by 415,527 ha of land granted for mining concessions (mainly gold, copper, and potassium). Not all area granted has actually been developed by the investors; however, when concessions were developed, they were often in primary (18%) or secondary forests (26%), but also in land that was previously used for shifting cultivation fallows (15%), gardens (9%), rice paddies (4%), grazing (4%) or upland agriculture (3%). Only 1% of concessions were allocated in degraded forest (Hett et al. 2020:67), where concessions initially were meant to be developed (GoL 2007). The neighboring countries of China, Vietnam, and Thailand are the most important investment and trading partners, each investing primarily (but not exclusively) in land concessions in geographic proximity.

Bolikhamxai and Vientiane in the center of the Laos are most affected by large amounts of land developed under both domestic and foreign concession agreements, where mostly mining concessions have been developed (Fig. 1); in Savannakhet and Champasak in the south, concessions were more evenly distributed among agriculture, tree plantations, and mining. In the north, Luang Namtha is almost exclusively affected by the development of tree plantations. Less affected regions can be found in remote areas (Messerli et al. 2015), such as Houaphan or Xiengkhoang.

Fig. 1. Most common concession types (pie charts) and concession occurrence (shades of blue) in all provinces in Laos based on data provided by the inventory of land leases and concessions in Laos (Hett et al. 2020).



Concession development has been a key driver of economic growth in Laos over the past 20 years (Nanhthavong et al. 2021). In the recent decade, however, mounting evidence of increasing land conflicts, declining commodity prices (especially for rubber), and low return on concessions investments due to lack of effective management structures in the Government of Laos led the government to announce several concession moratoria, starting in 2007 (Kenney-Lazar et al. 2018, Dwyer and Vongvisouk 2019, Hett et al. 2020). Most prominently, PM Decree No. 13/2012 suspended new concessions for rubber, eucalyptus, and mining exploration until the end of 2015, and was extended until 2020 (Hett et al. 2020). At the same time, the Government of Laos started to revise the Land Law of 2003 in an effort to move to quality investments. The amended Land Law of 2019 reduced the period of concessions from indefinite to 50 years (Art. 120) and implemented the compulsory approval by the National Assembly for concessions that exceed 10,000 ha (Art. 29.3) (National Assembly 2019). Furthermore, the law requires companies to survey and map out the actual land area before rather than after the concession is approved (Kenney-Lazar et al. 2018).

In the course of these adjustments, green growth strategies have increasingly complemented the Turning Land into Capital policy. International (development partner) organizations like the World Bank or the Green Climate Fund (which coordinates climate finance within the United Nations Framework Convention on Climate Change; e.g., reducing emissions from deforestation and forest degradation [REDD+]) account for the most important strategic proponents of these strategies. In the course of the Green Growth Development Policy Operation, for example, the World Bank has provided budget support, with payments, depending on the establishment of certain green growth policies: timber legality through Forest Law Enforcement, Governance, and Trade (FLEGT) in 2018, the establishment of Laos' largest national park, Nakai-Nam Theun Park, in 2019, and the adoption of the new Forestry Law in 2020 (FAO 18 Feb 2020, World Bank 5 March 2020, Vientiane, *personal communication*). In Laos, the National Institute for Economic Research has served as the focal point for establishing a national Green Growth Strategy: the sustainable intensification of agriculture as well as increasing forest cover through tree plantations represent the most important pillars to link economic and environmental interests in the Lao Green Growth Strategy (GoL 2018).

Contrary to the earlier moratoria on rubber and eucalyptus, PM Order 9 in 2018 and the Ministry of Agriculture and Forestry's Ministerial Instruction 1758 in 2019 opened 600,000 ha of degraded state forest land within National Production Forest Areas for private tree plantations (especially eucalyptus and acacia). This corresponds to an area larger than what has already been granted to date for agriculture and tree plantations combined. The contradictory handling of eucalyptus plantations illustrates the controversial debate on related benefits and risks: while eucalyptus apparently grows on degraded forest land and can be harvested after a short time, it also adversely affects the local water balance and poses the risk of encroachment on better land (Baird 2014).

METHODS

Data

We quantified biomass carbon emissions caused by land concessions in Laos in the period 2001–2017. To this end, we combined the recent inventory of "Land leases and concessions in the Lao PDR"(Hett et al. 2020) with national land cover maps and information on biomass carbon densities in different land use categories. In addition to investigating national-level trends, we took a closer look at two provinces, one in the north (Luang Namtha), and one in the south (Champasak), where large areas have been developed into concessions. Our analysis included all concessions already developed in agriculture, tree plantation, and mining subsectors (878 deals, 525,890 ha), but excluded projects that have not started (yet), that ceased operation during the contract period, that concluded contract and operation, or for which the exact location is unknown (327 deals, 42,160 ha). Hydropower concessions and contract farming are not part of this analysis either.

We quantified the emissions caused by concessions as the difference in biomass stocks before and after the implementation of each concession. To this end, we combined spatially explicit data on concessions granted, developed, and abandoned between 1993 and 2017 that were surveyed for the national inventory of land concessions (Hett et al. 2020) and had national land cover data available for five points in time (DoF 2000, 2005, 2010, 2015, 2020; see also Table A1.1). While the accuracy of the national land cover data sets was arguably limited, we considered it suitable and of sufficient quality for our analysis for two major reasons. Firstly, differences to other, larger scale land cover data sets of the region (e.g., Kang et al. 2019) result partly from differences in methodological approaches. The national land cover data set used here relies on visual interpretation of remote sensing data (see Table A1.1) rather than on machine learning. Results are less standardized than those from machine-learning approaches, but this method allows for context-dependent interpretation and is thus suitable for processing data on complex tropical land use systems like the ones in Laos (Leisz et al. 2005). Secondly, an accuracy assessment performed by the Lao Department of Forestry for the 2019 land cover data set (DoF 2020) indicated that the overall accuracy of classification among all classes was 79.8%, but the accuracy of classification as forest versus non-forest was 93.1%. This means that the classification that is most relevant for carbon stocks, and thus for our analysis, is quite accurate. Table A1.2 additionally states the level of accuracy for each land cover category, according to the Lao Department of Forestry (DoF 2020).

By integrating land cover data and data on land concessions, we created matrices that quantified concession-related land conversions in four time periods: 2001–2005, 2006–2010, 2011–2015, and 2016–2019. The concession-related land conversion matrices contained 18–19 categories of previous land cover (aggregation of two categories in 2015–2019), identical to national forest inventories, and 17 categories of subsequent concessions (Table A1.2). In the last time period between 2016 and 2019, the inventory provided information on concession development only until 2017, which led to an underestimation of land use change during that period.

Table 1. C density values of above and below ground biomass of different land-use categories

Land use category	C density (AGB, BGB)[†] (Mg C/ha)	Region/regional conditions	Source
Rubber	29.8	Laos	Bruun et al. (2018)
Eucalyptus	50.0	Southern China	Du et al. (2015)
Sugarcane	14.8	Southern Brazil	Bordonal et al. (2017)
Pasture	3.1	Moist tropical	IPCC (2006)
Coffee	12.8	Costa Rica	Hergoualc'h et al. (2012)
Jatropha	7.0	Mexico	Skutsch et al. (2011)
Oranges	76.3[‡]	Ghana	Kongsager et al. (2013)
Evergreen forest	200.0–205.8	Laos	DoF and JICA (2017), DoF (2020)
Mixed deciduous forest	87.7–87.9	Laos	DoF and JICA (2017), DoF (2020)
Dry dipterocarp forest	43.2–50.8	Laos	DoF and JICA (2017), DoF (2020)
Other forest	24.4–92.6	Laos	IPCC (2003), DoF and JICA (2017), DoF (2020)
Regenerating vegetation	10.4–17.4	Laos	DoF (2018, 2020)
Grassland, savannah, scrub	3.1–30.0	(Moist) tropical	IPCC (2003, 2006)
Agriculture categories	2.6–5.0	Moist tropical	IPCC (2003)

[†] C density of aboveground (AGB) and belowground biomass (BGB). Soil organic carbon excluded.
[‡] C density of aboveground biomass only.

Quantification of carbon emissions from land conversion

In order to quantify the biomass carbon emissions from concession development in Laos, we followed IPCC guidelines (IPCC 2006, 2019) and applied a stock-difference approach, quantifying the difference between biomass carbon stocks in aboveground and belowground vegetation before and after a concession was implemented, and divided the stock difference by the number of years between two time points to infer annual net carbon fluxes (see Appendix 2). We display all carbon fluxes in t CO_2e yr^{-1}, with positive values indicating emissions to the atmosphere (i.e., decreasing biomass carbon stocks) and negative values indicating carbon sequestration in biomass (i.e., decreasing biomass carbon stocks). Due to a lack of consistent data on soil organic carbon, an ecosystem carbon pool larger but less dynamic than biomass, our analysis is restricted to carbon fluxes from biomass.

We quantified biomass carbon pools in each land cover category by applying specific values for biomass carbon density (Mg C/ha) to the area of the respective category. Carbon density values of aboveground and belowground biomass were derived from the literature, using country-specific values wherever available (Table 1). For tree plantations, we used time-averaged carbon density values that reflected the typical mean stand age of plantations. While these data provided valuable information on the typical carbon density of the respective land use categories, data robustness was limited due to several factors: (1) use of mean rotation periods instead of exact stand ages, (2) non-consideration of soil degradation in our data set, (3) lack of country-specific data for certain land use types (see Table 1), and (4) use of national averages, which ignored regional deviations (Gibbs et al. 2007, Hett et al. 2011). Focusing on (1), we conducted a sensitivity analysis using minimum and maximum carbon density values reported in the literature for the categories with the most variable carbon densities to quantify the effect of data uncertainty on our major results (see Appendix 3). For land cover, the most critical category was regenerating vegetation, which corresponded to shifting cultivation fallows, and for concessions, the most crucial categories were rubber and eucalyptus plantations.

We compared our results to national emissions from all other land conversions (Bauernschuster et al. 2022) to investigate the changing role of concessions in the national carbon budget of land conversions in Laos.

RESULTS

Concessions as drivers of land use change

Between 2001 and 2017, an area of 526,248 ha, or 2% of the total land area in Laos, was converted into agricultural and tree plantations and mining sites (Fig. 2), which corresponded to roughly 12% of all land conversions that occurred during this period and approximately 52% of all concessions granted. Mixed deciduous forest and regenerating vegetation were the land cover categories most affected, and accounted for 33% and 32% of total concession-related land conversions, respectively (Fig. 2). Both of these land cover categories are associated with shifting cultivation fallows: regenerating vegetation contains young fallows (< 7 years), and mixed deciduous forest at least partly includes older fallows (7+ years) (DoF 2018). Other important land cover categories affected by land concessions included dry dipterocarp forest (13%), agricultural land (10%) such as rice paddies, and evergreen forest (5%).

A concession boom can be observed between 2001 and 2010 (402,226 ha), but it significantly slowed down between 2011 and 2017 (124,022 ha) (Fig. 3). The period of most pronounced concessions expansion was 2006–2010 (290,284 ha). The decline in new concessions after 2010 was due mainly to an almost complete end of tree plantations, and was accompanied by an increasing relative relevance of mining concessions toward the end of the investigation period. In 2016–2017, mining was the only subsector that recorded an increase in new concessions (63,064 ha) and constituted 96% of developed concessions in that period. Throughout the time between 2001 and 2017, mining concessions amounted to almost half (47%) of the total area converted into concessions (249,955 ha).

Tree plantations, predominantly rubber and eucalyptus (in sum, 95% of tree plantations), constituted the second largest share of concession area (38% or 198,320 ha). They dominated concession development during the boom period between 2001 and 2010,

Fig. 2. Cumulated land conversions to concessions between 2000 and 2017.

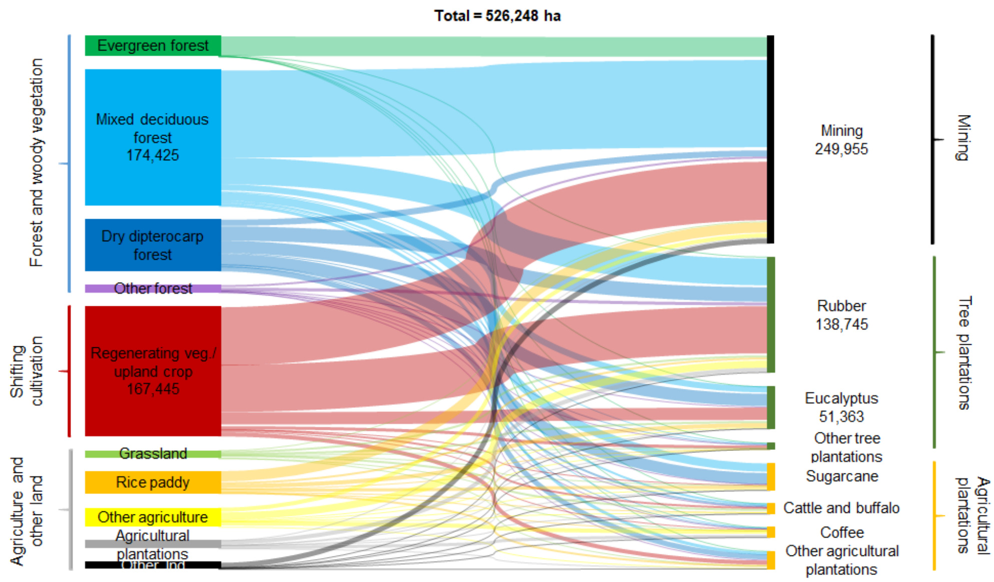
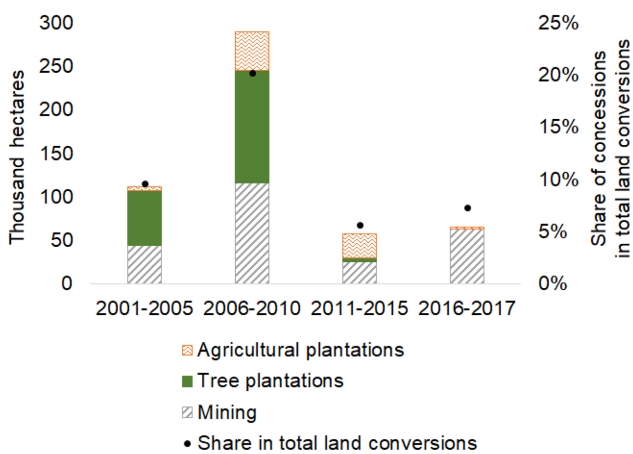


Fig. 3. Land concessions expansion and its share in total land conversions.



and amounted to 48% of total concession area (Fig. 3). Tree plantation development declined after 2010 even more steeply than mining concessions and made up only 4% of concessions or 5086 ha in 2011–2017.

Agricultural plantations constituted the smallest share (15% or 77,973 ha) of concession area. After a slow start in 2001–2005, a boom of land conversions into cash crop plantations such as sugarcane (32,282 ha), coffee (11,849 ha), and jatropha (2391 ha), as well as cattle grazing areas (10,567 ha), took place in 2006–2010, which superseded earlier fruit tree plantations (2256 ha in 2001–2005) (Fig. 3). Agricultural plantation development declined between 2011 and 2015 (27,424 ha), and vanished almost completely in 2016–2017 (2292 ha).

Concessions as drivers of carbon emissions

The development of mining concessions, tree plantations, and agricultural plantations in Laos resulted in average land use change-induced emissions of 4.9 Mt CO_2e yr^{-1} in the period 2001–2017. Concessions were thus responsible for 34% of emissions from land conversions in the country (Bauernschuster et al. 2022). Per unit of land converted, concessions caused emissions of 257 t CO_2e ha^{-1} yr^{-1} as compared to the national average excluding concessions of 47 t CO_2e ha^{-1} yr^{-1}.

In 2001–2005, emissions from concession development (1.4 Mt CO_2e yr^{-1}) were lower than the interannual average because the area expansion of concessions was small, and tree and agricultural plantations resulted in modest net carbon sinks, which slightly counterbalanced emissions from mining development (Fig. 4). In 2006–2010, both the area under new concessions and the carbon lost per area under new concession increased dramatically, which resulted in emissions of 7.0 Mt CO_2e yr^{-1}. In 2011–2015, emissions from concession development were 1.8 Mt CO_2e yr^{-1}, particularly because of the reduced mining development. In 2016–2017, mining development increased again and resulted in net emissions of 9.5 Mt CO_2e yr^{-1} (99.8% of concession-related emissions emerged from mining).

Conversions of forests, especially mixed deciduous forest, evergreen forest, and dry dipterocarp forest, into concessions caused the largest gross and net emissions between 2001 and 2017 (Fig. 5a). Conversions into mining concessions (4487 kt CO_2e yr^{-1}) dominated these emissions, followed by tree and agricultural plantations (104 kt CO_2e yr^{-1} and 326 kt CO_2e yr^{-1}, respectively). The largest gross sinks, on the other hand, occurred due to conversions of regenerating vegetation (266 kt CO_2e yr^{-1}), agricultural land (143 kt CO_2e yr^{-1}), and grassland (31 kt CO_2e yr^{-1}) into rubber (215 kt CO_2e yr^{-1}), eucalyptus (198 kt CO_2e yr^{-1}), and fruit tree plantations (18 kt CO_2e yr^{-1}) (Fig. 5b).

Fig. 4. Net emissions of land conversions in Mt CO_2e / yr from 2000-2017 (concession and non-concession area).

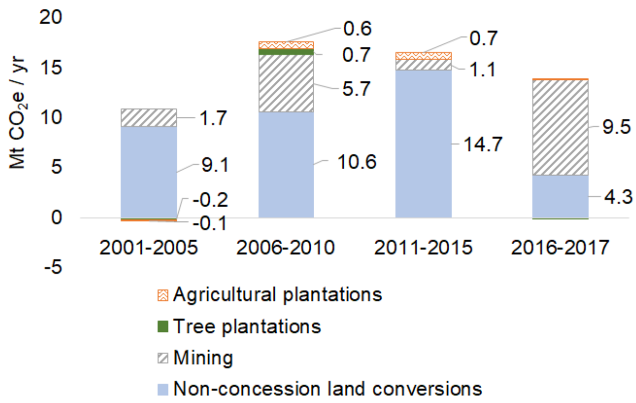


Fig. 6 shows the carbon emission intensity of land conversions; i.e., the amount of carbon emitted or sequestered per unit land, according to the different concession types, as well as all other land conversions outside of concessions (Bauernschuster et al. 2022). Conversions into concessions showed a significantly higher average carbon emission intensity (256 t CO_2e ha^{-1} yr^{-1}) than the national average of emissions from land conversions excluding concessions across the total time period (47 t CO_2e ha^{-1} yr^{-1}). From 2016 to 2017, the period of the highest emissions from concessions, land conversions into concessions resulted in 69% of net emissions from land conversions but accounted for only 7% of all land conversions (Fig. 3, Fig. 6), caused by the high carbon-emission intensity of mining concessions.

Across concession types, mining concessions were responsible for the highest net carbon emissions by far (4487 kt CO_2e yr^{-1} or 91%), which exceeded the emissions from the other concession subsectors by a factor of 10 (430 kt CO_2e yr^{-1} or 9%) (Fig. 5a). Mining concessions continued to cause high emissions even after the boom period of 2006–2010 (Fig. 4); 94% of those emissions occurred due to conversions from different forest types, especially mixed deciduous and evergreen forest. In terms of area, a large amount of regenerating vegetation was also converted to mining lands. In addition to eliminating carbon stocks in forest ecosystems, mining concessions resulted in no carbon sinks to balance the losses from land conversions because the typical open-pit mining sites allow for no vegetation cover (Delang et al. 2013).

Conversion to tree plantations caused both emissions and sinks, with a net effect amounting to carbon emissions of 104 kt CO_2e yr^{-1} or 2% of total concession emissions (Fig. 5b). Whether tree plantations act as emissions or sinks of carbon depends on the difference in carbon stocks between previous and succeeding land cover, and the two major tree plantations species show diverging effects: rubber has, on average, a lower carbon density than eucalyptus, and land concessions for rubber affected mostly mixed deciduous forests, a land cover class of comparatively high carbon density. This effect resulted in rubber concessions causing net emissions of 218 kt CO_2e yr^{-1} in 2001–2017. Conversions into eucalyptus, on the other hand, affected land cover categories of lower carbon densities such as regenerating vegetation, and resulted in net sinks of 137 kt CO_2e yr^{-1}. Overall, the emissions of rubber expansion were greater than the sinks caused by eucalyptus plantations. Those emissions, however, are subject to high uncertainty because the carbon densities both before land conversions, due to a high share of regenerating vegetation, and after land conversion may vary greatly depending on the respective rotation period, for which robust data are not available. Results of a sensitivity analysis are presented in the *Discussion: Limitations* section.

Conversions to agricultural plantations resulted in net carbon emissions that were approximately three times the emissions from tree plantations (326 kt CO_2e yr^{-1} or 7% of total concession emissions). This was because agricultural plantations, on average, have low carbon densities but replaced forest ecosystems with higher carbon stocks. Conversions into agricultural plantations affected mainly mixed deciduous and dry dipterocarp forests; this resulted in a large amount of gross emissions in 2001–2017 (351 kt CO_2e yr^{-1}), which by far offset the modest gross sinks related to conversions of rice paddy and other agriculture into agricultural plantations (-23 kt CO_2e yr^{-1}) (Fig. 5b).

Regional divergences

Due to geographic differences, including diverging topography, varying degrees of infrastructure development, and heterogeneous demographic structures, we observed differences in the context and nature of concessions in different parts of the country.

Luang Namtha Province

Luang Namtha Province (9534 km^2) is located in Northern Laos bordering China (Fig. 1). Evergreen and mixed deciduous forest cover almost 60% of its area, followed by regenerating vegetation (30%), and agricultural land (9%). In 2011, agricultural households accounted for 80–90% of all households in the province, and shifting cultivation was practiced widely (Epprecht et al. 2018), despite efforts at reduction and replacement (with rubber), for example, in the course of China's opium replacement program (Lu 2017).

Concessions in Luang Namtha add up to approximately 2.5% of the total land area in the province (Fig. 1). The concessions almost exclusively comprise rubber plantations (95%) and a small area of mining concessions (5%). Nearly half of all area converted into concessions was originally regenerating vegetation, followed by mixed deciduous forest, which resulted in net emissions in 2001–2017 of 91 kt CO_2e yr^{-1}. Emission intensity of concession development in Luang Namtha increased drastically in 2016–2017 when emissions from mining concessions, which affected only 20 ha, exceeded those from tree plantations.

Champasak Province

Champasak Province (14,978 km^2) is located in Southern Laos (Fig. 1). Here, 71% of the land is covered by evergreen, mixed deciduous, and dry dipterocarp forests, followed by agricultural land (18%) and regenerating vegetation (4%). The fertile Bolaven Plateau, located in Champasak, produces 58% of all coffee in Laos (Delang et al. 2013, Epprecht et al. 2018).

The concession landscape in Champasak differs from Luang Namtha's in many aspects: concessions add up to 5% of the total land area and show great diversity (Table 2). While rubber plays a dominant role here, too (30,000 ha or 39% of the total developed area in the province), dozens of other products are also produced in concessions, such as bauxite in the mining sector (25% of total

Fig. 5. Emissions of concession development 2000–2017 in Mt CO_2e/yr: (a) all concessions (b) tree and agricultural plantations only (SC: shifting cultivation; e: gross emissions to the atmosphere; s: gross sinks in biomass).

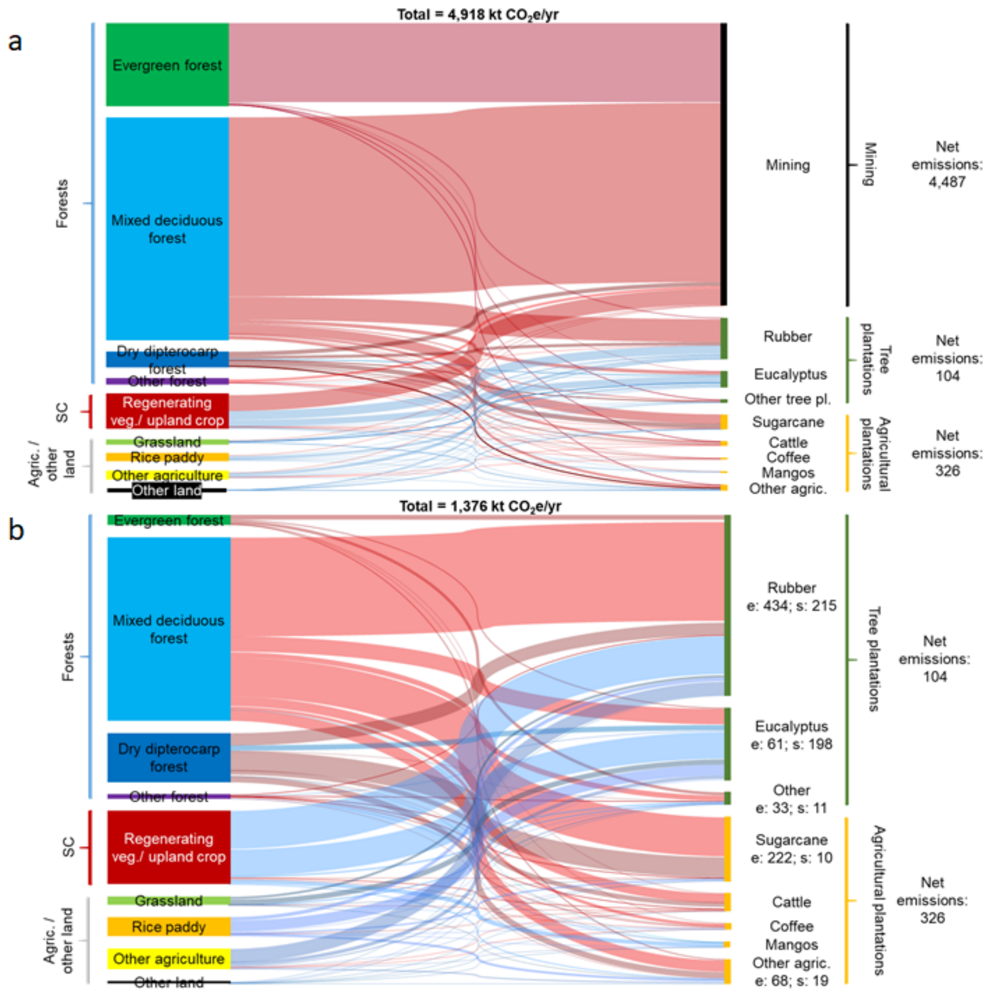
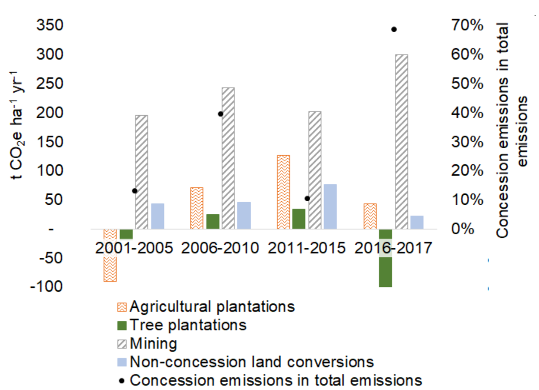


Fig. 6. Emission intensity of land conversions in t CO_2e ha-1 yr-1 (concession and non-concession area) and share of concession-induced emissions in total emissions of land conversions.



concession area), and coffee (15%), sugarcane (11%), cattle (2%), and rice (2%), followed by a variety of more than 20 different fruit trees, vegetables, and livestock concessions in the agricultural sector. More than half of the developed concession area was originally forest, 25% was regenerating vegetation, and 18% was agricultural land and rice paddy, which resulted in net emissions in 2001–2017 of 425 kt CO_2e yr^{-1}.

DISCUSSION

Concession development in Laos in the past 20 years resulted in net carbon emissions of 4.9 Mt CO_2e yr^{-1}. While concession development represents a relatively small share of domestic land conversions (12%), it caused a large share of land use change-induced emissions (34%). Concession development is thus characterized by an emission intensity that is seven times as high as that of other land conversions.

Limitations

The validity of our findings critically relies on the quality of the empirical input data, as well as on the chosen system boundaries.

Table 2. Concession area and emissions in Luang Namtha (L) and Champasak (C)

	2001–2005		2006–2010		2011–2015		2016–2017	
	L	C	L	C	L	C	L	C
Mining (ha)	425	–	558	14,775	175	4,423	20	25
Tree plantations (ha)	1,900	18,865	20,336	11,944	138	95	–	15
Agriculture (ha)	–	948	23	15,019	–	10,346	–	630
Emissions (kt CO_2e/yr)	39	67	322	948	2	646	3	16
Emission intensity (t CO_2e/ha/yr)	17	3	15	23	8	44	123	59

Restricting the analysis to carbon fluxes from biomass, while excluding soil organic carbon, increases the robustness but also limits the scope of our study. Limited evidence of soil organic carbon change due to the expansion of tree plantations is available for Northern Laos (Bruun et al. 2018, 2021) and neighboring Yunnan (de Blécourt et al. 2013). Those studies found that the development of rubber plantations was associated with steep losses in soil organic carbon when compared to shifting cultivation systems or other secondary forests. This suggests that our results are a conservative estimate of the emissions impact of land concessions expansion in Laos.

Data uncertainties pertain to our analysis, specifically with regard to the extent (see *Methods*) and carbon density of regenerating vegetation, and the carbon density of tree plantations. To quantify the impact of the latter on our results, we conducted a sensitivity analysis by applying minimum and maximum values of carbon density from the literature to the most crucial land categories of regenerating vegetation, rubber, and eucalyptus plantations, and by assuming high and low values representing long and short rotation periods (see Appendix 3). The analysis showed that depending on the assumptions of rotation lengths in regenerating vegetation and tree plantations, tree plantations may have acted as even stronger sources of carbon emissions (9.2 Mt CO_2e yr^{-1}) but also as carbon sinks (-2.9 Mt CO_2e yr^{-1}) when compared to our best guess estimate of 0.1 Mt CO_2e yr^{-1} in 2001–2017. The uncertainty about rotation lengths of shifting cultivation fallows and, to a lesser extent, tree plantations thus impeded our ability to draw definite conclusions about the emissions impacts of tree plantations, and about concession development on shifting cultivation fallows. The results of our analysis underscore calls for improved data availability regarding the actual rotation periods and carbon densities in tree plantations and shifting cultivation lands (Mertz et al. 2021). However, our data show that uncertainties are not large enough to reverse the general finding that concession development in general caused significant net carbon emissions across the entire 2001–2017 period.

Policy implications: land acquisitions and sustainable land use

Our results show that despite green intentions of policy-makers, concessions in the Lao People's Democratic Republic resulted in net carbon emissions because they were characterized mainly by low carbon density and were established mainly in carbon-rich forest ecosystems, even if such land was classified as degraded land. To mitigate the adverse impacts on carbon emissions and local livelihoods of future land acquisitions, policy options include (a) a reduction in land acquisitions as the most emissions-intensive type of land conversion, and (b) the minimization of emissions and social conflict induced by granted concessions, which differ across concession types.

To reduce land acquisitions, the Government of Laos recently started to impose moratoria on rubber, eucalyptus, and mining concessions after having promoted land concessions for these activities since 2000. Promotion and moratoria of certain land deals are reflected in the boom and bust of Laos's concession development and the peak in emissions in 2006–2010. However, continued development of mining sites even after moratoria indicates the long-lasting impacts of concessions once granted due to time lags between the grant of a concession and the development of the respective activity. For example, in 2016–2017, the shortest period analyzed in this study, existing contracts for mining concessions became effective, which resulted in the development of new mining sites and subsequently the highest emissions of all time periods and concession types. Moratoria are an important lever in reducing the adverse effect of land acquisitions, but they become effective only after a certain delay. However, future concessions that provoke further environmental or livelihood conflicts on currently unaffected land might be effectively prevented by moratoria.

In addition, while moratoria take time to reveal effectiveness on the ground, concessions once granted have long-lasting effects far into the future: concessions contracts typically cover up to 70 years, with possible infinite extensions (PM Order 135 in 2009), and were only recently restricted to 50 years (National Assembly 2016). Access restrictions to granted concessions are not lifted by moratoria, so that local people who depend on forest resources for subsistence or sale lose this important food and income source (Broegaard et al. 2017, Keovilignavong and Suhardiman 2020) and are negatively affected by land acquisitions in the long term (Shi 2015, *personal communication*, Nanhthavong et al. 2020, Müller et al. 2021). Political maneuvering space regarding existing concession contracts is thus limited. Future concessions, if granted, should be regulated and monitored closely and continuously to ensure their contribution to national development plans and local needs, as well as to assess their long-term environmental impacts, and contracts should allow for termination if they turn out to be destructive (Lay et al. 2021). Investors need to be held accountable for environmental consequences of their land acquisitions, for example, by being obliged to restore land after the end of a concession contract, as is already requested in the Lao Forestry Law (GoL 2007).

To minimize the environmental and social impacts induced by land concessions, Lao land use and development policies have focused on degraded land (GoL 2005:11, National Assembly 2007, 2019). However, there is no consensus among different stakeholders on its definition. For example, land zoned as degraded by government authorities is often not perceived as degraded by users of that land (Lestrelin 2010, Baird 2014). Land degradation appears to be a concept used by authorities and investors to justify the development of concessions on certain land (mostly shifting cultivation fallows, as our data show) and thereby restrict access by previous land users. However, if that land were actually degraded, concessionaires would show no interest, and successful operation of plantations would be highly unlikely (Baird 2014). Our results confirm that such lands may host carbon-rich ecosystems. The concession landscape on the Bolaven Plateau (5% of total land) in Champasak, for example, shows how investors are eager to get hold of the fertile and resource-rich land, which by no means had been degraded but was used particularly by smallholding coffee farmers before tens of thousands of hectares were transformed to rubber, coffee, and bauxite concessions (Delang et al. 2013).

Allocation of land classified as degraded to investors indicates a preference for plantations at the expense of smallholding farmers and shifting cultivators based on the assumption that their practices are unproductive, and in the case of shifting cultivation, destructive and cause emissions. Such generalized narratives consider neither any positive impacts of shifting cultivation (for biodiversity, or conservation of soil organic carbon stocks) (Scheidel and Work 2018, Bruun et al. 2021), nor the emission intensity of the practice compared to the high emission intensity of many land concessions demonstrated in this study. Instead, the carbon sequestration potential of the preferred tree plantations is likely overestimated. Moreover, the much lower carbon sequestration potential of agricultural plantations compared to young and old fallows, as well as hidden emissions related to more industrialized, intensified land use, are mostly neglected or quietly accepted (Scheidel 2018, Gingrich et al. 2019). Our findings highlight that the degraded land classification is not suited to identifying areas of low carbon density. Instead of relying on a vague, normative classification, a more data-based classification of land in terms of carbon density is an immediate prerequisite for policies to identify locations for plantations where the emissions impact is low.

Options for minimizing negative social and ecological impacts of future land deals differ across concessions types. Mining concessions depend on resource deposits and have to be allocated to resource-rich locations, causing emissions or social conflicts, or not granted at all. Agricultural and tree plantations, on the other hand, are not constrained to a specific location. In the case of new deals, such as the opening of 600,000 ha of land for private tree plantations (*Introduction: From Turning Land into Capital*), considering location flexibilities of concessions can mitigate some adverse social and ecological impacts. In fact, Lao land use policies (GoL 2005:11, National Assembly 2007, 2019) already focus their development efforts on unused or degraded land. However, despite Laos' low population density and myth of vast empty land, most land is used by people with "land-extensive lifestyles (shifting cultivation, cattle raising in pastures or forests, and the collection of forest products)" (Delang et al. 2013:151). Research has shown that not much land is available for investment without displacing current land users (Kenney-Lazar et al. 2018). Allocating land under use to concessionaires poses the risk that displaced land users either shorten fallow periods of remaining fallows and intensify land use with possibly land-degrading impacts (Ducourtieux and Castella 2006, Martin et al. 2018), or encroach on previously forested land (Zaehringer et al. 2018), both of which result in carbon emissions.

In terms of their climate impacts, agricultural and tree plantations will cause the least emissions if the area where they are granted has lower carbon densities than the subsequent plantation. For agricultural plantations, this means that, with the exception of permanent crops such as fruit trees, expansion of agricultural plantations will either cause emissions when areas under no or very extensive use are cleared, or affect land already cleared and under other use; e.g., for smallholder agriculture. By contrast, climate change-mitigating effects of tree plantations can be achieved if (a) the plantations are characterized by high carbon density, like eucalyptus plantations (Du et al. 2015), and (b) they are established in land with low or modest carbon stocks, such as actually degraded forest, grassland, or agricultural land; this, however, risks socioeconomic trade-offs (Kongsager et al. 2013, Liao et al. 2021). Free, prior, informed consent and inclusion of smallholder farmers from the earliest planning stages should be a prerequisite for any new concession contracts in order to potentially mitigate negative consequences for local communities (Lay et al. 2021).

CONCLUSION

The development of land concessions in Laos over the past 20 years caused carbon emissions and has long-term implications for local livelihoods. Striving for socially and ecologically just development, the Government of Laos will have to consider carefully which locations for and species of future plantations cause the least harm to local communities and carbon budgets. If mining concessions are granted, compensation measurements such as afforestation should be set in place to offset emissions that are induced by land use conversions into sites with no inherent capacity for carbon storage. When allocating land for the 600,000 ha of tree plantations in the course of Laos' green growth strategy, the Government of Laos should make every effort to prevent land use competition. If land use competition cannot be avoided, the Government of Laos should offer genuine consultation and acquire free, prior, and informed consent of all affected land users in order to potentially mitigate negative impacts of land acquisitions. If concessions are granted, communities should be provided sufficient compensation for lost land and resources. Not granting new concessions and shifting away from land-sparing approaches toward an acceptance of multifunctional landscapes are also options within the political maneuvering space that have potentially positive social and environmental outcomes.

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[1] The terms "concession" and "land acquisition" are used interchangeably in this article.

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Data Availability:

The data presented in this analysis are available at https://doi.org/10.5281/zenodo.5797965

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Appendix 1

Table A1.1 satellite images underlying the land cover dataset

Name	SPOT4 / 5 MS	RapidEye	RapidEye	Sentinel-2
Forest Type Map	2005	2010	2015	2019
Observation term	From Oct. 2004 to Apr. 2006	From Nov. 2010 to Mar. 2011	From Nov. 2014 to Feb. 2015	From Jan. 2019 to Mar. 2019
Number of scene	114	146	94	229
Spatial resolution	10m	5m	5m	10m
Bands	Band1: Green Band2: Red Band3: NIR Band4: SWIR	Band1: Blue Band2: Green Band3: Red Band4: Red edge Band5: NIR	Band1: Blue Band2: Green Band3: Red Band4: Red edge Band5: NIR	Band2: Blue Band3: Green Band5: Red Band8: NIR Band11: SWIR

We generate matrices which show land conversions in four time periods from 2001-05, 2006-10, 2011-15 and 2016-17. They contain 18-19 categories of former land use (also used in national forest inventories; aggregation of two categories in 2016-17, see Table A1.1), and 3 categories of subsequent concessions, namely tree plantations, agricultural plantations, and mining.

Table A1.2 Land cover and concessions categories

Land cover categories	Accuracy (DoF, 2020)	Concessions categories
Evergreen Forest	99.5%	**Tree plantations**
Mixed Deciduous Forest	93.6%	Rubber
Dry Dipterocarp Forest	81.3%	Eucalyptus
Coniferous Forest	100.0%	“Other” tree plantations
Mixed Coniferous and Broadleaved Forest	100.0%	
Forest Plantation	43.2%	

Bamboo	90.0%	**Agricultural plantations**
Regenerating Vegetation	63.7%	Cashew nuts
Savannah		Cassava
Scrub		Corn/Maize
Grassland		Sugarcane
Swamp		Cattle and buffalo
Upland Crop		Coffee
Rice Paddy		Jatropha
Other Agriculture		Mangoes
(Agricultural Plantations)		Oranges
Urban		"Other" agricultural plantations
Barren Land and Rock		
Other Land		**Mining**

We divide the categories "tree plantation" and "agricultural plantation" into sub-categories according to most common concessions set out in the inventory of land leases and concessions in Laos (Hett et al., 2020). We assume that land use under mining does not differ significantly between different mining products and therefore forego the subdivision of this category.

In order to produce said land-use change matrices we combined spatially explicit, nationwide data on concessions surveyed for the inventory of land leases and concessions in Laos (Hett et al., 2020) with national land cover data (DoF, 2015, 2010, 2005, 2000). This enables us to compare pre- and post-concession land uses: we compare concession-related land conversions in the respective time periods (2001-05, 2006-10, 2011-15, 2016-17) when the concessions have been approved with former land use at the same geographic location in the base years 2000, 2005, 2010 and 2015. 328 Land deals without known geographic location had to be excluded from analysis.

Figures A1.1-A1.4 display cumulated concession-related land conversions for the time periods 2001-2005 (Fig. A1.1), 2006-2010 (Fig. A1.2), 2011-2015 (Fig. A1.3), and 2016-2017 (Fig. A1.4).

Figure A1.1) Land conversions in 2001-2005

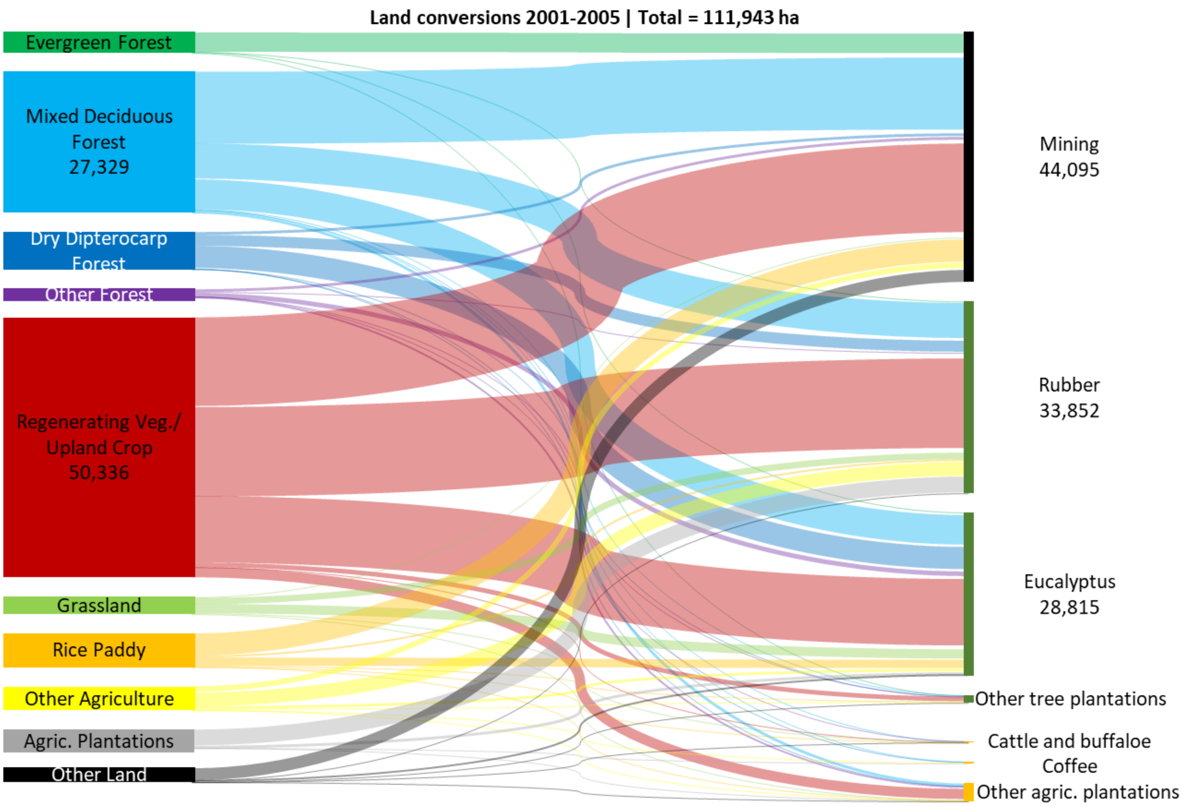


Figure A1.2) Land conversions in 2006-2010

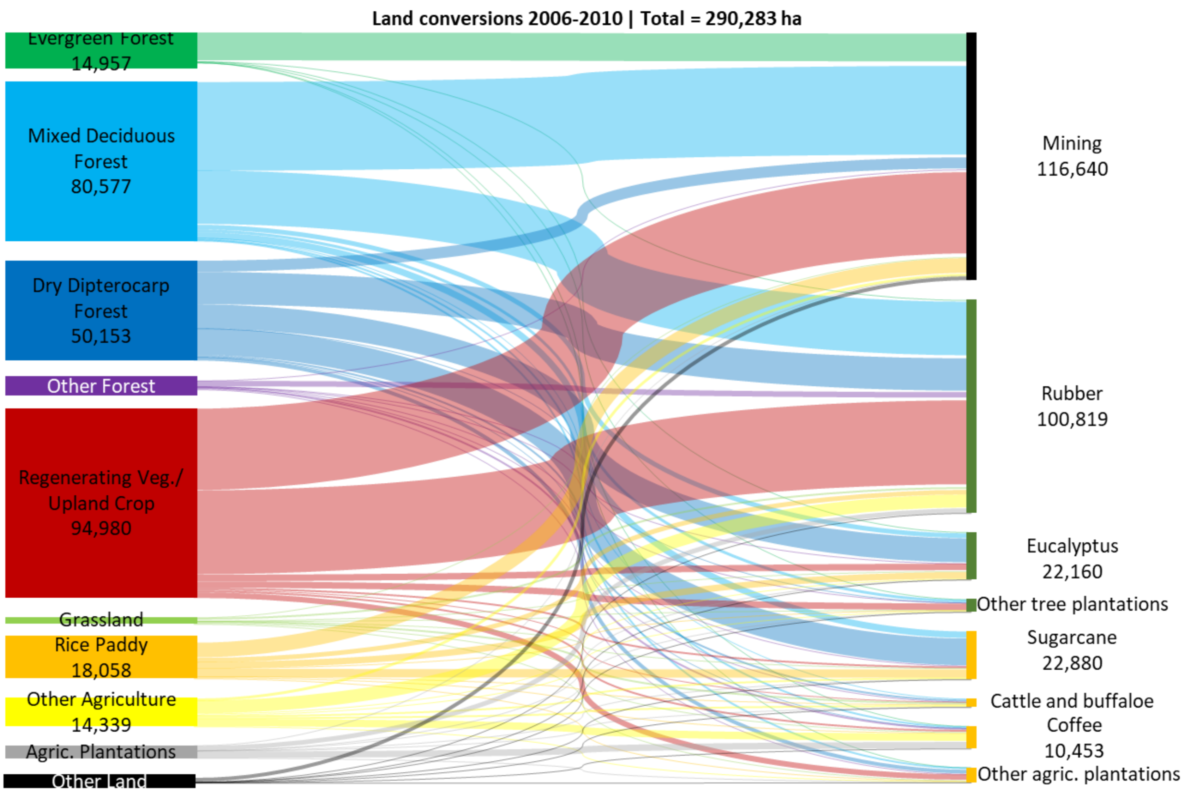


Figure A1.3) Land conversions in 2011-2015

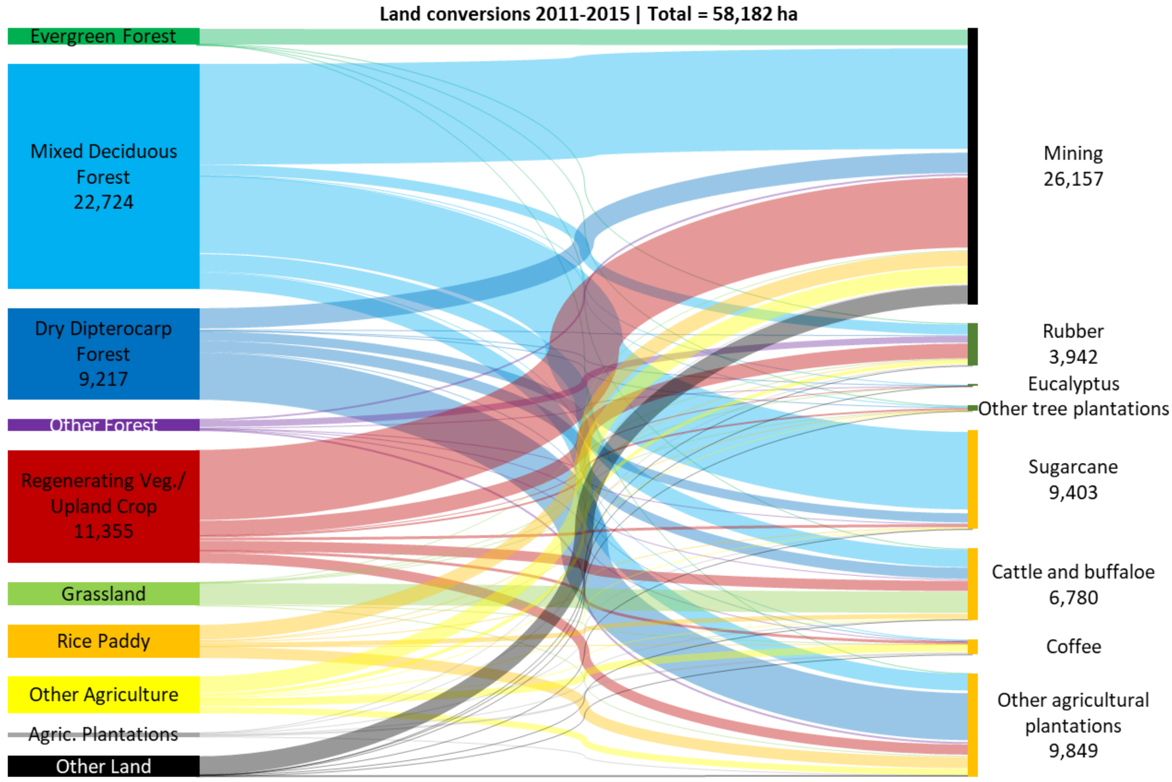
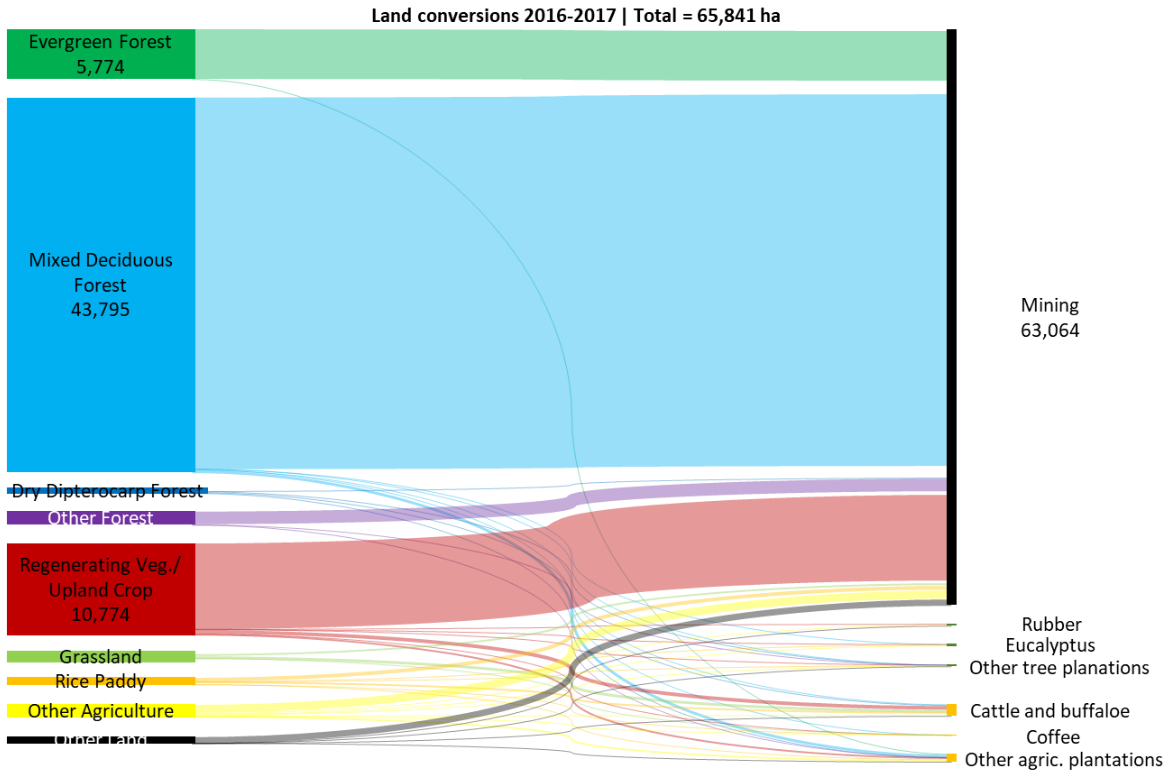


Figure A1.4) Land conversions in 2016-2017



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Appendix 2

Forests, grassland, agricultural land

C stock values for different forest, grassland and agricultural land categories are adopted from a range of national reports and IPCC guidelines, see Table A2.1 below.

Table A2.1: C stock values of forest, grassland, and agricultural land categories

	2001-2015		**2016-2017**	
Land-use category	**Mg C/ha**	**Source**	**Mg C/ha**	**Source**
Evergreen Forest	200.0	DoF and JICA, 2017	205.8	DoF, 2020
Mixed Deciduous Forest	87.7	DoF and JICA, 2017	87.9	DoF, 2020
Dry Dipterocarp Forest	43.2	DoF and JICA, 2017	50.8	DoF, 2020
Coniferous Forest	92.6	DoF and JICA, 2017	77.1	DoF, 2020
Mixed coniferous and broadleaved forest	114.7	DoF and JICA, 2017	87.6	DoF, 2020
Forest plantations	37.2	IPCC, 2003 (Annex 3A.1; table 3A.1.6)		
Bamboo	24.4	DoF, 2018 (Annex 2)		
Regenerating vegetation	17.4	DoF, 2018 (Annex 2)	10.4	DoF, 2020
Savannah	11.9	IPCC EFDB; ID 513130		
Scrub	30.0	IPCC, 2006 (Vol. 4, Chapter 4, table 4.7)		
Grassland	3.1	IPCC, 2003 (Chapter 3, table 3.4.2)		
Upland Crop	5.0	IPCC, 2003 (Chapter 3, table 3.3.8)		
Rice Paddy	5.0	IPCC, 2003 (Chapter 3, table 3.3.8)		
Other Agriculture	2.6	IPCC, 2003 (Chapter 3, table 3.3.4)		
Agricultural plantations	30.0	IPCC EFDB; ID 511318		

Tree and agricultural plantations

Table A2.2 lists all C stock values of different plantation types we derived from the literature.

Table A2.2: C stock values of different plantation categories

Land-use category	Mg C/ha	Source
Forest plantations		
Rubber	29.8	Bruun et al., 2018
Eucalyptus	50.0	Du et al., 2015
Other tree plantations	24.2	Hergoualc'h and Verchot, 2011
Agricultural plantations		
Cashew nuts	30.0	IPCC EFDB; ID: 511318
Cassava	4.7	IPCC, 2019 (Volume 4, Chapter 5, table 5.9)
Corn/Maize	4.7	IPCC, 2019 (Volume 4, Chapter 5, table 5.9)
Sugarcane	14.8	Bordonal et al., 2017
Cattle and buffalo (grassland)	3.1	IPCC, 2003 (Chapter 3, table 3.4.2)
Coffee (monoculture)	12.8	Hergoualc'h et al., 2012
Jatropha	7.0	Skutsch et al., 2011
Mangoes	76.3	Kongsager et al., 2013
Oranges	76.3	Kongsager et al., 2013
Other agricultural plantations	30.0	IPCC EFDB; ID 511318

We derive time-averaged C stock values (29.8 Mg C ha^{-1}) of **Rubber** plantations from Bruun et al. (2018) who analyzed C stock changes due to conversions of shifting cultivation systems into rubber plantations in Northern Laos. This sort of conversion is very common in Laos.

Whenever possible we use time-averaged C stock values[1]. However, when time-averaged values are unavailable, we choose C stock values that reflect the typical mean stand age of

[1] "The carbon storage potential of rotational land use systems like swidden agriculture and rubber plantations is not determined by the carbon stock at any point in time, but by the average amount of carbon stored in the system during its entire rotation – referred to as the time-averaged carbon stock" (Bruun et al., 2018, p. 240).

plantations (e.g. C stock of 4-year-old Eucalyptus plantation with a harvesting period of 7-8 years).

C stock values of **Eucalyptus** plantations vary most among the tree plantations values. We choose Du et al.'s C stock values for 4-5-year-old Eucalyptus plantations which is the mean stand age of Eucalyptus plantations in Laos (harvest at around 7 years (Zhou et al., 2017)).

For **Teak, Acacia, Agarwood** and "**other tree plantations**" we allocate time-averaged C stock values from Hergoualc'h and Verchot (2011).

Cassava and **corn** are common annual agricultural concession crops. Following IPCC guidelines, we adopt the default C stock value for annual cropland one year after conversion (IPCC, 2019; table 5.9).

Sugarcane as a perennial crop has a harvesting period of 3-4 years (National Agriculture and Forestry Research Institute, 2003). In order to achieve average C stock values for this 3-4 period we multiplied annual C inputs of 7.4 Mg ha^{-1} with 2 (years mean plantation duration) (Bordonal et al., 2017).

"**Cattle and buffaloes**" as concession category translates into grazing area or grassland after conversion. We therefore use default IPCC estimates for biomass in grassland and multiply it with 0.5 to obtain its C content (IPCC, 2003, table 3.4.2).

Coffee plants are typically pruned after 7 years in order to prevent declining yields (Winston and FAO Regional Office for Asia and the Pacific, 2005). We assume that aboveground biomass remains more or less constant from then on with regular pruning. Therefore, we use Hergoualc'h et al.'s C stock values of 7-year-old monoculture coffee plantations (Hergoualc'h et al., 2012).

Jatropha is a perennial crop for which we use C stock values from Skutsch et al. (2011) for plantations with 10 years stand age.

C stock values for **Orange** plantations are derived from Kongsager et al. (2013) for aboveground biomass in plantations with 25 years stand age. We assume the same values for **Mango** plantations.

For all **other agricultural plantations** (such as cashew nut trees) we allocate default IPCC estimates for biomass in plantations and multiply them with 0.5 to obtain C stock values of 30.0 Mg C ha^{-1} (IPCC EFDB; ID: 511318).

Mining

Ecosystem C stocks in the typically surface mining sites in Laos are assumed to equal zero (Delang et al., 2013). There might be regenerating vegetation in abandoned mining sites; abandoned mining concessions are, however, marginal in spatial extent and therefore not additionally considered. An overestimation of emissions due to overlooked conversions of mining sites into regenerating vegetation is therefore possible, although probably also marginal.

Limitations

We focus on the C pool in aboveground and belowground biomass. We do not consider C in soils due to limited data availability and reliability on a national scale.

C stock differences

We multiply stock-difference values of land conversions (e.g. conversion of evergreen forest into cassava plantations equal an ecosystem C stock difference of 195 Mg C ha^{-1}) with respective land conversion matrices and achieve C stock difference matrices. We divide the results by 5 (or 2 in case of the last period between 2016-17, the last year investigated in the concession inventory) to achieve annual values, and multiply them with 44/12 to convert the values into Mg CO_2e yr^{-1}. Positive values indicate C emissions, negative values indicate C sinks due to the respective land conversions.

Carbon emission intensity of land conversions (concessions and non-concessions)

We compare C emission intensity of land conversions into concessions (net emissions per ha total land per year) with C emission intensity of all other land conversions. Data base for the latter is Bauernschuster et al. (under review).

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Appendix 3

We conduct a sensitivity analysis to quantify the effect of data uncertainty on our major results. For that we use minimum and maximum C density values reported in the literature covering a range of young and old stand ages of the most crucial land use categories “regenerating vegetation”, “rubber” and “eucalyptus plantations”.

Land use category	Min. C density [Mg C / ha] (stand age)	Source	Max. C density [Mg C / ha] (stand age)	Source
Rubber	29 (time-averaged)	Yang et al. 2016	37.6 (time-averaged)	Guillaume et al. 2018
Eucalyptus	26.9 (4 yr.)	Zhou et al. 2017	95.6 (13 yrs.)	Zhou et al. 2017
Regenerating Vegetation	3 (< 5 yrs.)	Ziegler et al., 2012	138 (10-25+ yrs.)	Ziegler et al., 2012

Figure A3.1) Maximum emissions: Impact of the allocation of minimum values to the land-use categories rubber and eucalyptus, and maximum values to “regenerating vegetation” (RV), on C emissions/sinks of tree plantation development in comparison to the time-averaged values used for the main findings.

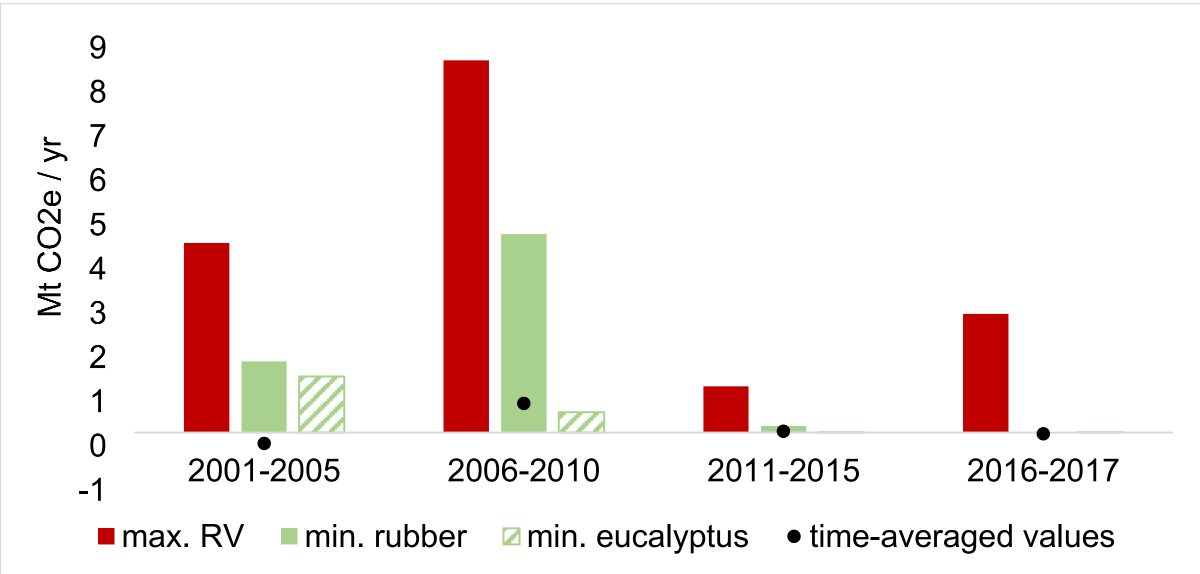


Figure A3.2) Maximum sink: Impact of the allocation of maximum values to the land-use categories rubber and eucalyptus, and minimum values to "regenerating vegetation" (RV), on C emissions/sinks of tree plantation development in comparison to the time-averaged values used for the main findings.

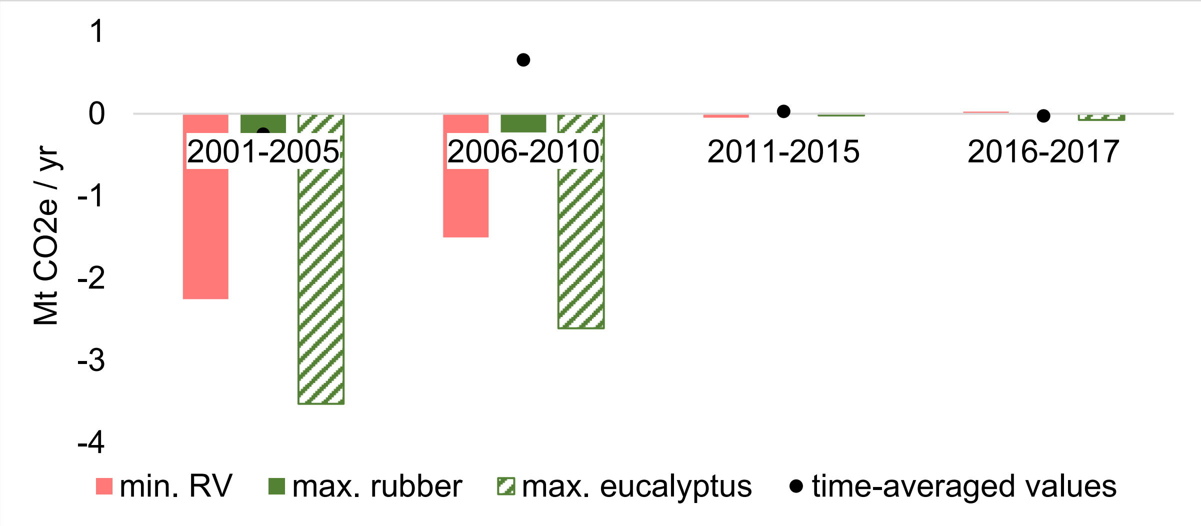
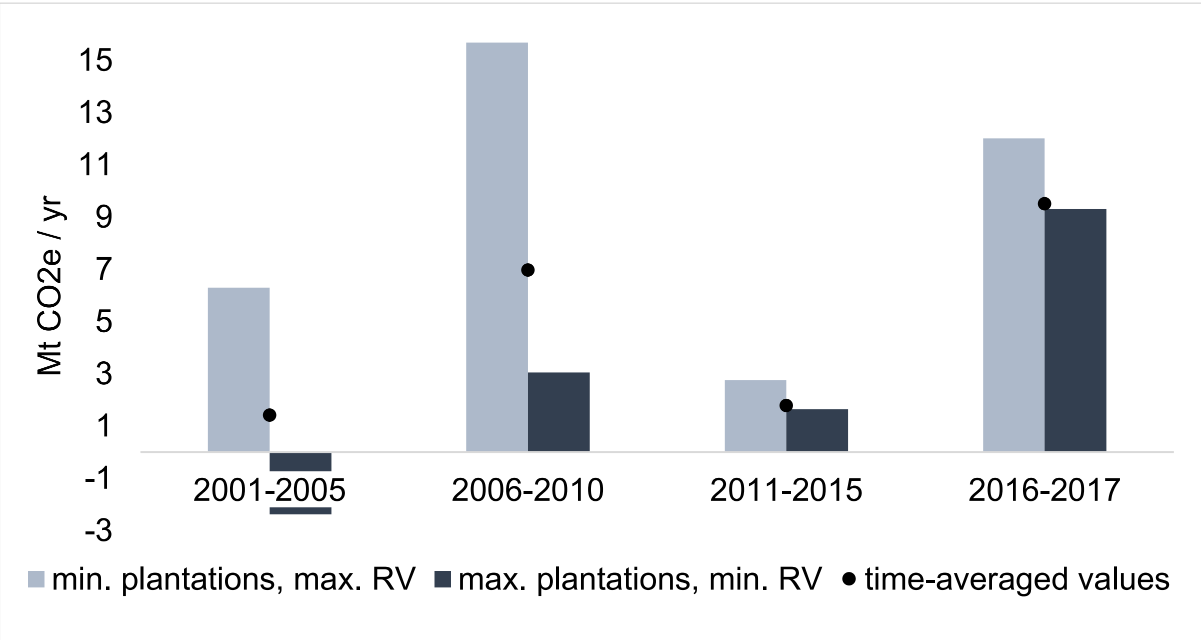


Figure A3.3) Net maximum-emissions and net maximum-sink scenarios: Impact of aggregated minimum and maximum values of the land-use categories "regenerating vegetation" (RV), rubber, and eucalyptus on C emissions/sinks of overall concession development (tree, agricultural and mining concessions) in comparison to the time-averaged values used for the main findings.



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