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LETTER

Regional carbon fluxes from land use and land cover change in Asia, 1980–2009

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Keywords: land use change, deforestation, DGVM, carbon budget

Supplementary material for this article is available online

OPEN ACCESS

RECEIVED
1 December 2015

REVISED
10 May 2016

ACCEPTED FOR PUBLICATION
14 June 2016

PUBLISHED
8 July 2016

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Abstract

We present a synthesis of the land-atmosphere carbon flux from land use and land cover change (LULCC) in Asia using multiple data sources and paying particular attention to deforestation and forest regrowth fluxes. The data sources are quasi-independent and include the U.N. Food and Agriculture Organization-Forest Resource Assessment (FAO-FRA 2015; country-level inventory estimates), the Emission Database for Global Atmospheric Research (EDGARv4.3), the 'Houghton' bookkeeping model that incorporates FAO-FRA data, an ensemble of 8 state-of-the-art Dynamic Global Vegetation Models (DGVM), and 2 recently published independent studies using primarily remote sensing techniques. The estimates are aggregated spatially to Southeast, East, and South Asia and temporally for three decades, 1980–1989, 1990–1999 and 2000–2009. Since 1980, net carbon emissions from LULCC in Asia were responsible for 20%–40% of global LULCC emissions, with emissions from Southeast Asia alone accounting for 15%–25% of global LULCC emissions during the same period. In the 2000s and for all Asia, three estimates (FAO-FRA, DGVM, Houghton) were in agreement of a net source of carbon to the atmosphere, with mean estimates ranging between 0.24 to 0.41 Pg C yr^{-1}, whereas EDGARv4.3 suggested a net carbon sink of −0.17 Pg C yr^{-1}. Three of 4 estimates suggest that LULCC carbon emissions declined by at least 34% in the preceding decade (1990–2000). Spread in the estimates is due to the inclusion of different flux components and their treatments, showing the importance to include emissions from carbon rich peatlands and land management, such as shifting cultivation and wood harvesting, which appear to be consistently underreported.

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1. Introduction

Unprecedented growth in energy consumption and rapid land use change in Asia has led to a major reshaping of the regional distribution and magnitude of greenhouse gas (GHG) sources and sinks. Although the combustion of fossil fuels accounts for the largest fraction of anthropogenic carbon emissions in Asia (Liu *et al* 2015), land transformation in this region has some of the fastest rates of change in the world and high spatial contrast with deforestation in tropical Asia and reforestation in East Asia (Hansen *et al* 2013, FAO-FRA 2015). Globally, net carbon emissions from land use and land cover change (LULCC) are estimated at about 1.0 ± 0.8 Pg C yr^{-1} (Ciais *et al* 2013, Le Quéré *et al* 2015). Asia is responsible for a growing fraction of the global LULCC flux, partly because of the slowdown of deforestation in South America (Hansen *et al* 2013, Federici *et al* 2015, Kim *et al* 2015). However, the contributing gross fluxes of the net LULCC flux, in Asia and globally, are among the most uncertain quantities of the anthropogenic global carbon budget (Harris *et al* 2012a, Pongratz *et al* 2014).

The magnitude of LULCC net CO_2 flux depends on the size of the carbon pools immediately combusted or respired biomass (wood, leaves, roots), the fate of on-site slash materials, subsequent land-management practices and effects on soil carbon (e.g., slash and burn, shifting cultivation, permanent agriculture) and the fate of off-site harvested wood products, e.g., wood harvested for paper, fuel, pulp, and building material (Hurtt *et al* 2006, 2011, Earles *et al* 2012). The Intergovernmental Panel on Climate Change Assessment Report 5 (IPCC AR5; Ciais *et al* 2013) reports a 50%–100% likelihood that global LULCC carbon emissions decreased between the 1990s (1.5 ± 0.8 Pg C yr^{-1}) and the 2000s (1.0 ± 0.8 Pg C yr^{-1}). However, large uncertainties are associated with the magnitude of change and with the regional attribution of carbon fluxes (Foley *et al* 2005, Friedlingstein *et al* 2010, Hansen *et al* 2013, Ciais *et al* 2013, Kim *et al* 2015). Carbon emissions from deforestation and forest degradation are uncertain in Asia, and particularly in Southeast Asia (Hansen *et al* 2013, Achard *et al* 2014). A full and updated quantification of Asia's LULCC fluxes and their sources of uncertainty are necessary to constrain the perturbation of the global carbon budget, and to help understand the role of terrestrial ecosystems in Asia in contributing to, and mitigating increases of, GHG concentrations.

Here we present a comprehensive synthesis of the regional net carbon flux from LULCC in Asia using multiple data sources and models, and paying particular attention to its contributing fluxes. Estimates of LULCC fluxes are analyzed from a variety of quasi-independent data sources, including the FAO-FRA, the Emission Database for Global Atmospheric Research (EDGARv4.3), a bookkeeping model by Houghton *et al* (2012), an ensemble of 8 state-of-the-art Dynamic Global Vegetation Models (DGVM) (table S1 in supplementary material). These analyses are supplemented with estimates taken from two remote-sensing studies. The estimates are aggregated spatially to Southeast Asia, East Asia, and South Asia (figure 1; countries listed in table S2), and provided for three decades, 1980–1989, 1990–1999 and 2000–2009.

2. Methods

2.1. Datasets on emissions from LULCC

Three data sources were analyzed for this study, representing the major approaches frequently used in LULCC assessments (Ciais *et al* 2013). These data sources vary by the methods used to estimate LULCC fluxes, particularly with regards to the use of different sources for LULCC, carbon stocks, and methods to account for forest regrowth and legacy emissions (table 1). Here, we categorize the data sources by their general methodologies: (i) bookkeeping model (Houghton *et al* 2012) and inventory accounting (EDGARv3.1, FAO-FRA 2015), (ii) eight carbon-cycle models (DGVMs), and (iii) literature estimates from remote-sensing studies (Harris *et al* 2012b, Achard *et al* 2014).

For all data sources, carbon fluxes (sources and sinks) from natural lands (including forests) were considered, but only some datasets included emissions from agricultural lands (table 2). All datasets included fluxes from aboveground and belowground biomass, whereas only a few datasets included emissions from litter, soil, fire, or land management. Secondary forest regrowth contributes to carbon uptake, but it was not included consistently across the data sources (table 2). The DGVM carbon-cycle models and the bookkeeping model differed from the other approaches based on their inclusion of *instantaneous* (e.g., the immediate combustion of fuel wood) as well as *legacy* (or delayed) emissions (Pongratz *et al* 2014), e.g., from slash left on-site or delayed decomposition of wood products used in furniture or homes. The importance of the distinction is that emissions associated with legacy fluxes are partly realized and included in present and future emission estimates, and can amount to as much as instantaneous emissions themselves (Houghton *et al* 2012). We summarize the data sources in detail below, but refer to the supplementary material (section S1) for a more detailed description of the datasets and their methods.

2.1.1. Bookkeeping and inventory approaches

The bookkeeping model (Houghton *et al* 2012) tracks all carbon pools (i.e., wood, roots, leaves, soil, litter) within a hectare, updating carbon pools over time based on ecosystem-specific growth and decay equations; the size of the carbon pools are initialized based on inventories. In contrast, standard inventory approaches, including the FAO-FRA and EDGAR used

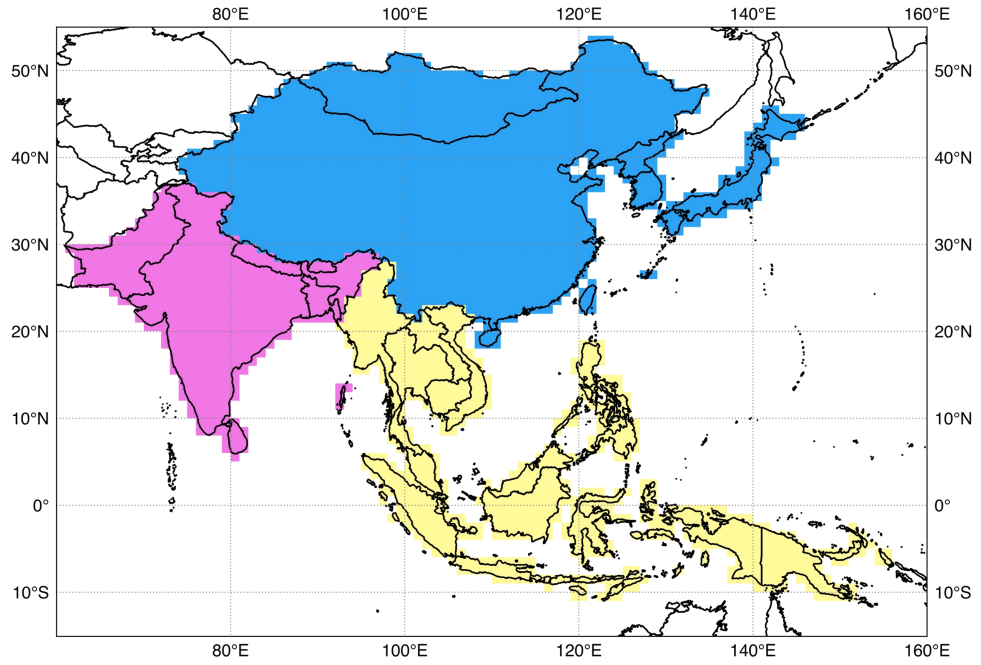

Figure 1. Geographic areas were pre-defined for this study, corresponding to Southeast Asia (green), East Asia (blue), and South Asia (purple).

Table 1. Datasets and methods used for determining land use and land cover, carbon stocks, and forest regrowth. The HYDE data model version 3.0 (Goldewijk 2001) determines land use in the DGVMs, and an updated version of HYDEv3.1 is used in the Tao *et al* (2013) study. The Global Land Cover 2000 (GLC 2000) and the FAO Global Ecological Zone map (FAO-GEZ) provide land use and land cover for the EDGARv4.3 dataset.

Dataset	Land use and land cover	Carbon stocks	Forest regrowth
FAO-FRA	IPCC 2006 Tier1 methods Country-level reporting	IPCC 2006 Tier1 methods Carbon per hectare by Biome or Region	N/A
EDGARv4.3	GLC 2000 and FAO-GEZ map for forest area FAO-FRA for area change	IPCC 2006 Tier1 methods Carbon per hectare by Biome	IPCC 2006 Tier1 methods Biomass increment factors
DGVMs	HYDE	Process-based estimate	Process-based estimate[a]
Achard *et al* (2014)	Remote-sensing	Remote-sensing, allometric model	Implicit[a]
Harris *et al* (2012b)	Remote-sensing	Remote-sensing, allometric model	N/A
Houghton *et al* (2012)	FAO-FRA	Bookkeeping model Country-level statistics	Biomass Growth equation
Pan *et al* (2011)	FAO-FRA, Govt. reports	FAO-FRA, Houghton *et al* (2012)	Houghton *et al* (2012)
Tao *et al* (2013)	HYDE 3.1	Process-based estimate	Process-based estimate[a]

[a] Transient response to climate and CO_2 fertilization is included; implicit inclusion in Achard *et al* (2014).

here, use similar accounting to track carbon over time, but typically they do not track carbon losses from soils and litter and use country-level estimates for carbon aboveground vegetation. A common underlying source for the change in forest area used in the bookkeeping and inventory approaches (FAO-FRA, EDGARv3.1) comes from country-level FAO-FRA reporting. The inventory approaches utilize IPCC (2006) Tier 1 methods (Ruesch and Gibbs 2008) to estimate LULCC emissions at the country level by the difference in carbon gained from biomass growth and carbon lost from deforestation. The bookkeeping model and EDGARv4.3 both include carbon emissions from peatland fires. We compare the inventory estimates analyzed in this study with a similar approach adopted by Pan *et al* (2011). Pan *et al* (2011) utilized a variety of national-level forest inventories other than FAO-FRA to estimate forest area, changes in forest area, and carbon stocks, but they utilized the Houghton (2003) bookkeeping model to estimate forest regrowth and legacy fluxes from soil carbon after land use change.

2.1.2. Carbon-cycle models

As part of the TRENDY model inter-comparison project, version 3 (Sitch *et al* 2015), the eight DGVMs in this study were used to estimate carbon stocks and fluxes using process-based approaches and to predict global vegetation distribution based on impacts of climate, atmospheric CO_2 concentrations, and land

Table 2. Component carbon emissions and factors affecting carbon stocks (IRR, FERT, transient response) included in each of the datasets in this study. Emissions from changes in aboveground and belowground live biomass (AGB and BGB, respectively) are included in all datasets. Emissions from fire may also be included as an emission source, and these may be independent of emissions from land use change. Forest regrowth can offset carbon emissions and the rate of regrowth can be modified by changes in climate (clim) or from CO_2 fertilization (CO_2), which is defined as a transient response; these effects are implicitly included in the remote sensing study by Achard *et al* (2014). The carbon emissions from wood harvest products (WH) are reported separately for the EDGARv4.3 dataset; these emissions could not be separated from Houghton *et al* (2012) or Pan *et al* (2011). The relative weight score reflects the inclusion carbon fluxes from individual carbon stocks, fire and forest regrowth, relative to the dataset with the maximum number of component fluxes included in the estimate.

				Change in carbon stock						Land management					Forest regrowth		
Dataset	Relative weight	Emission timescale	Land types	AGB	BGB	Litter	Soil	Peat	Fire	SC	WH	CH	IRR	FERT	Transient response		
FAO-FRA	0.67	I, L[a]	N, Ag	✓	✓		✓		✓[b]								
EDGARv4.3	1.00	I	N	✓	✓		✓[c]	✓[c]	✓						✓		
DGVMs	1.00	I, L	N, Ag	✓	✓	✓	✓		✓	[d,e]	[d,e]	[d,e]	[d,e]	[d,e]	✓	clim	CO_2
Achard *et al* (2014)	0.63	I	N	✓	✓										✓	clim	CO_2
Harris *et al* (2012b)	0.50	I	N	✓	✓												
Houghton *et al* (2012)	1.00	I, L	N, Ag	✓	✓	✓	✓		✓	✓	✓				✓		
Pan *et al* (2011)	0.88	I	N, Ag	✓	✓	✓			✓		✓				✓		
Tao *et al* (2013)	0.88	I, L	N, Ag	✓	✓	✓	✓					✓	✓	✓	✓	clim	CO_2

Emission timescale: immediate (I), legacy (L).

Land types: natural (N), agriculture (Ag).

Carbon stock: aboveground biomass (AGB), belowground biomass (BGB).

Land management: shifting cultivation (SC), wood harvest (WH), crop harvest (CH), irrigation (IRR), nitrogen fertilization (FERT).

[a] Legacy emissions are only included for losses to organic soil carbon from agricultural areas.

[b] Emissions from combustion of organic soils during biomass burning.

[c] Emissions from losses to organic and peat soils is derived from fire emissions in the GFEDv3.1 dataset (van der Werf *et al* 2010).

[d] VISIT model included SC, WH,CH, IRR, and FERT.

[e] CLMv4.5 included SC,WH, CH, IRR, and FERT.

cover change. Some models include an interactive nitrogen cycle (such as CLMv4.5, LPX, OCN), which often result in smaller forest regrowth than models without C–N coupling (Yang *et al* 2010). The DGVM models (Sitch *et al* 2015) utilized alternate versions of land cover from the HistorY Database of the global Environment, HYDE version 3 (Goldewijk 2001) (table 1) to determine land use change. DGVM estimates of LULCC fluxes are obtained by difference of the net land-atmosphere CO_2 flux between one simulation (S3) with land use change, transient CO_2 concentrations and variable climate and an alternate simulation (S2) with only transient CO_2, variable climate, and pre-industrial land cover in 1860 (Sitch *et al* 2015). Only the CLMv4.5, LPX and VISIT models accounted for gross land cover transitions (e.g. parallel abandonment to and from agricultural land within a grid cell), and only CLMv4.5 and VISIT accounted for carbon fluxes from wood and crop harvest. Finally, we compare the DGVM estimates with the estimates from a regionally-parametrized carbon-cycle model by Tao *et al* (2013), which included fluxes from crop harvest, irrigation and nitrogen fertilization.

2.1.3. Remote-sensing Studies

We use literature estimates from two remote-sensing-based studies (Harris *et al* 2012b, Achard *et al* 2014) estimated forest area, changes in forest area, and carbon stocks from independent sources of satellite data for both land cover and biomass. Their emission estimates do not include emissions from the decay of litter, soils, including peatlands, or the effects of forest degradation and land management.

2.2. Analyses

2.2.1. Changes in forest area

Changes in forest area and carbon stocks are two major determinants of LULCC emissions (Houghton *et al* 2012). Therefore, we provide estimates of changes in forest area from FRA 2015 and the HYDE data product, supplemented with observed changes reported in recent literature. Different carbon-cycle modeling groups were responsible for determining rules for land cover transitions (e.g. primary forest -> agriculture, or secondary forest -> agriculture), and therefore make different assumptions about how to specify land-use transitions prescribed by HYDE. One approach assumes an equivalent loss of forest area for an increase in either cropland or pasture (section S4.1; figure S1). The differences in approaches were not quantified, but can introduce carbon fluxes that are included in some, but not all DGVMs. The changes in forest area, by region and decade, are provided in the supplementary material (section S4.1; figure S1).

2.2.2. Carbon in biomass and DGVM performance ranking

In this study, biomass estimates based on remote-sensing studies from Baccini *et al* (2012), and Liu *et al* (2015) are used as benchmarks to filter-out DGVMs with unreasonably high carbon stock in vegetation, and therefore, biased carbon fluxes from LULCC (supplementary materials section 3). Based on the biomass benchmarks, the CLMv4.5, OCN, and ORCHIDEE models were filtered-out from DGVM emission estimates from Southeast Asia, and the CLMv4.5, JULES, and OCN models were filtered-out from DGVM emission estimates from East Asia; no models were filtered-out for South Asia. We also provide IPCC 2006 Tier 1, country-level, estimates of aboveground biomass from the FRA 2010 report. We provide summary estimates of carbon in total and aboveground biomass by region, and country (supplementary material section S4.1; figures S2 and S3). .

2.2.3. Carbon emissions from LULCC: statistical summaries by geographic regions

The LULCC emissions were summarized with mean and standard deviations for each decade and region. Emission estimates reported by the DGVM ensemble have been summarized by taking the mean of decadal-mean estimates from individual DGVMs in the ensemble, after omitting individual models with unrealistic biomass (see section 2.2.2); the range of estimates among the models is provided as a measure of uncertainty. We use an approach similar to the one of IPCC AR5 (Ciais *et al* 2013) and from Kirschke *et al* (2013) to assign a level of confidence in the sign of the emissions estimate and to the direction of change in emissions between decades by indicating the level of agreement (low, medium, high) among studies and the robustness of evidence (number of studies). In addition, we present a weighted-mean estimate of the mean decadal estimates from each approach (table 3), which helps to address the inclusion of different component fluxes among estimates. First, we convert table 2 into a binary table and we focus only on fluxes from carbon stocks, fire, and forest regrowth (e.g., if a particular estimate includes fire flux, then it is scored 1, otherwise 0). We give each of these component fluxes equal weight, but we refrain from scoring legacy fluxes, fluxes from climate response, and fluxes from land management because we cannot quantify their contribution relative to the other fluxes. The relative weight for each approach (table 2) reflects the maximum number of component fluxes in any single approach. The weighted-mean of mean decadal estimates is presented in table 4, along with the qualitative assessment of confidence in the magnitude and change among decades.

Table 3. Regional carbon emissions from LULCC in Asia by decade (petagram carbon per year). Uncertainty is presented as mean ± standard deviation or as a range of maximum and minimum estimates.

Region	Ensemble/Study	1980–1989	1990–1999	2000–2009
Southeast Asia	DGVMs	0.22 [0.15, 0.39]	0.33 [0.16, 0.54]	0.31 [0.18, 0.53]
	FAO-FRA		0.33 ± 0.06	0.41 ± 0.06
	EDGAR v4.3			0.11 ± 0.13
	Houghton *et al* (2012)[a]	0.29 ± 0.02[a]	0.66 ± 0.36[a]	0.46 ± 0.13[a]
	Achard *et al* (2014)		[0.24, 0.35]	[0.24, 0.37]
	Harris *et al* (2012b)[b]			[0.17, 0.32][b]
	Pan *et al* (2011)[a]		0.30[a]	0.14[a]
	Tao *et al* (2013)	[0.23, 0.26]	[0.21, 0.24]	
East Asia	DGVMs	0.29 [0.16, 0.44]	0.27 [0.12, 0.40]	0.05 [−0.06, 0.16]
	FAO-FRA		−0.11 ± 0.0003	−0.12 ± 0.02
	EDGAR v4.3			−0.25 ± 0.02
	Houghton *et al* (2012)	−0.02 ± 0.006	−0.03 ± 0.002	−0.04 ± 0.005
	Pan *et al* (2011)[a]		−0.21[a]	−0.24[a]
South Asia	DGVMs	0.04 [0.01, 0.13]	0.09 [0.03, 0.19]	0.04 [0.001, 0.12]
	FAO-FRA		0.012 ± 0.00	−0.018 ± 0.01
	EDGAR v4.3			−0.03 ± 0.01
	Houghton *et al* (2012)	−0.006 ± 0.002	−0.014 ± 0.005	−0.015 ± 0.005
	Harris *et al* (2012b)*			[0.014, 0.027]*

[a] Includes carbon emissions from wood harvest, both instantaneous and legacy.

[b] Gross carbon emissions from deforestation only, for years between 2000 and 2005.

Table 4. Ranking of agreement and confidence among data sources for estimates of change and sign of emissions by region and decade. The weighted-mean of all mean decadal estimates is also listed by region and decade (mean Pg C per year ± SD of means). Triangle indicates a carbon source (up, red) or carbon sink (down, green), or an increasing (up, red) or deceasing (down, green) change from previous decade; a circle indicates that there is no change, given the stated uncertainties, between the decade considered and the previous one. Size of the triangle/circle indicates the number of independent estimates in agreement; small: 1 studies, medium: 2–3 studies, large: 4+ studies. Estimates with high agreement have only a single triangle, and high confidence is evident in estimates with the largest triangles.

Region	1980–1989		1990–1999		2000–2009	
	Source/Sink	Change	Source/Sink	Change	Source/Sink	Change
Southeast Asia	0.255 ± 0.019		0.363 ± 0.131		0.271 ± 0.116	
	Source/Sink	Change	Source/Sink	Change	Source/Sink	Change
East Asia	0.135 ± 0.083		0.001 ± 0129		−0.077 ± 0.076	
	Source/Sink	Change	Source/Sink	Change	Source/Sink	Change
South Asia	0.017 ± 0.013		0.032 ± 0.029		−0.003 ± 0.021	

3. Results: carbon emissions from LULCC

3.1. Southeast Asia

There was high agreement among all estimates in the magnitude of carbon emissions from LULCC during the 1980s in Southeast Asia (tables 3, 4; figure 2), ranging from 0.22 to 0.29 Pg C yr^{-1}. In the 1990s, there was also high agreement and high confidence that the emissions were at *least* 0.21 Pg C yr^{-1}, but this value was not well constrained with a range of [0.21, 0.66] Pg C yr^{-1}. Between the 1980s and 1990s there was moderate agreement for increasing emissions, although the magnitude of the increase was uncertain. In comparison, Tao *et al* (2013) reported emission estimates that overlapped between the two time periods, suggesting little to no change in emissions. During the 2000s, there was high agreement among data sources and high confidence indicating that emission estimates were *at least* 0.11 Pg C yr^{-1}. Although the range of the estimates ([0.11,

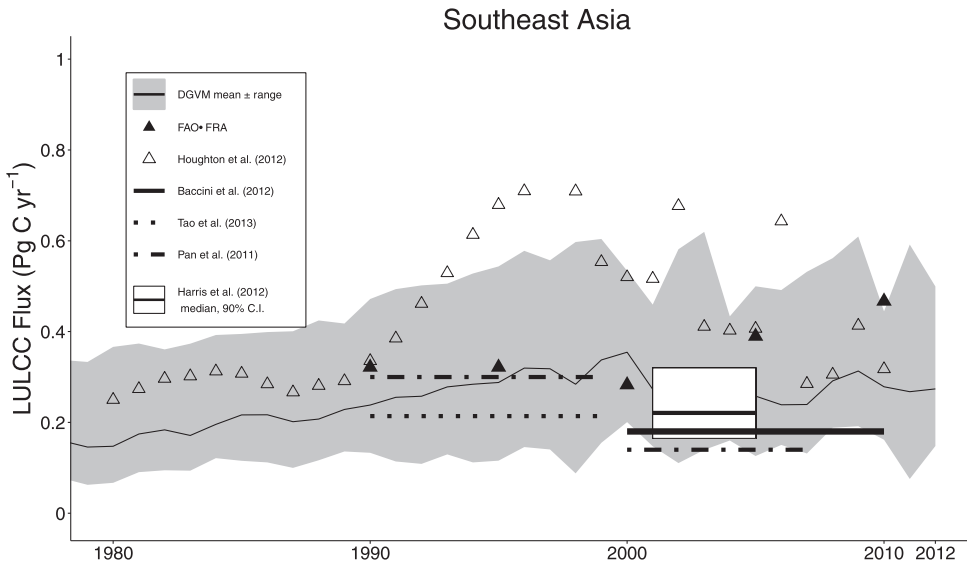

Figure 2. Carbon emissions from land use and land cover change (LULCC) in Southeast Asia between 1980 and 2012. Houghton *et al* (2012) also reports an outlier emission estimate of 1.61 Pg C in 1997 (not shown), resulting from extensive peat fires in the region; these emissions were not included in the estimates of other studies reported here. The DGVM ensemble {JULES, LPJ, LPJ-GUESS, LPX, VISIT} mean estimate (thin solid line) is presented along with the range of annual estimates among the models (gray shaded area). Previously published estimates are provided as point and decadal (boxplot, and the horizontal dashed, dotted and solid lines) mean estimates.

0.46] Pg C yr^{-1}) was smaller than in the previous decade, the weighted-mean estimate in the 2000s (0.363 ± 0.131 Pg C yr^{-1}) was larger than weighted-mean estimate for the 1990s (0.255 ± 0.019 Pg C yr^{-1}). Among all estimates, there was low agreement in the change of emissions between the 1990s and the 2000s. The bookkeeping model and Pan *et al* (2011), both of which utilized similar data sources from FAO-FRA, suggested a 30%–53% reduction in emissions, respectively, between the 1990s and 2000s. The DGVMs and Achard *et al* (2014) suggested a smaller reduction of less than 10% or no change in emissions, respectively, between the 1990s and the 2000s. By contrast, the FAO-FRA suggested an increase in emissions (24%+) between the 1990s and 2000s (table 3), but it is unclear how the absence of legacy and regrowth fluxes (table 2) may have influenced their estimates. Similarly, the inclusion of emissions from harvested wood products in the estimates by the bookkeeping model and Pan *et al* (2011) resulted in higher emissions than those from other data sources that did not include these important fluxes, although its inclusion would not have impacted an assessment of change in emissions between decades because wood harvest volumes did not change appreciably among decades according to the FRA (2015).

Overall, the carbon emissions from LULCC in Southeast Asia, taken as the weighted-mean estimate among all data sources, is estimated to be 0.363 ± 0.131 Pg C yr^{-1} in the 1990s and $+0.271 \pm 0.116$ Pg C yr^{-1} in the 2000s (table 4), or 20%–30% of global LULCC emissions, respectively, using global LULCC estimates based on the bookkeeping model. The increasing fraction of carbon emissions from LULCC in Southeast Asia, relative to global LULCC emissions, is partly due to near constant emissions during the 1990s and 2000s, and at the same time, declining global emissions from LULCC (figure 3).

3.2. East Asia

In East Asia, there was low agreement in the estimate of net fluxes from LULCC in the 1980s between the bookkeeping model and the DGVMs (tables 3, 4). The DGVMs also simulated higher emissions during the 1990s that were of similar magnitude as LULCC emissions in Southeast Asia during the 2000s (table 3). By contrast in the 1990s, there was moderate agreement among data sources and medium confidence indicating a small forest regrowth sink (tables 3, 4). In the 2000s, there was also moderate agreement in the deforestation and regrowth trends, and high agreement in the strengthening of a carbon sink compared to fluxes from the 1990s; only the magnitude of the change between decades differed among the data sources (table 4). The DGVMs generally estimated much higher emissions in the 1980s and 1990s, but there was a strong decline in emissions during the 2000s from previous decades, and a regrowth sink was evident in a few of the models (figures S5, S8).

DGVMs do not quantify explicitly how the legacy emissions from past land use change contribute to higher emission estimates, but it is clear that emissions from LULCC in East Asia have declined substantially (figure S8), to less than 10% of the global emissions from LULCC in the 2000s (figure 3). The decreasing fraction of emissions from LULCC in East Asia,

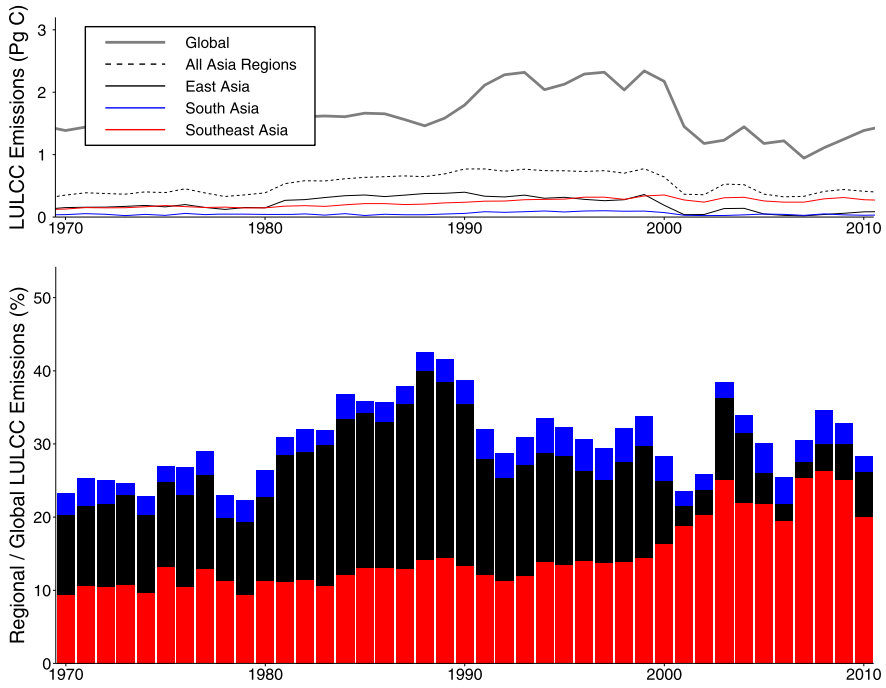

Figure 3. Total emissions from land use and land cover change (LULCC) (top) and the contribution of LULCC emissions in Asia as a percent of Global LULCC emissions (bottom) for years 1901–2012. Estimates for Global and Asian LULCC fluxes are obtained from DGVM ensemble means ($n = 8$). In the late 2000s, emissions from LULCC in Southeast Asia have accounted for 15%–25% of global LULCC emissions. Emissions from LULCC in East Asia peaked in the late 1980s at 25% of global LULCC emissions. A decline in the percent contribution of LULCC emissions in Asia to global LULCC emissions during the 1990's results mainly from an increase in Global LULCC emissions during the same time period.

according to DGVMs, can be attributed to a stronger decline in emissions from this region than the decline in LULCC emissions observed at the global scale; this pattern is driven largely by a strong decline in LULCC emissions and an intensification of the land sink in China, due to reforestation and forest regrowth according to some estimates (Fang *et al* 2001, Piao *et al* 2009, Li *et al* 2015).

3.3. South Asia

In South Asia, there was low agreement among LULCC net flux estimates during the 1980s, with the bookkeeping model estimating a carbon sink, and the DGVMs a carbon source (table 3). In the 1990s, there was moderate agreement in the sign and magnitude of the LULCC flux being a net source of carbon as estimated by the DGVMs and FAO-FRA (less than 33% difference), whereas the bookkeeping model continued to estimate a carbon sink (table 3). There was also low agreement about the direction of change in emissions (increasing or decreasing) between the 1980s and 1990s, with the DGVMs suggesting that carbon emissions doubled between the two time periods, and the bookkeeping model suggesting the opposite, that the strength of the regrowth sink increased during the 1990s relative to 1980s levels (table 3). In the 2000s, there was high agreement among data sources and medium confidence in decreasing emissions compared to estimates from the 1990s, along with moderate agreement in a regrowth sink (tables 3 and 4, and figure S9). Although the emissions estimated by the DGVMs were mostly positive (figure S6), it is clear that modeled carbon in biomass was not a factor because there was little bias between individual DGVMs and the biomass benchmarks (figures S2, S3). Therefore, it is possible that factors related to climate could have influenced the emission estimates in the DGVMs, but which would not have been included in the other estimates (table 2). Overall, emissions from LULCC in South Asia are estimated to be less than 5% of global LULCC emissions (figure 3), the bulk of these carbon emissions are from India alone, and the decline in emissions between 1990s and 2000s is shown in most estimates (figure S9).

4. Discussion

4.1. Regional emissions

The goal of this article was to present the carbon emissions from LULCC as estimated by a range of approaches and for these estimates to serve as a baseline for future studies. The problems associated with having multiple estimates of the net carbon flux of LULCC based on different contributing fluxes have

been discussed at length before (Pongratz *et al* 2014, Rosa *et al* 2014), as well as adding unwarranted controversy with regards to the magnitude of the carbon flux (Harris *et al* 2012a). We provided a weighted-means approach to account for the inclusion of component fluxes in some, but not in all estimates, and we treated each component flux with similar weight. The weighted-mean estimates provide some satisfaction for an ensemble-mean estimate of the LULCC flux, but it does have its own inherent biases. For example, some component fluxes will be important in some regions, but not in others (e.g. peat flux), and therefore the relative contribution of the component flux to the overall LULCC flux will be greater (or less). The accuracy of the weighted-means approach can therefore be improved if we can ascribe some value [0, 1] to the relative influence of each component flux to the overall net carbon flux estimate. For example, if the wood harvest flux can be quantified and is known to be 90% of the LULCC flux in a particular region or time period, then those methods that include a wood harvest flux would be weighted higher than those methods that do not include wood harvest, and a more accurate ensemble estimate would prevail; until the relative contribution of the component fluxes can be quantified the weighted-mean ensemble estimates should be used with discretion. Below, we discuss the major patterns in emissions among regions as evidenced by this study, and we review the magnitude and contribution of each component flux to the total net LULCC flux from a review of the literature.

The bookkeeping model and DGVMs both suggest that total Asian emissions have declined by at least 34% between 1990s and 2000s, driven largely from an increasing carbon sink in China, with the carbon sink of South Asia playing a smaller role. However, the inventory data (FAO-FRA) suggests that emissions grew by 17% across Asia between 1990s and 2000s, but it was more due to larger increases in carbon emissions from Southeast Asia than a smaller decreases in carbon emissions from East and South Asia regions, which is consistent with the bookkeeping model and DGVMs. For Southeast Asia, most methods suggest similar carbon fluxes between 1990s and 2000s (figure S7), and at most, a decline in carbon fluxes between the 1990s than in the 2000s, which suggests that the missing fluxes of a tier-1 approach such as the FAO-FRA has important effects on the net flux; alternatively, carbon stocks at the country-level could be over estimated which would also lead to higher emissions fluxes.

In Southeast Asia, there is general agreement among the bookkeeping model, the FAO-FRA, and DGVMs showing that net carbon emissions from LULCC in Southeast Asia is responsible for 75%–88% of Asian LULCC fluxes in the 2000s. Recent remote-sensing studies of deforestation activity in Southeast Asia showed that forest loss has been constant or increasing during the past two decades (Hansen *et al* 2013, Achard *et al* 2014, Margano *et al* 2014, Stibig *et al* 2014, Kim *et al* 2015), suggesting that LULCC emissions should be constant or increasing as well, consistent with the changes in carbon emissions between decades reported in this study. As a caveat, Loarie *et al* (2009) and Song *et al* (2015) reported that, independent of gross losses to forest areas, carbon emissions from LULCC can be largely driven by spatial heterogeneity in carbon density. It is therefore plausible that decreasing trends in carbon emissions from LULCC in Southeast Asia between 1990s and 2000s, from the bookkeeping model as reported by Pan *et al* (2011), occurred as a result of the use of carbon stock datasets that were derived from country-level statistics, and were therefore biased too low (figures S2, S3). Before progress can be made on reducing the uncertainty in LULCC emissions in this region, it may be prudent to first evaluate the relative impact on LULCC emissions from the uncertainties inherent in the spatial variability in carbon density and areal changes in forest cover.

In East Asia, an increase in forest regrowth is responsible for reversing a carbon source to carbon sink from LULCC in East Asia between the decades 1990s and 2000s, at the very latest, and this is mainly driven by China, confirming similar reports by Piao *et al* (2012). The inclusion of legacy emissions may be the cause of an apparent lag in the source-sink dynamics observed in the DGVM emission estimates in East Asia between the 1980s, 1990s (both carbon sources) and the 2000s, during which there is a noticeable decline in emissions from previous decades (figure 4) and a carbon sink estimated by a few models (figure S5). The inclusion, or omission, of legacy emissions may explain the differences in decadal estimates for East Asia made by the DGVMs and inventory methods. Even still, the high agreement among the data sources suggest high confidence in East Asia trending towards a stronger carbon sink than in past decades even while accounting for LULCC in the region (figure S8).

4.2. Land management

Wood harvesting practices in Borneo and Indonesia are particularly relevant drivers of emissions, as widespread practice of selective logging and clear-cutting results in considerable loss of biomass and carbon uptake capacity (Carlson *et al* 2012, Gaveau *et al* 2014, Kemen-Austin *et al* 2015). Wood harvest practices result in forest-degradation and deforestation and can also create increasingly fragmented forests, but the effects of fragmentation, which are largely ignored, can amount to carbon emissions of 0.12–0.24 Pg C yr^{-1} across all tropical forests (Pütz *et al* 2014). In their carbon-cycle model, Tao *et al* (2013) also prescribed cropping rotations, irrigation and fertilization amounts from FAO country-level statistics. However, it is unclear to what degree these practices impact carbon fluxes because Tao *et al*

(2013)'s emission estimates were roughly inline with other data sources reported here, which did not include these land management practices. The following emissions from wood harvest practices are based on EDGARv4.3, and these were not used for the EDGARv4.3 total LULCC emissions presented in table 3, to allow adequate comparison to other estimates. Including emissions from wood harvest alone would increase emission estimates by 0.28 ± 0.01 Pg C yr^{-1} in East Asia, by 0.48 ± 0.01 Pg C yr^{-1} in South Asia, and 0.40 ± 0.01 Pg C yr^{-1} in Southeast Asia, which would then switch East and South Asia regions to net carbon emitters from LULCC.

4.3. Peat and soil carbon losses from fire

Only the EDGARv4.3 emission estimates, which utilized the GFEDv3.1 dataset from van der Werf *et al* (2006), include emissions from peat fires; although the DGVMs and the bookkeeping model did include carbon fluxes from soils, conditions promoting the carbon density of peat soils were not modeled explicitly. Further, none of the estimates in this study reported fluxes from the areal changes in peatlands (Miettinen *et al* 2016) or the degradation and decomposition of peat soils, which are more carbon dense and result in higher fluxes than the typically represented organic soils (Hooijer *et al* 2010). Emissions from peat fires are substantial fluxes in themselves and can be of the same order of magnitude as carbon emissions due to deforestation at the country-scale (van der Werf *et al* 2006, Hooijer *et al* 2010, Miettinen *et al* 2011, Prentice *et al* 2011). The carbon flux from peat fires in Southeast Asia are estimated to be at minimum 0.38 Pg C yr^{-1} for 1997–2006 (Hooijer *et al* 2006), and 0.08–0.18 Pg C yr^{-1} for 2000–2006 (van der Werf *et al* 2008), but annual emissions from peat fires have ranged from 0.81 to 2.57 Pg C in fire intensive years like in 1997–98 (Page *et al* 2002); however, the *maximum* emissions from fire anomalies in Asia may be closer to 1.3 Pg C, according to an inverse modeling study by Patra *et al* (2005).

4.4. Gross versus net land use change

Shifting cultivation is a method of rotational cropping that is commonly practiced in the Tropics; it is defined as the simultaneous clearing of forest for agriculture and abandonment of older agricultural land of equal area (Houghton *et al* 2010). Shifting cultivation (i.e., gross changes in land use) can amount to a 30% increase in carbon emissions compared to emissions estimated by net changes in land use (Shevliakova *et al* 2009, Stocker *et al* 2014). In this study, only the bookkeeping model, CLMv4.5, LPX and VISIT models included emission estimates from gross changes in land use. Accounting for shifting cultivation is problematic for FAO-FRA emission estimates, and other inventory approaches, because net forest area may not change under shifting cultivation and may be underreported. Remote-sensing surveys may be able to capture gross changes in forest cover, but will require more frequent surveys and correct attribution of young forest to the abandonment of managed land, as opposed to natural fires or disturbance. For an in depth review of the effects of gross versus net changes in land use, see (Shevliakova *et al* 2009, Houghton *et al* 2012, Stocker *et al* 2014, Wilkenskjeld *et al* 2014).

4.5. Forest cover and land use change

Consideration should be given to the use of gridded LULCC datasets that use detailed historical reconstructions from country-specific studies. For example, Tian *et al* (2014) raised concerns about notable land use changes in India that were under-documented and missing in global LULCC datasets, such as HYDE. The discrepancies in the HYDE data model are apparent (figure S1), but ideally need to be checked against more reliable data sources, such as satellite imagery. A recent land-use study in China (Liu and Tian 2010) also suggested a different spatial distribution of cropland and pasture than the distribution predicted by the HYDE dataset, which could have influenced both the magnitude and change in emissions between decades in the DGVM estimates.

4.6. Carbon stocks

In an analysis by Langner *et al* (2014), biomass maps by Baccini *et al* (2012) and Saatchi *et al* (2011) were supported for REDD+ reporting, and one approach for their use as a discriminating filter for constraining emission estimates was presented in this study, for example by omitting DGVMs that simulated unrealistic biomass. The DGVMs and the remote-sensing studies account for spatial variability in carbon density, which is lacking in FAO-FRA and derivative emission estimates. This study used Baccini *et al* (2012), and Liu *et al* (2015) biomass maps as a benchmark to discriminate between DGVM models that were simulating unreasonably high carbon stocks.

5. Summary

In summary, the range in the magnitude of carbon fluxes from LULCC in each region was large among methods due to the inclusion of different component fluxes, but the direction of change in carbon fluxes between decades was internally consistent among methods (figures S7–S9). A weighted-means approach was used to derive an overall estimate for each region, with each estimate weighted by the number of component fluxes included, but the relative contribution of each component flux to the total estimate could be improved.

- In Southeast Asia, there is robust evidence that carbon emissions from LULCC (ignoring peat

degradation) were at least 0.19 and 0.11 Pg C yr^{-1} in the 1990s and 2000s, respectively. Southeast Asia is contributing a large fraction of the regional carbon emissions from LULCC, between 75%–88% of regional LULCC emissions in the 2000s.

- There is robust evidence that East Asia switched from a carbon source to a carbon sink (median = −0.12 Pg C yr^{-1}, range = [+0.05, −0.25] Pg C yr^{-1}) from LULCC activities occurring between the 1990s and 2000s.
- In South Asia, there was low agreement in the sign of emissions, but moderate agreement in the presence of a carbon sink, and medium evidence of a change towards a carbon-sink between the 1990s and 2000s.
- To improve the accuracy of LULCC emissions, a reduction in uncertainty is needed in the estimates of carbon in biomass and soils, with particular attention to peatlands, as well as increased focus on providing separate estimates, along with their uncertainties, for the component fluxes that make up the emissions from LULCC.
- Since 1980, carbons emissions from LULCC in Asia have comprised 20%–40% of global LULCC emissions, with carbon emissions from LULCC in Southeast Asia accounting for 15%–25% of global LULCC emissions during the same period.

Acknowledgments

This work was supported by the Asia Pacific Network for Global Change Research (ARCP2013-01CMY-Patra/Canadell). LC was supported by the National Science Foundation East Asia Pacific Summer Institute (EAPSI) Fellowship. KI and PP were supported by the Environment Research and Technology Development Funds (2-1401) from the Ministry of the Environment of Japan. JGC thanks the support from the Australian Climate Change Science Program. AI and EK were supported by ERTDF (S-10) by the Ministry of the Environment, Japan. CK is supported by DOE-BER through BGC-Feedbacks SFA and NGEE-Tropics. AW was supported by the Joint UK DECC/Defra Met Office Hadley Centre Climate Programme (GA01101) and EU FP7 Funding through project LUC4C (603542).

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