Environmental Research Letters

LETTER • OPEN ACCESS

# Direct and indirect land-use change caused by large-scale land acquisitions in Cambodia

To cite this article: Nicholas R Magliocca *et al* 2020 *Environ. Res. Lett.* **15** 024010

Environmental Research Letters

LETTER

OPEN ACCESS

RECEIVED
12 July 2019

REVISED
3 December 2019

ACCEPTED FOR PUBLICATION
18 December 2019

PUBLISHED
30 January 2020



# Direct and indirect land-use change caused by large-scale land acquisitions in Cambodia

Nicholas R Magliocca[1,5], Quy Van Khuc[2], Ariane de Bremond[3,4] and Evan A Ellicott[3]

[1] Department of Geography, University of Alabama, Tuscaloosa, Alabama, United States of America
[2] Faculty of Economics and Finance, PHENIKAA University, Hanoi 12116, Vietnam
[3] Department of Geographical Sciences, University of Maryland, College Park, Maryland, United States of America
[4] Centre for Development and Environment (CDE), University of Bern, Bern, Switzerland
[5] Author to whom any correspondence should be addressed.

E-mail: nrmagliocca@ua.edu

Keywords: deforestation, agricultural commodities, telecoupling, cascading effects, displacement effects

Supplementary material for this article is available online

## Abstract

Large-scale land acquisitions (LSLAs) have received considerable scholarly attention over the last decade, and progress has been made towards quantifying their direct impacts. There is also a growing recognition of the importance of indirect effects of LSLAs, such as 'spillover' or indirect land-use change (iLUC), and the substantial challenges they pose for attribution and quantification. In fact, the relative contributions of direct and indirect LUC associated with LSLAs are unknown. This study aims to address these knowledge gaps using Economic Land Concessions (ELCs) in Cambodia, now the most targeted country for LSLAs in Southeast Asia. We leverage findings on archetypical pathways of direct and indirect LUC in Cambodia, developed through previous mixed-methods synthesis efforts, to quantify remotely sensed forest loss to specific ELCs. During 2000–2016, Cambodia roughly 1611 kha of forest, or 22% of total forest cover. Although ELCs (as of 2016) contained roughly 16% of Cambodia's forest cover (2000), forest lost within ELC boundaries accounted for nearly 30% (476 kha) of total forest lost by 2016. Furthermore, iLUC contributed an additional 49–174 kha of forest loss (3.0%–10.7% of all forest lost in Cambodia) over the same period. Thus, iLUC contributed to Cambodia's total forest loss at the rate of 11.4%–40.8% of direct LUC caused by ELCs. Such findings suggest that the total amount of LUC caused by LSLAs may well be underestimated globally. This and related synthesis research efforts can be valuable approaches for better targeting remote sensing analyses to specific locations and time periods needed to disentangle and quantify forest loss due to direct and indirect land change processes.

## 1. Introduction

More than 49 Mha have been leased globally to transnational investors in tracts greater than 200 ha, known as large-scale land acquisitions (LSLAs), and another almost 20 Mha are pending [1, 2]. While LSLAs have become common practice within an increasingly globalized and teleconnected world system, LSLAs are unique among agricultural commodity production practices in their potential for rapid and large-scale deforestation [3] and displacement of local communities [4–8]. Due to a lack of transparency and geographic specificity in reported LSLAs, there are few quantitative estimates of the scope and magnitude of environmental impacts of LSLAs [3, 9–11], and these focus mainly on direct land-use changes (LUC) associated with LSLA implementation. Indirect land-use change (iLUC), a type of 'spillover' or 'leakage' effect, is a widely acknowledged consequence of large-scale agriculture operations [12] with environmental impacts potentially comparable to direct LUC, but the impacts of iLUC have been quantified in only a few isolated contexts [13, 14]. LSLAs are a global phenomenon and yet estimates of the magnitude of deforestation attributable to LSLA-caused iLUC are missing. Fully accounting for direct *and* indirect LUCs would broaden our understanding of the scope of social and environmental impacts associated with LSLAs.

Cambodia offers a potentially important example as it is the second-most targeted country for LSLAs globally [15]. While the term 'land acquisitions' is employed in the literature to refer to any type of land deal regardless of origin and type of investment, 'economic land concessions' (ELCs) such as those that occur in Cambodia specifically refer to a subset of LSLAs, wherein the state grants land, in either concession or lease form, to foreign and national investors in areas that are categorized as pertaining to the state [16, 17]. Since 2000, lands leased through ELCs encompass 2277 kha and contained roughly 16% of Cambodia's forest cover in 2000. The first assessment of forest loss associated with ELCs, conducted by Davis *et al* (2015), covered the period of 2000–2012, during which total forest loss within ELCs was an estimated 260 kha, and occurred at an annual loss rate 29%–105% higher than in comparable areas elsewhere in the country. Since that study, and following mounting domestic and international pressures, a moratorium of all new ELCs was declared in 2012, which required active production to begin or the concession would be revoked [18]. What followed was an abrupt increase in forest clearing after 2012 prompting many new and emerging land disputes that remain unresolved [19, 20]. Until now, forest loss due to iLUC, often associated with such land disputes around ELCs [19–21], has yet to be quantified.

This study has two main objectives. First, we assess forest loss due to direct LUC within ELC boundaries post-moratorium, updating the estimates presented by Davis *et al* [3]. Updating the quantity of forest loss in Cambodia is critical, as forest loss observed after 2012 was markedly higher than in preceding years due, in large part, to a policy-induced (rather than market-induced) response. Second, we quantify forest loss attributed to iLUC caused by ELCs across all of Cambodia from 2000 to 2016. In doing so, we quantify localized iLUC, which has to this point only been conducted through local case studies or for specific frontier regions worldwide (e.g. Brazil, Argentina).

iLUC occurs when land-use changes in one location displace previous land uses to another location [13, 22]. The occurrence and impacts of iLUC have received the most scholarly attention in the context of biofuel production [22–24]. Cultivation of biofuels often occurs within existing agricultural systems, displacing previous agricultural activities, and the greenhouse gas (GHG) emissions that result from the reestablishment of displaced agricultural activities elsewhere can negate any GHG mitigation that may have occurred through the use of biofuels. Quantifying the GHG emissions resulting from biofuel-induced iLUC is typically done through global-scale, equilibrium-based modeling approaches [23]. Outside of the biofuel context, quantification of iLUC at the sub-national scale has been rare. Applying spatial regression in the case of the Brazilian Amazon, Arima *et al* [13] estimated that a 10% reduction in land cultivated for soy would have avoided as much as 40% of indirect deforestation from displaced cattle pastures. While these approaches produce quantifiable estimates of iLUC, they do not explicitly address the causal mechanisms that link LUC in a specific time and place to iLUC elsewhere. Causal analysis of iLUC remains a conceptual and methodological challenge, because the mechanisms for reestablishment of displaced land uses are often unobservable. Novel approaches that integrate qualitative information about displacement processes are needed to connect distal LUCs in space and time.

Recent findings [21] suggest that ELCs in Cambodia produced iLUC that contributed substantially to total forest loss. The amount of direct LUC and likelihood of iLUC were quantified using a novel synthesis approach combining remote sensing, propensity score matching, survival analysis, and qualitative comparative analysis (QCA) of case studies. Causal relationships between iLUC and ELCs with specific characteristics were established by triangulating the findings from each analysis. Survival analysis demonstrated statistically significantly faster rates of forest loss within the boundaries of ELCs (i.e. direct LUC) producing rubber. Propensity score matching results demonstrated that, in comparison with paired control communes, forest loss outside of ELCs (i.e. iLUC) was 25.9% higher in communes containing ELCs producing rubber, experiencing direct LUC within 3 years of establishment, and in provinces with more than 20% of land area in ELCs. QCA showed that iLUC was associated with conditions of conflict, displacement, and dispossession stemming from rapid direct LUC, most often coinciding with rubber production. The counterfactual was also observed in which slower direct LUC, associated with different crops (e.g. cassava, oil palm), was less likely to lead to iLUC. Importantly, the localized case studies used in the QCA provided direct observations of the causal mechanisms of LUC, which then informed the statistical and remote sensing analyses to extend those causal mechanisms to all ELCs based on their observable characteristics and LUC outcomes.

This mixed-methods, triangulation approach resulted in the systematic identification of archetypical pathways of ELCs that did and did *not* lead to iLUC [21]. Archetype analysis is a comparative approach that seeks to identify a set of recurring, theoretically-grounded 'building-blocks' of factors and/or processes that can be combined in various ways to simply describe or infer causal mechanisms from a population of cases [25]. Twelve distinct archetypical pathways—five leading to iLUC and seven leading to negligible iLUC—described 210 ELCs across Cambodia (figure 1).

Archetypical pathways that did not lead to iLUC included local resistance preventing ELC production, ELC revocation by the Cambodian government, speculative production ELCs exhibiting little to no direct LUC, or ELCs that went into full or partial

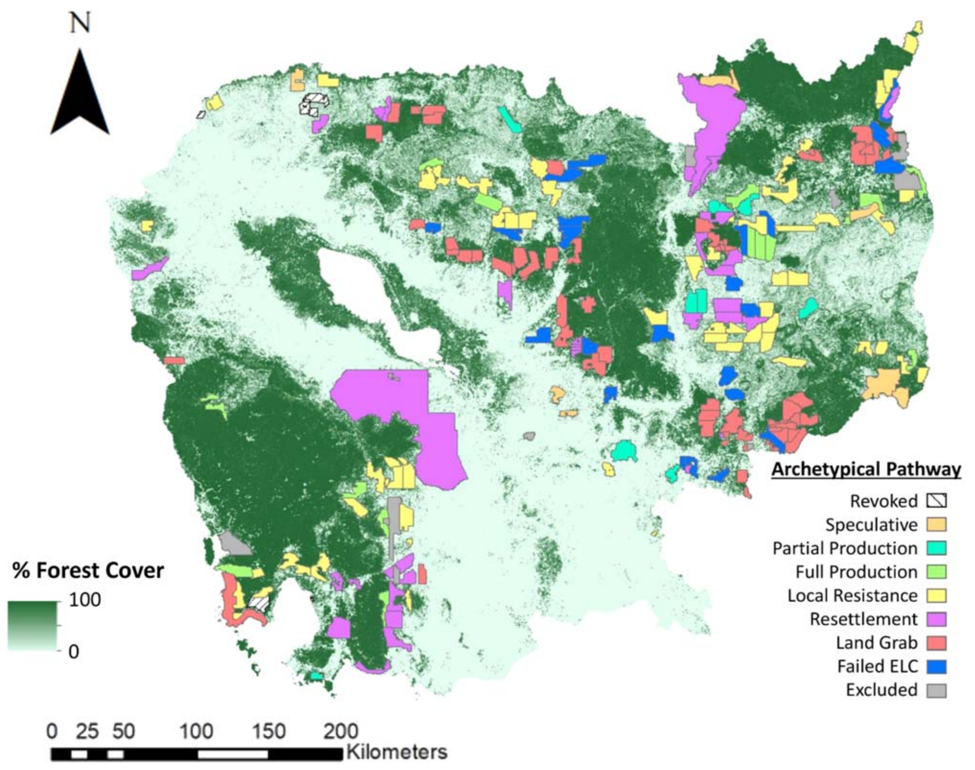


**Figure 1.** Map of ELC archetypes. Archetypical pathways leading to iLUC include resettlement (purple), land grab (red), and failed ELC (blue). The background layer represents % forest cover in the 2000.

production [21] (figure 1). Generally, the lack of significant conflict in these cases, either through no or relatively slow ELC implementation, avoided iLUC adjacent to ELC boundaries. Archetypical pathways associated with iLUC included land grabs with and without physical displacement of local communities, resettlement of displaced communities, and failed ELCs [21] (figure 1). Land grab pathways often involved political-economic means of dispossession of communal land, exploitation of informal or incomplete land titling of marginalized communities, and/or a lack of transparency in the concession-granting process. In these cases, iLUC often resulted immediately adjacent to ELC boundaries in an effort by smallholders to halt further expansion of large-scale agriculture by establishing land ownership claims to resist displacement, or by the establishment of farms by in-migrants employed by the concessionaires [26]. The resettlement pathway was characterized by forced or negotiated resettlement of communities dispossessed and displaced by an ELC, often to less productive land, which resulted in forest clearing and establishment of new cultivated plots in the nearby resettled areas. Finally, in a small number of cases (e.g. [27]), smallholders alerted to the granting of an ELC preemptively cleared and occupied land within and around the planned ELC boundaries and prevented it from going into production. ELCs categorized as one of these three archetypical pathways were used to estimate forest loss due to ELC-induced iLUC.

## 2. Methods

Economic land concession data was obtained from Open Development Cambodia (ODC) [28], a non-governmental organization that provides freely available geospatial data about Cambodia's economic, social, and environmental change. ODC currently contains 210 ELCs with polygon features representing the spatial location of a deal (figure 1). ELCs from ODC were cross-validated with the Land Matrix database [29] to insure there were no gaps; however, since the Land Matrix often pulls its information from ODC, we did not expect, nor found, any discrepancies. Forest loss was estimated within and outside of ELC boundaries between 2000 and 2016 using the updated Global Forest Change product [26]. Based on previous findings [3, 21], we assumed that forest cover loss associated with tree plantations established prior to 2000 would have a negligible effect on our national-level estimates and were therefore not distinguished from native forest cover in our analysis (see supplementary information is available online at stacks.iop.org/ERL/15/024010/mmedia). Total forest loss estimates were made from the full set of ELCs occurring after 2000 (210 ELCs). A 500 m buffer was added around the boundaries of all ELCs to capture direct LUC associated with ELC implementation that exceeded the predefined concession boundaries (figure S1). Forest loss was considered in three imposed geographic zones (figure 2): within ELC

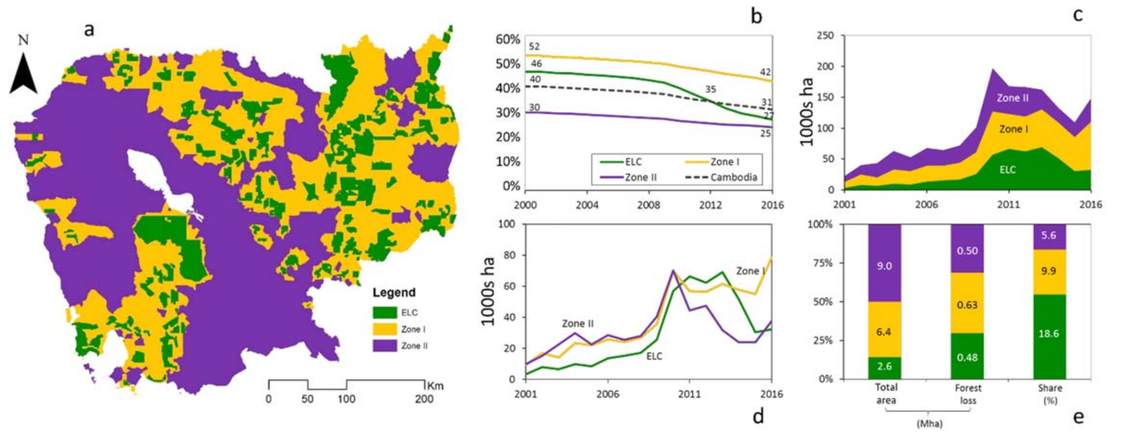


**Figure 2.** Overall extent, share, and annual rate of forest loss within a 500 m buffer of ELC boundaries, communes containing ELCs (Zone I), and all other communes without ELCs (Zone II). The map (a) shows the spatial framework for forest loss estimation. Dynamics of percent forest cover for each area of interest are shown in (b). Total and disaggregated annual areas of forest loss are shown in (c) and (d), respectively, and (e) compares the shares of total area and forest loss of each area of interest.

boundaries (i.e. direct LUC) including a 500 m buffer[6], Zone I (communes that contain an ELC), and Zone II (all other communes that do not contain an ELC). In situations where buffers of adjacent ELCs overlapped, potential double-counting of forest loss was avoided by merging all ELC buffer boundaries present in a given year into a single area for national analysis (see supplementary information). With the addition of the 500 m buffers, the area analyzed for ELC-caused forest loss via direct LUC expanded to from 2277 to 2561 kha.

We estimated forest loss resulting from direct and indirect LUC based on observed forest change within varying spatial and temporal proximities of ELCs. Direct and indirect LUC may or may not have ensued soon after the establishment of an ELC, and variations in this dynamic were of particular interest. We defined two alternative reference points in time from which to begin tabulating direct and indirect forest loss. (1) The year in which an ELC was established, either by contract or government decree, was considered the 'establishment year'. (2) The first year total forest loss exceeded of 10% within the ELC buffer boundaries (i.e. direct LUC) was defined as the 'implementation year'. These two starting points were chosen because previous findings indicated that iLUC could be initiated by either event depending on the specific commodity crop, land acquisition process, timing and rate of direct LUC, and socio-economic impacts [21]. Estimates of direct LUC were made from both establishment and implementation dates for areas within the 500 m buffer around georeferenced ELC boundaries.

[6] The area of land put into production often extended beyond the official georeferenced ELC boundaries provided by Open Development Cambodia. A 500 m buffer was used around ELCs in our analyses to capture forest loss due to implementation of ELC production (i.e. direct land-use change). See figure S1 for examples and further explanation.

Estimates of iLUC were made from the subset ($n = 114$) of ELCs associated with the archetypical pathways [21] leading to iLUC: land grabs, resettlement, and failed ELCs. In addition to the causal mechanisms entailed in these archetypical pathways, membership in one of these three required total forest loss in adjacent communes above 7.5% after the ELC establishment or implementation date. A sensitivity analysis was conducted with 10%, 7.5%, 5%, and 3% threshold values. A value of 7.5% was chosen based on the methods detailed in [21] and corroborated with visual inspection of each ELC using Google Earth Pro.

While archetypical pathways indicated the presence of iLUC and important socio-economic processes involved, no spatially-explicit information was found about where and when iLUC was observed in proximity to ELCs. Qualitative evidence from case study narratives and general patterns of remotely sensed forest loss suggested that attribution of iLUC to a specific ELC became more tenuous as distance from the ELC boundary and time since the establishment or implementation of an ELC increased. Estimating iLUC forest loss therefore required a series of assumptions about the spatial and temporal extents under which iLUC could be reliably attributed to a given ELC. Upper and lower bound estimates for the spatial extent of ELC-caused iLUC accounted for all forest loss within the commune (i.e. administrative unit) surrounding an ELC or within a 2 km buffer of the ELC boundary, respectively. For each spatial frame, we accounted for all forest loss occurring 0 (i.e. same year) to 4 years after ELC establishment or implementation. Analogous to a difference-in-difference approach, time lags were calculated relative to each ELC's specific establishment or implementation year to facilitate an event-based estimation of forest loss across all ELCs associated with iLUC ($n = 114$).

Estimates of average and maximum annual iLUC forest loss for any given year were calculated for all

**Table 1.** Estimates of total and proportional forest loss during the period of 2000–2016.

| Area of interest (AOI) | Total forest area in 2000 (kha) | Total forest loss (kha) | % of Cambodia forest cover (2000) lost | % of AOI forest (2000) lost | % of Cambodia forest loss (2000–2016) |
|---|---|---|---|---|---|
| ELC + 500 m buffer | 1177 (16.3%) | 476.4 | 6.5 | 39.8 | 29.8 |
| Zone I | 3343 (46.2%) | 633.2 | 8.7 | 18.9 | 39.1 |
| Zone II | 2717 (37.5%) | 501.7 | 6.9 | 18.5 | 31.1 |
| Cambodia | 7226 (100%) | 1611 | 22.1 | — | — |

**Table 2.** Estimates of forest loss due to indirect land-use change (iLUC) attributable to ELCs within two different spatial footprints and over five alternative time lags since any given ELC's establishment and implementation years. Area statistics were calculated from the aggregation of all ELCs over the specified time lag.

| | | iLUC Forest loss within 2 km Buffer | | | iLUC Forest loss within commune | | |
|---|---|---|---|---|---|---|---|
| Time lag | | Avg. annual total (kha $yr^{-1}$) | Max. annual total (kha $yr^{-1}$) | Total (kha) | Avg. annual total (kha $yr^{-1}$) | Max. annual total (kha $yr^{-1}$) | Total (k ha) |
| Since Estblsh. Year | 0 | 1.87 | 7.79 | 22.42 | 5.61 | 25.04 | 67.38 |
| | 1 | 2.98 | 10.63 | 35.76 | 9.06 | 29.50 | 108.70 |
| | 2 | 4.06 | 11.25 | 48.71 | 13.05 | 32.66 | 156.54 |
| | 3 | 5.16 | 11.56 | 61.96 | 17.28 | 35.81 | 207.31 |
| | 4 | 6.05 | 12.60 | 72.65 | 21.23 | 39.57 | 254.79 |
| Since Implmnt. Year | 0 | 2.26 | 10.95 | 29.38 | 6.61 | 27.04 | 85.95 |
| | 1 | 3.43 | 11.57 | 44.57 | 10.10 | 31.16 | 131.26 |
| | 2 | 4.49 | 12.86 | 58.39 | 13.39 | 37.30 | 174.01 |
| | 3 | 5.41 | 12.97 | 64.96 | 17.20 | 37.38 | 206.46 |
| | 4 | 6.28 | 13.85 | 69.09 | 21.03 | 41.18 | 231.30 |

'eligible' ELCs. For an ELC to be 'eligible' in a given year, it must have been categorized as one of the ELCs associated with iLUC, and its establishment/implementation date was within a specified time lag of the year of estimation. For example, a calculation of average annual total iLUC for the year 2012, based on establishment year and with a time lag of 2 years, could have included iLUC forest loss associated with ELCs established in 2010, 2011, or 2012. Area-based estimates of iLUC for 2012 were then calculated by aggregating *only forest loss that occurred in* 2012 within the given spatial boundaries of the 'eligible' ELCs, producing an annual total estimate. Average and maximum annual total forest loss were then calculated across years from 2000 to 2016 by modifying the set of 'eligible' ELCs each based on the analytical frame and their individual timing. Due to uncertainty in attribution of iLUC to a particular ELC event, it was necessary to account for iLUC in this way in order to estimate total iLUC occurring in each year. The overall total forest loss was a cumulative measure of iLUC associated with eligible ELCs from 2000 to 2016.

## 3. Results

### 3.1. Total forest loss and direct LUC

During the span of 2000–2016, Cambodia lost approximately 1611 kha of forest, or 21.5% of total forest cover (table 1). Zone II (figure 2)—where LUC was presumably unrelated to ELCs—contained 2717 kha (37.5%) of Cambodia's initial forest cover (2000), and lost 501.7 kha from 2000 to 2016 or equivalent to 31.1% of total forest loss in Cambodia during the study period. Zone I areas contained 3343 kha (46.2%) of Cambodia's forest in 2000, and lost 633.2 kha during the study period accounting for 39.1% of all forest lost. In contrast, ELCs lost 476.4 kha, or 29.8% of total forest loss in Cambodia, while only containing 1177 kha (16.3%) of forest cover in 2000. Furthermore, forest loss in ELC and Zone I areas intensified during the time span of 2013–2016 (table S1–S3). Average annual forest loss rates in Zone II decreased from 0.4% during 2000–2012 to 0.3% during 2013–2016. During the same periods, average annual forest loss rates in ELC and Zone I areas increased from 1.0% and 0.5% during 2000–2012 to 1.8% and 1.0% during 2013–2016, respectively. The rapid increase in forest loss due to direct LUC in ELCs has been attributed to the Cambodian government's Order 01 in May 2012, which issued a moratorium on new ELCs and required that active production begin or the concession would be revoked [18]. The contemporaneous increase in forest loss within communes containing ELCs (i.e. Zone I) has not been quantified until this point.

Table 2 displays estimates of forest loss attributable to ELC-caused iLUC for all combinations of spatial and temporal assumptions. The most conservative estimate of iLUC forest loss was 22.4 kha during the year of ELC establishment or 29.4 kha during the year

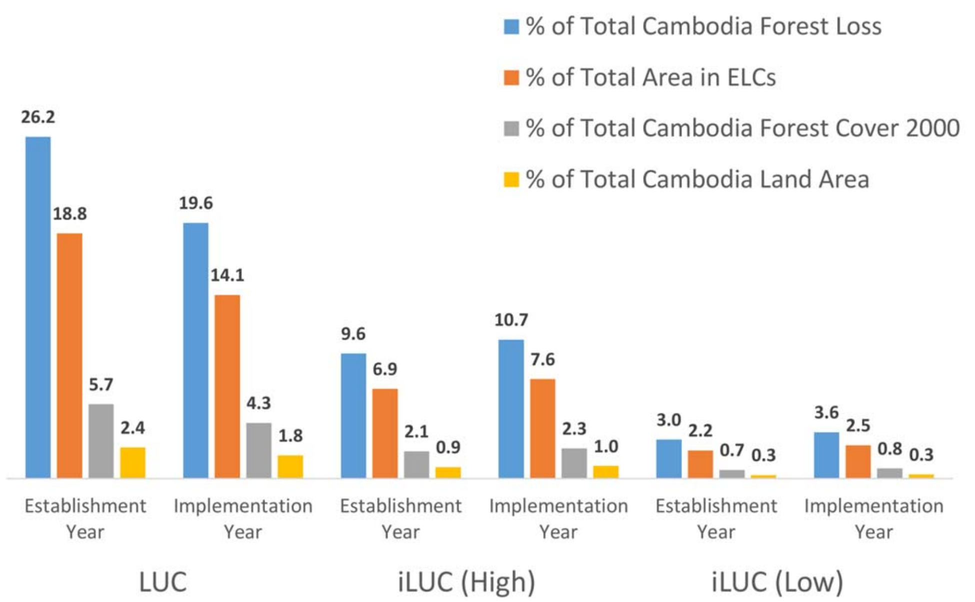


**Figure 3.** Comparison of direct and indirect land-use change (LUC) using a 2 year time lag from the year of ELC establishment or implementation and varying spatial assumptions. Establishment year is the year in which the ELC deal occurred, and implementation year is the year in which production within the ELC boundary was initiated. High and low estimates of indirect LUC are associated with forest loss estimates within the commune containing the ELC (i.e. Zone I) and within a 2 km buffer around the ELC, respectively.

of ELC implementation. Expanding the spatial extent of analysis from the 2 km buffer to the commune, but without time lags, estimates increased to 67.4 or 86.0 kha for the year of establishment or implementation, respectively. Extending the time lag to 4 years increased forest loss estimates within 2 km buffers to roughly 72.3 and 69.1 kha for ELC establishment or implementation estimates, respectively, and were comparable to the upper bound spatial estimates (commune-level) with no time lag. However, extending both the spatial and temporal extents of the analysis yielded forest loss estimates of 255 and 231 kha since ELC establishment or implementation, respectively, more than a 3 fold increase. Overall, estimates of iLUC forest loss were most sensitive to the spatial extent of the analysis.

Since the time of ELC establishment (i.e. *not* total forest loss from 2000 to 2016), approximately 428 kha (26.2%) of forest loss occurred attributable to direct LUC within the ELC areas, which represented a loss of 18.8% of forest area within ELCs and 5.7% of all forested area in Cambodia. (figure 3). In comparison, the contribution of iLUC to Cambodia's total forest loss ranged from 3.0% to 10.7%. This was equivalent to roughly 49–174 kha of forest loss. Regardless of the spatial or temporal assumptions, iLUC was a non-trivial contribution to Cambodia's overall forest loss.

## 4. Discussion

The causal mechanisms that link direct LUC to iLUC elsewhere are often unobservable because of their separation in time and space. This article built on previous work [21] that used a variety of methods attending to different aspects of ELCs: global commodity market signals, spatial patterns of LUC, timing of ELC establishment and implementation, and localized processes of land acquisition and LUC. A mixed methods triangulation approach [30, 31] used qualitative findings from one analysis to structure quantitative data for another and vice versa, such that inferences with one method would not be possible without inferences made by another. The result was the construction of archetypical pathways of ELCs leading to iLUC, which established the causality needed in the present work to quantify iLUC attributed to the location and timing of specific ELCs. This work explored varying spatial and temporal analytical frames to quantify localized iLUC, which has to this point only been conducted through local case studies or for specific frontier regions worldwide. We found iLUC contributed to Cambodia's total forest loss at the rate of 11.4%–40.8% of direct LUC caused by ELCs.

Several assumptions were necessary to conduct this analysis. First, we assumed that LUC observed within the boundaries of ELCs were causally related to their establishment and/or implementation. Alternative causes of LUC were possible, but we justified attributing forest loss within ELC boundaries to ELCs for two reasons. Using covariate matching, Davis *et al* [3] demonstrated that ELCs increased rates of forest loss relative to comparable areas from 2000 to 2012. It is unlikely that ELCs would not remain the leading cause of LUC within their boundaries from 2013 to 2016, particularly with the documented response by ELC operators to the 2012 moratorium resulting in increased rates and scales of forest loss. In addition, our previous work [21] relied on localized case studies that reported direct observations of the land acquisition and direct and indirect LUC processes. Those observations ranged from reports of direct forest clearing by the ELC operating companies, e.g. [27], to community members alerted to ELC establishment and rapidly clearing the forest within the ELC boundaries in an attempt to establish land claims, e.g. [32]. ELCs were also observed via remote sensing with no or only partial LUC, suggesting that important variations in the production dynamics of ELCs were observed.

Second, assumptions about the appropriate spatial and temporal extents over which forest loss could be reasonably attributed to ELC-caused iLUC were necessary. No theory exists to inform inference about where and when cascading socio-economic impacts of any given ELC might manifest as iLUC. Previous efforts have noted that attribution of iLUC becomes more uncertain as distance from and time since the initiating cause increases due to the increasing likelihood of intervening factors [13, 33]. Indeed, we observed forest loss adjacent to ELC boundaries continued to increase as we expanded the spatial and temporal extents of the analysis (table 2). While these trends could be artefacts of our chosen analytical framing, the qualitative, process-based insights gleaned from the synthesis of local case studies (i.e. used to develop the archetypical pathways) implicated specific mechanisms—namely resettlement, displacement, and/or land dispossession of local communities—leading to iLUC. Displaced local communities often cleared land at the fringes of the ELC boundary to compensate for lost access to land resources, halt further expansion by ELC companies, and/or establish actively cultivated land as a means to pursue formal land titling [27, 34, 35]. Alternatively, previously landless migrants became the agents of forest loss. Cultivated plots were also established at the fringes of ELCs by those employed by the production company, and/or speculative land clearing occurred within the same commune in anticipation of future ELCs leading to compensation, land titling, or employment [34, 36, 37]. For ELCs classified in one of the three archetypes leading to iLUC, forest loss in adjacent areas was visually inspected using Google Earth Pro time series imagery to verify correct assignment of the ELC to an archetype associated with iLUC. A full description of this process is available in [21].

In addition, we followed the approach of Arima *et al* [13] and derived estimates of iLUC under varying spatial and temporal assumptions for attributing forest loss to specific ELCs.Generally, forest loss associated with iLUC was higher when measured from implementation rather than establishment year. This was expected because ELC implementation involved active land conversion, which was often associated with displacement of local populations. However, for a time lag of 3 years or more, the pattern was reversed, with total forest loss roughly equal to, or greater for, time since establishment than implementation. This reversal, we argue, is a plausible indicator of the appropriate temporal scale at which to study iLUC in this context. Many of the ELCs linked to iLUC were associated with rapid direct LUC (i.e. implementation within 3 years or less of establishment), which means that accounting from the establishment year captured rapid (e.g. land clearing by local communities to deter ELC establishment or implementation [38]) *and* gradual processes of iLUC (e.g. resettlement [18] or land clearing by ELC workers [35, 38]). Accounting from implementation year likely omitted processes of iLUC responding to ELC establishment, and therefore the trend reversal may be signaling the diminished indirect effects of a given ELC over time. Based on these logical inferences, all estimates of ELC-caused indirect LUCs were reported in figure 3 using a 2 year time lag.

LSLAs have received considerable scholarly attention over the last decade (e.g. [5, 39, 40]), and progress has been made towards quantifying their direct impacts (e.g. [3, 4, 10]). These is also a growing recognition of the importance of indirect effects of LSLAs, particularly iLUC, and the substantial challenges they pose for attribution and quantification [41, 42]. This study is the first to quantify and compare direct and indirect LUC caused by LSLAs at the country scale. The integration of archetype and remote sensing analyses makes a key methodological advance in efforts to understand LUCs associated with the land acquisition and production dynamics of LSLAs. However, causally linking direct and indirect LUC depends on pinpointing the location and timing of initiating causes relative to their responses. The data necessary to accomplish this is typically not available or highly heterogeneous across LSLA settings. The primary constraint on scaling this approach to other contexts is the lack of georeferenced information on LSLA locations and/or timing of LSLA establishment [40, 43]. When such data is available, the analysis of direct and indirect LUC caused by LSLAs would need to be tailored to the land system context. For example, attributing the timing and location of iLUC to LSLAs is likely easier in forested land systems, where the direct and indirect LUCs are visible via remote sensing as distinct patches of forest loss. In contrast, LUC due to LSLAs in semi-arid land systems, such as Sudan [44], or established agricultural frontiers, such the Dry Chaco of Argentina [45], may be difficult to detect precisely, and requires rigorous sensitivity testing of LSLA implementation thresholds. Finally, the ability to causally link iLUC to LSLAs depends critically on the quality and availability of in-depth, localized case study information about the land acquisition process experienced on the ground (e.g. conflict, contestation), land tenure arrangements, and impacts to local communities and their livelihoods (e.g. displacement). Applying this approach to data limited contexts will likely require non-traditional data sources (e.g. grey literature, investigative journalism, social media) to be feasible.

## 5. Conclusion

Our findings pose a larger hypothesis for LSLA research that needs to be tested beyond Cambodia: namely, the total amount of LUC attributable to LSLAs is globally underestimated. Our results demonstrate that land-use impacts from LSLAs can extend far beyond deal boundaries in space, time, and magnitude. The prevalence of iLUC in connection with LSLAs not only challenges LUC research, but has implications for policies seeking to mitigate the negative environmental effects of LSLAs. The transformative potential of LSLAs extends beyond their formal boundaries, and can catalyze rural social and economic changes, such as smallholder immigration, speculative land grabbing, and/or disrupted land tenure arrangements [35, 38], that result in substantial direct and indirect LUC. This calls into question the effectiveness of reactive policy interventions, such as the Cambodian government's Directive 01 in 2012, which in some cases had the unintended effect of encouraging rapid land clearing in and near ELCs [20]. Policies designed to mitigate the environment impacts of LSLA's must anticipate the potential for iLUC at both national and international scales. More broadly, the iLUC potential of LSLAs must be taken into account in assessments of their impacts globally.

## Acknowledgments

The authors acknowledge support from NASA ROSES Land Cover Land Use Change project LCLUC project Award #NNX17AI15G. This study contributes to the Global Land Programme (https://glp.earth).

## Data availability statement

Any data that support the findings of this study are included within the article.

## ORCID iDs

Nicholas R Magliocca https://orcid.org/0000-0002-0971-0207
Quy Van Khuc https://orcid.org/0000-0001-9516-2413

## References

[1] Anseeuw W, Lay J, Messerli P, Giger M and Taylor M 2013 Creating a public tool to assess and promote transparency in global land deals: the experience of the Land Matrix *J. Peasant Stud.* **40** 521–30
[2] Land Matrix Global Observatory 2018 (ILC) International Land Coalition, C. Centre de Coopération Internationale en Recherche Agronomique pour le Développement, (CDE) Centre for Development and Environment, (GIGA) German Institute of Global and Area Studies, and (GIZ) Deutsche Gesellschaft für Internationale Zusammenarbeit, "The Land Matrix Global Observatory." (Accessed: 05 August 2018) (http://landmatrix.org/en/)
[3] Davis K F, Yu K, Rulli M C, Pichdara L and D'Odorico P 2015 Accelerated deforestation driven by large-scale land acquisitions in Cambodia *Nat. Geosci.* **8** 772–5
[4] Carter S, Manceur A M, Seppelt R, Hermans-Neumann K, Herold M and Verchot L 2017 Large scale land acquisitions and REDD+: a synthesis of conflicts and opportunities *Environ. Res. Lett.* **12** 035010
[5] Oberlack C, Tejada L, Messerli P, Rist S and Giger M 2016 Sustainable livelihoods in the global land rush? Archetypes of livelihood vulnerability and sustainability potentials *Glob. Environ. Change* **41** 153–71
[6] Dell'Angelo J, D'Odorico P, Rulli M C and Marchand P 2017 The tragedy of the grabbed commons: coercion and dispossession in the global land rush *World Dev.* **92** 1–12
[7] Baird I G 2017 Resistance and contingent contestations to large-scale land concessions in Southern Laos and Northeastern Cambodia *Land* **6** 16
[8] Borras S M, Kay C, Gómez S and Wilkinson J 2012 Land grabbing and global capitalist accumulation: key features in Latin America *Can. J. Dev. Stud. Can. Dév.* **33** 402–16
[9] Balehegn M 2015 Unintended consequences: the ecological repercussions of Land Grabbing in Sub-Saharan Africa *Environ. Sci. Policy Sustain. Dev.* **57** 4–21
[10] Breu T, Bader C, Messerli P, Heinimann A, Rist S and Eckert S 2016 Large-scale land acquisition and its effects on the water balance in investor and host countries *PLoS One* **11** e0150901
[11] Nolte C, Gobbi B, le Polain de Waroux Y, Piquer-Rodrïguez M, Butsic V and Lambin E F 2017 Decentralized land use zoning reduces large-scale deforestation in a major agricultural frontier *Ecol. Econ.* **136** 30–40
[12] Lambin E F and Meyfroidt P 2011 Global land use change, economic globalization, and the looming land scarcity *Proc. Natl Acad. Sci. USA* **108** 3465–72
[13] Arima E Y, Richards P, Walker R and Caldas M M 2011 Statistical confirmation of indirect land use change in the Brazilian Amazon *Environ. Res. Lett.* **6** 024010
[14] Deininger K and Xia F 2016 Quantifying spillover effects from large land-based investment: the case of Mozambique *World Dev.* **87** 227–41
[15] Land Matrix Global Observatory 2018 'Land Matrix.' (https://landmatrix.org/en/) (Accessed: 03 August 2018)
[16] Schönweger O, Heinimann A, Epprecht M, Lu J, Thalongsengchanh P and Bernensia G 2012 Concessions and leases in the Lao PDR: taking stock of land investments *Center for Development and Environment (CDE)* (Bern and Vientiane: University of Bern) (https://data.opendevelopmentmekong.net/library_record/concessions-and-leases-in-the-lao-pdr-taking-stock-of-land-investments)
[17] Gironde C and Portilla G S 2016 From lagging behind to losing ground: Cambodian and Laotian household economy and large-scale land acquisitions *Large-Scale Land Acquisitions: Focus on South-East Asia* 6 (Leiden and Boston: Brill Nijhoff) pp 172–204
[18] Oldenburg C and Neef A 2014 Reversing land grabs or aggravating tenure insecurity? Competing perspectives on economic land concessions and land titling in Cambodia *Law Dev. Rev.* **7** 49–77
[19] Milne S 2015 Cambodia's unofficial regime of extraction: illicit logging in the shadow of transnational governance and investment *Crit. Asian Stud.* **47** 200–28
[20] Dwyer M B 2015 The formalization fix? Land titling, land concessions and the politics of spatial transparency in Cambodia *J. Peasant Stud.* **42** 903–28
[21] Magliocca N, Van Khuc Q, de Bremond A and Ellicott E 2019 Archetypical pathways of direct and indirect land-use change caused by Cambodia's economic land concessions *Ecol. Soc.* **24** 25
[22] Searchinger T *et al* 2008 Use of US croplands for biofuels increases greenhouse gases through emissions from land-use change *Science* **319** 1238–40

[23] Khanna M and Crago C L 2012 Measuring indirect land use change with biofuels: implications for policy *Annu. Rev. Resour. Econ.* **4** 161–84

[24] Plevin R J, O'Hare M, Jones A D, Torn M S and Gibbs H K 2010 Greenhouse gas emissions from biofuels' indirect land use change are uncertain but may be much greater than previously estimated *Environ. Sci. Technol.* **44** 8015–21

[25] Oberlack C *et al* 2019 Archetype analysis in sustainability research: meanings, motivations, and evidence-based policy making *Ecol. Soc.* **24** 26

[26] Hansen M C *et al* 2013 High-resolution global maps of 21st-century forest cover change *Science* **342** 850–3

[27] Gironde C and Peeters A 2015 Land acquisitions in Northeastern Cambodia: space and time matters *LDPI Conf. in Chiang Mai University* pp 5–6

[28] (ODC) Open Development Cambodia 2018 'Open Development Cambodia (ODC).' (https://opendevelopmentcambodia.net/) (Accessed: 07 May 2018).

[29] Land Matrix Global Observatory 2018 'Get the Detail.' (https://landmatrix.org/en/get-the-detail/). (Accessed: 20 December 2018).

[30] Morse J M 1991 Approaches to qualitative-quantitative methodological triangulation *Nurs. Res.* **40** 120–3

[31] Mertens D M and Hesse-Biber S 2012 Triangulation and mixed methods research *J. Mix. Methods Res.* **6** 75–9

[32] Schoenberger L 2017 Struggling against excuses: winning back land in Cambodia *J. Peasant Stud.* **44** 933–53

[33] Babcock B A 2009 Measuring unmeasurable land-use changes from biofuels *Iowa Ag Rev.* **15** 4–6

[34] Lamb V, Schoenberger L, Middleton C and Un B 2017 Gendered eviction, protest and recovery: a feminist political ecology engagement with land grabbing in rural Cambodia *J. Peasant Stud.* **44** 1215–34

[35] Baird I G and Fox J 2015 How land concessions affect places elsewhere: telecoupling, political ecology, and large-scale plantations in Southern Laos and Northeastern Cambodia *Land* **4** 436–53

[36] Neef A, Touch S and Chiengthong J 2013 The politics and ethics of land concessions in rural Cambodia *J. Agric. Environ. Ethics* **26** 1085–103

[37] Hall R 2011 The many faces of the investor rush in Southern Africa: towards a typology of commercial land deals *ICAS Rev. Pap. Ser.* **2** 1 (https://www.tni.org/files/Hall%20ICAS%20WP%202.pdf)

[38] Fox J, Nghiem T, Kimkong H, Hurni K and Baird I 2018 Large-scale land concessions, migration, and land use: the paradox of industrial estates in the red river delta of vietnam and rubber plantations of Northeast Cambodia *Land* **7** 77

[39] Gironde C, Golay C and Messerli P 2016 *Large-Scale Land Acquisitions* (Leiden and Boston: Brill Nijhoff)

[40] Messerli P, Giger M, Dwyer M B, Breu T and Eckert S 2014 The geography of large-scale land acquisitions: analysing socio-ecological patterns of target contexts in the global South *Appl. Geogr.* **53** 449–59

[41] Parra Paitan C and Verburg P H 2019 Methods to assess the impacts and indirect land use change caused by telecoupled agricultural supply chains: a review *Sustainability* **11** 1162

[42] Millington J *et al* 2017 Integrating modelling approaches for understanding telecoupling: global food trade and local land use *Land* **6** 56

[43] Eckert S, Giger M and Messerli P 2016 Contextualizing local-scale point sample data using global-scale spatial datasets: Lessons learnt from the analysis of large-scale land acquisitions *Appl. Geogr.* **68** 84–94

[44] Sulieman H M 2018 Exploring the spatio-temporal processes of communal rangeland grabbing in Sudan *Pastoralism* **8** 14

[45] Volante J N, Mosciaro M J, Gavier-Pizarro G I and Paruelo J M 2016 Agricultural expansion in the Semiarid Chaco: poorly selective contagious advance *Land Use Policy* **55** 154–65