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Cost-effectiveness of reducing emissions from tropical deforestation, 2016–2050

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Cost-effectiveness of reducing emissions from tropical deforestation, 2016–2050

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Abstract

Reducing tropical deforestation is potentially a large-scale and low-cost strategy for mitigating climate change. Yet previous efforts to project the cost-effectiveness of policies to reduce greenhouse gas emissions from future deforestation across the tropics were hampered by crude available data on historical forest loss. Here we use recently available satellite-based maps of annual forest loss between 2001–2012, along with information on topography, accessibility, protected status, potential agricultural revenue, and an observed inverted-U-shaped relationship between forest cover loss and forest cover, to project tropical deforestation from 2016–2050 under alternative policy scenarios and to construct new marginal abatement cost curves for reducing emissions from tropical deforestation. We project that without new forest conservation policies 289 million hectares of tropical forest will be cleared from 2016–2050, releasing 169 GtCO₂. A carbon price of US\$20/tCO₂ (\$50/tCO₂) across tropical countries would avoid 41 GtCO₂ (77 GtCO₂) from 2016–2050. By comparison, we estimate that Brazil's restrictive policies in the Amazon between 2004–2012 successfully decoupled potential agricultural revenue from deforestation and reduced deforestation by 47% below what would have otherwise occurred, preventing the emission of 5.2 GtCO₂. All tropical countries enacting restrictive anti-deforestation policies as effective as those in the Brazilian Amazon between 2004–2012 would avoid 58 GtCO₂ from 2016–2050.

Introduction

Tropical deforestation, forest degradation, and peatland conversion emitted 2.3–10.3 GtCO₂yr⁻¹ during the 2000s (median estimate: 4.9 GtCO₂ yr⁻¹; van der Werf *et al* 2009, Pan *et al* 2011, Baccini *et al* 2012, Harris *et al* 2012, Achard *et al* 2014, Grace *et al* 2014, Tubiello *et al* 2014, Tyukavina *et al* 2015, Liu *et al* 2015, Zarin *et al* 2016), while tropical forest regrowth removed 4.3–6.2 GtCO₂ yr⁻¹ (median estimate: 4.8 GtCO₂ yr⁻¹; Pan *et al* 2011, Baccini *et al* 2012, Grace *et al* 2014) (supplementary appendix table S1 available at stacks.iop.org/ERL/12/015001/mmedia). Reducing tropical deforestation has previously been identified as a cost-effective potential source of greenhouse gas emission reductions relative to other sectors based on analysis of government expenditures (Fogliano *et al* 2016),

site-specific case studies (Phan *et al* 2014), integrated assessment models (Overmars *et al* 2014), and partial equilibrium models that presented their results in the form of marginal abatement cost (MAC) curves (Grieg-Gran 2006, Kindermann *et al* 2008, Naucler and Enkvist 2009, Nepstad *et al* 2009, Strassburg *et al* 2009, Coren *et al* 2011). MAC curves illustrate how many emission reductions can be achieved at a particular cost at a particular place and time (Kesicki and Strachan 2011). They can help policymakers prioritize the most cost-effective actions across or within sectors.

We are motivated to produce new MAC curves for reducing emissions from tropical deforestation in light of two recent developments. First, recently available data on forest-cover loss derived from satellite measurements (Hansen *et al* 2013) represent a radical step-change in improvement in spatial resolution,

temporal resolution, and consistency of methods relative to the coarse data (FAO 2005) used to construct previous MAC curves (supplementary appendix table S2; see e.g. Grainger 2008). Second, from 2004–2012 Brazil reduced deforestation in the Amazon by 60%–80% (INPE 2014, Hansen *et al* 2013). This achievement occurred after the time ranges of the data used to generate previously published MAC curves. Notably, Brazil reduced deforestation not by introducing a carbon price, as modeled by previous MAC curves, but through restrictive public policies and private measures ('restrictive policies'), including new protected areas and indigenous lands, law enforcement backed by satellite monitoring, restrictions on credit to farmers in jurisdictions with high deforestation rates, and moratoria on the purchase of soy and cattle from recently deforested areas (Nepstad *et al* 2014).

Here we construct new MAC curves for reducing tropical deforestation that take advantage of recent satellite data and account for the drop in deforestation in the Brazilian Amazon. We do so by projecting future emissions from deforestation in a business-as-usual scenario and then estimating how many emissions would be avoided if tropical forest governments enacted domestic carbon pricing policies. In tropical forest countries a carbon price could take the form of some combination of taxes on emissions or payments for emission reductions, with the potential to receive external funding from international carbon markets or public funds. Because there is as yet little direct empirical evidence with which to calibrate the responsiveness of deforestation to carbon prices, we turn to evidence on the historical responsiveness of deforestation to agricultural prices.

Ours is the first pan-tropical MAC curve to estimate the price-responsiveness of deforestation empirically based on historically observed land-use decisions (a 'revealed preference' approach, as applied in individual countries by Plantinga *et al* 1999, Stavins 1999, Lubowski *et al* 2006, Pfaff *et al* 2007, Busch *et al* 2012), rather than relying on the assumption in previous pan-tropical MAC curves that land would be entirely maintained as forests wherever potential carbon payments exceed net revenue from alternative land uses, and would be entirely deforested otherwise (an 'opportunity-cost' approach). By estimating the average effect of changes in prices on deforestation, the revealed preference approach implicitly accounts for real patterns of land tenure, farm size, integration with global markets, and other factors. Thus our MAC curve addresses one common shortcoming of MAC curves (limited treatment of behavioral aspects) even while remaining sensitive to other shortcomings (e.g. limited consideration of ancillary non-carbon benefits and non-financial costs) (Kesicki and Ekins 2012).

In developing new MAC curves for reducing emissions tropical deforestation, we make two additional contributions. First, by using the spatially resolved Hansen *et al* (2013) data we observe and document

an inverted-U-shaped relationship between forest loss and forest cover at the site level. Such a relationship had previously been simulated (e.g. Soares-Filho *et al* 2006) but we are aware of no previous reports of it being observed in data. Accounting for this relationship can improve projections of the rate and pattern of future pan-tropical deforestation.

And second, by using data from tropical countries beyond Brazil we are able to estimate the impact of Brazil's anti-deforestation policies in aggregate. A number of recent studies have used spatial data from within Brazil to evaluate the impact on Amazon deforestation of *individual* anti-deforestation policies, e.g. law enforcement (Hargrave and Kis-Katos 2013, Arima *et al* 2014, Borner *et al* 2015a), satellite monitoring (Assunção *et al* 2013a), protected areas and indigenous territories (Soares-Filho *et al* 2010), credit restrictions (Assunção *et al* 2013b), jurisdictional blacklists (Assunção and Rocha 2014, Cisneros *et al* 2015), and the soy moratorium (Gibbs *et al* 2014), as well as agricultural prices (Assunção *et al* 2015). But aside from Assunção *et al* (2015), no other study has estimated the effect of Brazil's many intertwined policies in aggregate. We use this estimate to project future reductions in emissions from deforestation if all tropical countries were able to replicate the impact of Brazil's restrictive policies with equivalent effectiveness in their own policy settings, and then compare this level of reductions to those resulting from carbon pricing.

Methods

We obtained data on annual pan-tropical forest cover loss from 2001–2012 by classifying 30 m Landsat-derived tree-cover loss data (Hansen *et al* 2013) into forest or non-forest using a tree-cover threshold of 25%. We did not consider forest gain (Hansen *et al* 2013), as these data do not capture regrowing forests below 5 m in height by 2012 nor growth within forests established before 2000 (Tyukavina *et al* 2015).

We compiled data on other geographic factors known to affect the likelihood of deforestation (Busch and Ferretti-Gallon 2017). These included average slope and elevation (Jarvis 2008), distance to a large city in the year 2010 (UNDESA 2012), and protected areas (WDPA 2014), and initial forest cover (Hansen *et al* 2013). We did not include roads because available data on road density varied too widely across countries to be useful for a comparative pan-tropical analysis.

We constructed an original data layer on annual potential gross agricultural revenue by multiplying potential yields for 21 crops based on global agro-ecological zones (IIASA/FAO 2012) by a production-weighted average of national farmgate prices (FAO 2014) for the top five producer countries, adapting the methods of Naidoo and Iwamura (2007). We did not include revenues for cattle or

logging for which no pan-tropical spatial data on potential production were available.

We calculated emission factors for deforestation and peat degradation based on the release upon deforestation of 100% of aboveground carbon in forest biomass (Baccini *et al* 2012), belowground biomass equal to 26% of aboveground biomass (Mokany *et al* 2006, Harris *et al* 2012), 59.4 GtCO₂ ha⁻¹ yr⁻¹ for 30 years on peat soil (Murdiyarso *et al* 2010), and 8.5% of soil carbon in the top 30 cm of non-peat soil (FAO/IIASA/ISRIC/ISSCAS/JRC 2008, Powers 2011).

We restricted the geographic scope of our analysis to the pan-tropics as defined in Baccini *et al* (2012), spanning 101 countries across Latin America, Sub-Saharan Africa, and tropical Asia. We gridded and aggregated data to 1.5 million grid cells measuring 0.05° × 0.05° (approximately 5.5 km × 5.5 km at the equator). With 12 time-steps for each grid cell our full data set included 18 million observations.

We constructed a multivariate regression model to explain observed annual fractional grid-cell-level deforestation based on spatial and temporal variation in cells' geographic characteristics. We included a fourth-order polynomial for forest cover to allow for a flexible relationship between deforestation and forest cover. To account for regional variation in drivers of deforestation (Rudel *et al* 2009, Fisher 2010) we constructed three separate models for each of the tropical regions (Sub-Saharan Africa; Latin America, Tropical Asia). Within the Latin America region, the aggregate effect of Brazil's restrictive policies consisted of two components: a dummy variable for post-2004 (i.e. 2005–2012) Brazilian Amazon, and an interaction term between post-2004 Brazilian Amazon and agricultural prices. We estimated the influence of explanatory variables on deforestation in R using a Poisson quasi-maximum likelihood estimator (Wooldridge 2002, Burgess *et al* 2012, Busch *et al* 2012, Busch *et al* 2015).

We projected future deforestation from 2013 to 2050 under a business-as-usual (no-policy) scenario using a dynamic recursive model. We calculated forest cover at the start of the year 2013 by subtracting observed forest loss between 2001–2012 from observed forest cover in the year 2000. Forest cover at the start of each subsequent year through 2050 was calculated by subtracting projected deforestation in the previous year from forest cover at the start of the previous year, subject to the constraint that forest cover could not drop below zero. Projected deforestation in a cell-year was calculated by applying the regression model to assumed characteristics of the cell in that year, including the fourth-order polynomial relationship with the cell's forest cover.

We modeled the effect of a carbon pricing policy such as a national cap-and-trade program or symmetric carbon tax-and-subsidy for emissions from deforestation, assuming full participation across all grid cells in all tropical countries. A carbon price lowered the

potential to gain agricultural revenue from converting forests for crops relative to the potential to gain carbon revenue from conserving forests, resulting in lower expected deforestation. We calibrated the marginal effect of a carbon price on deforestation using the empirical relationship between the observed pattern of historical deforestation and variation across space and time in agricultural prices. We assumed that land users would respond equivalently to agricultural prices and carbon prices.

We constructed a counterfactual scenario in which restrictive policies had not been put in place in the Brazilian Amazon by setting the parameter values associated with restrictive policies to zero in all years. We constructed the counterfactual scenario in which all countries implemented restrictive policies as effective as those in the Brazilian Amazon by applying the parameter values associated with restrictive policies in all cells in all years.

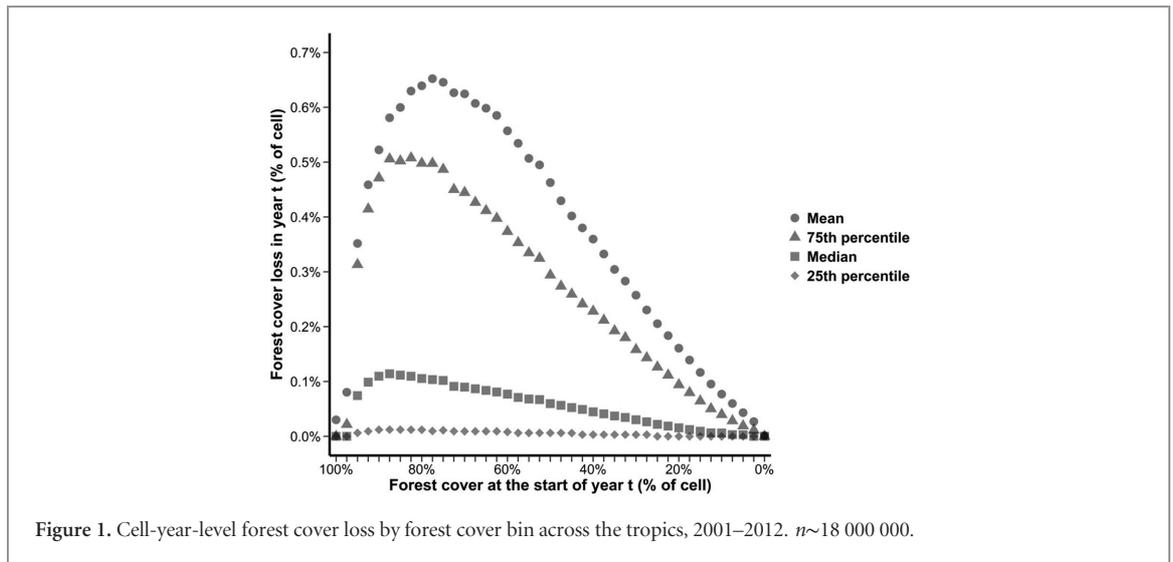
We tested the sensitivity of our results to a variety of model and parameter assumptions, including future agricultural prices, carbon stock data sets, carbon pools included, peat emission factor, functional form, the sensitivity of land-use change to changes in prices, and whether or not Brazil would continue to maintain its restrictive policies. We also tested the sensitivity of results to the inclusion of uniform per-hectare transaction costs or management costs, and uniform per-hectare benefits representing ancillary co-benefits of forest conservation (e.g. forest goods; water-cleaning services; preference for intact ecosystems). And we tested the sensitivity of our results to the effect of potential leakage, that is, avoided deforestation in one place causing the displacement of deforestation elsewhere due to market feedbacks.

For more detail on data, methods, assumptions, and sensitivity analyses see the supplementary information.

Results

Tropical forest cover loss totaled 96.6 million hectares from 2001–2012 (i.e. the twelve-year period from 1 January 2001 to 31 December 2012) across the 101 countries included in our study. Associated emissions totaled 47.1 GtCO₂ (supplementary appendix figure S1). Of these emissions, 24.6 GtCO₂e (52%) were from aboveground biomass; 6.4 GtCO₂ (14%) were from belowground biomass; 1.5 GtCO₂ (3.2%) were from non-peat soils; and 14.6 GtCO₂ (31%) of emissions were from peat soils. Our estimate of annual emissions from forest loss and peat emissions from 2001–2012, 3.9 GtCO₂e yr⁻¹, is comparable to the estimates of most other studies of emissions during this period (supplementary appendix table S1).

We observed that on average deforestation had an inverted-U-shaped relationship with respect to remaining forest cover (figure 1). Grid cells with very high



levels of forest cover had low levels of deforestation on average. Cells' average level of deforestation increased rapidly as less forest cover remained, reaching a peak at a forest cover of 75%–90% before decreasing at lower levels of forest cover. This inverted-U-shaped relationship was robust to region (supplementary appendix figure S2), year (supplementary appendix figure S3), and the use of an alternative data set on forest cover loss from Brazil (INPE 2014, supplementary appendix figure S4). This relationship is consistent with deforestation as a spatial diffusion process (Skole 1994) in which forests remain passively protected by difficulty of access (Peres and Terborgh 1995) until nearby deforestation brings them into closer proximity to cleared land. While such a relationship has been simulated in geographic models in which deforestation is a function of proximity to previously deforestation land (e.g. Soares-Filho *et al* 2006), to our knowledge it has not previously been reported to have been observed. It has not been included in spatially explicit econometric analyses of determinants of deforestation (Busch and Ferretti-Gallon 2017) nor previous MAC curves. The inverted-U-shaped relationship at any point in time implies that the trajectory of forest cover through time follows an inverted-S shape (supplementary appendix figure S5).

Determinants of deforestation generally conformed to expectations of their signs and significance (Busch and Ferretti-Gallon 2017), though the magnitude of their influence varied across continents. Generally, deforestation was higher at lower slope, lower elevation, outside of protected areas, and closer to cities, controlling for other factors (supplementary appendix table S3). Exceptions included the time-invariant factors of elevation and distance to cities in Latin America and slope in Africa. Strictly protected areas reduced deforestation more than multiple-use protected areas across all continents, controlling for other factors. Across all continents, greater potential agricultural revenue increased deforestation. We estimated that every

additional US\$100 ha yr⁻¹ in potential agricultural revenue increased the rate of deforestation by an average of 0.98% in Latin America, 1.60% in Africa, and 2.42% in Asia, controlling for other factors—a variation of 2.5 across continents. Average potential agricultural revenues were \$2978 ha yr⁻¹, \$2304 ha yr⁻¹, and \$3278 ha yr⁻¹ on each continent respectively, implying a price elasticity of supply of deforestation of 0.29, 0.37, and 0.79 for each continent respectively. Brazil's restrictive policies had the effect of reducing post-2004 deforestation by 47% for a grid-cell with average characteristics, due in part to decoupling potential agricultural revenue from deforestation.

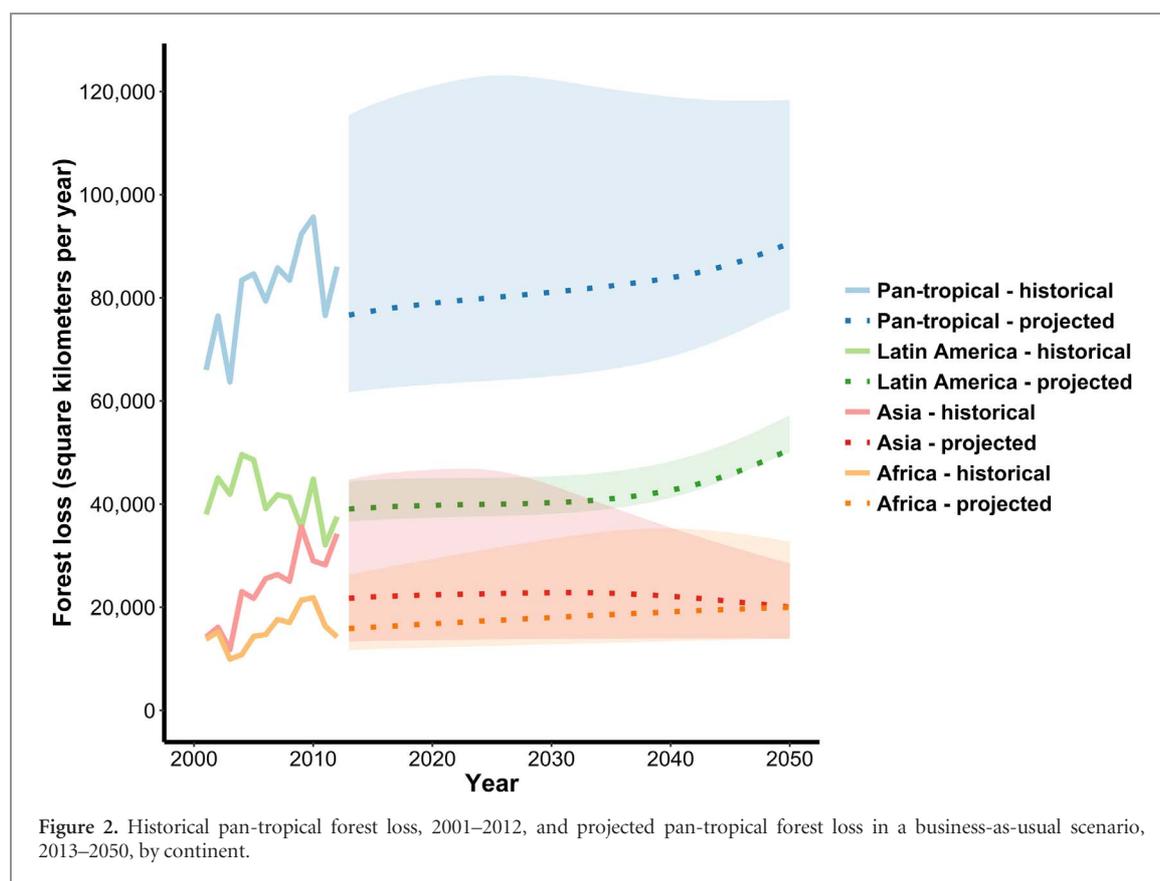
In the business-as-usual scenario, we projected that 289 million hectares of tropical forest would be deforested from 2016–2050—about the same as the land area of India (297 million hectares; World Bank 2014), and about one-seventh the total area of tropical forest in the year 2000 (Hansen *et al* 2013). Our projected tropical forest loss is larger than a projection that 232 million hectares of forest will be cleared worldwide by 2050 (WWF/IIASA 2011).

We projected that business-as-usual tropical forest loss would release 169 GtCO₂—one-sixth of the remaining planetary carbon budget of 1000 GtCO₂ that provides a two-thirds likelihood of global temperatures rising less than 2 °C (IPCC 2014). About half of these emissions (50%) would come from Latin America, with about one-third (33%) from Asia and one-sixth (16%) from Africa (table 1).

We projected the rate of pan-tropical forest loss to climb slowly through the 2020s and 2030s before accelerating in the 2040s as areas of high forest cover in Latin America that are currently experiencing little deforestation come under greater threat, for example, as recently constructed logging roads lead to accelerating rates of deforestation in the future (figure 2). Our projection of rising future deforestation is a function of the inverted-U-shaped relationship between deforestation and forest cover and not of a residual temporal trend in

Table 1. Deforestation and associated emissions under alternative policy scenarios, 2016–2050.

	Deforestation (million ha)				Emissions (GtCO ₂)			
	Tropical total	Latin America	Africa	Asia	Tropical total	Latin America	Africa	Asia
Historical (2001–2012)	96.6	49.2	18.5	28.9	47.1	19.2	7.1	20.8
Future (2016–2050) business-as-usual	289	148	64	77	169	85	28	56
Carbon price: \$20/tCO ₂	244	130	56	58	128	69	22	37
Carbon price: \$50/tCO ₂	198	111	47	40	92	54	17	21
Brazil abandons restrictive policies	365	224	64	77	224	141	28	56
Rest of tropics adopts restrictive policies	192	115	34	44	111	66	14	31
Rest of tropics adopts restrictive policies + \$20/tCO ₂	163	101	30	33	85	54	11	20
Rest of tropics adopts restrictive policies + \$50/tCO ₂	134	86	25	23	62	42	8.6	12

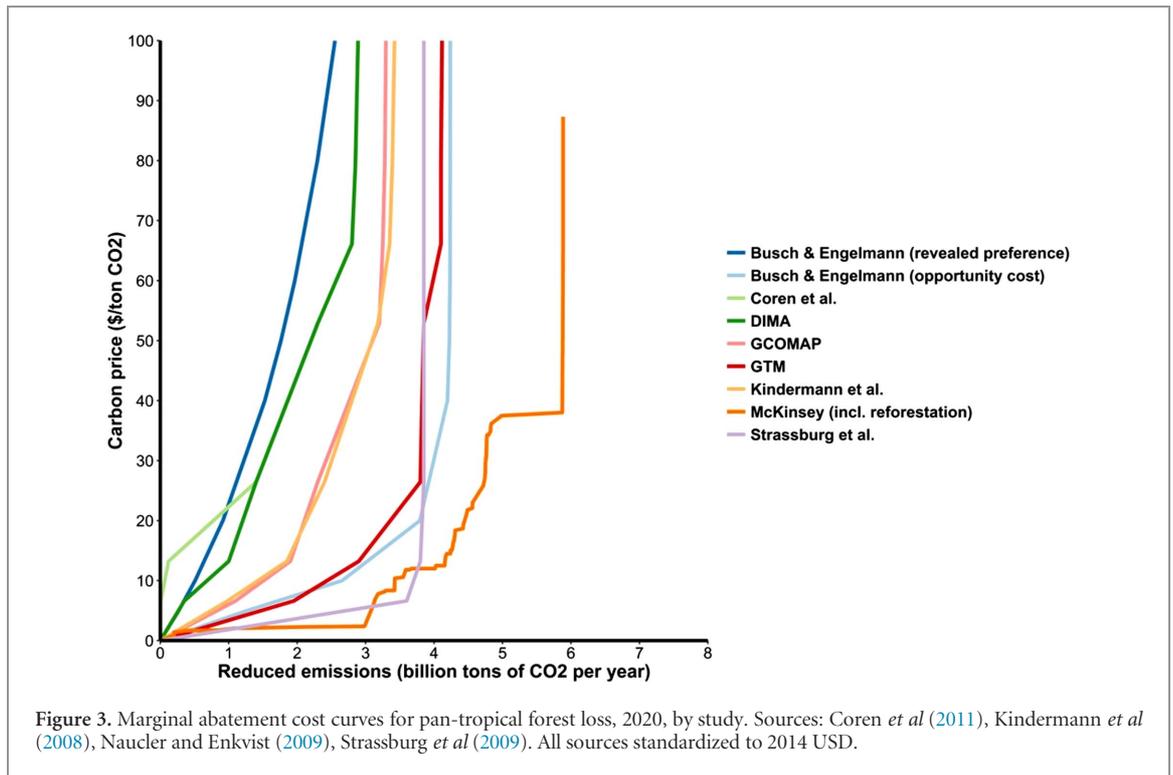

Figure 2. Historical pan-tropical forest loss, 2001–2012, and projected pan-tropical forest loss in a business-as-usual scenario, 2013–2050, by continent.

historical data; if the inverted-U-shaped relationship were not considered, projected annual deforestation would instead decline gradually in future decades. Our projection of rising tropical deforestation contrasts with projections of diminishing global deforestation based on FAO FRA data (d'Annunzio *et al* 2015).

Because we project deforestation to shift into higher-carbon forests, we project annual emissions from deforestation to rise by 42% between 2016 and 2050 even as annual deforestation rises by 16% over the same time period. This projection of rising emissions is consistent with the Global Change Assessment Model (Thompson *et al* 2010), which projects that emissions from deforestation will rise until 2035 before falling, but is at odds with the partial equilibrium models presented in Kindermann *et al* (2008) which project emissions from deforestation will fall between 2020 and 2030 (supplementary appendix figure S9). The projection of rising emissions also contrasts with the projection

of falling emissions in partial equilibrium models and integrated assessment models reviewed in Lubowski and Rose (2013), though those were projections of mitigation scenarios rather than business-as-usual scenarios (supplementary appendix figure S9).

The introduction of a carbon pricing policy would decrease emissions from deforestation below business-as-usual levels (supplementary appendix figure S10; table 1). A carbon price of \$20/tCO₂, equivalent to an average cost to land users of \$9/tCO₂, would reduce emissions from deforestation by 4.4 GtCO₂ (21.1%) from 2016–2020 and by 40.9 GtCO₂ (24.2%) from 2016–2050. ‘Hotspot’ regions of the tropics where the most emissions from deforestation could be avoided by a carbon price of \$20/tCO₂ include island Southeast Asia, many regions of mainland Southeast Asia, Central and West Africa, many regions of Amazonia, and eastern Central America (supplementary appendix figure S6). A carbon price of \$50/tCO₂, equivalent to an



average cost to land users of \$21/tCO₂, would reduce emissions from deforestation by 8.5 GtCO₂ (40.9%) from 2016–2020 and by 77.1 GtCO₂ (45.7%) from 2016–2050.

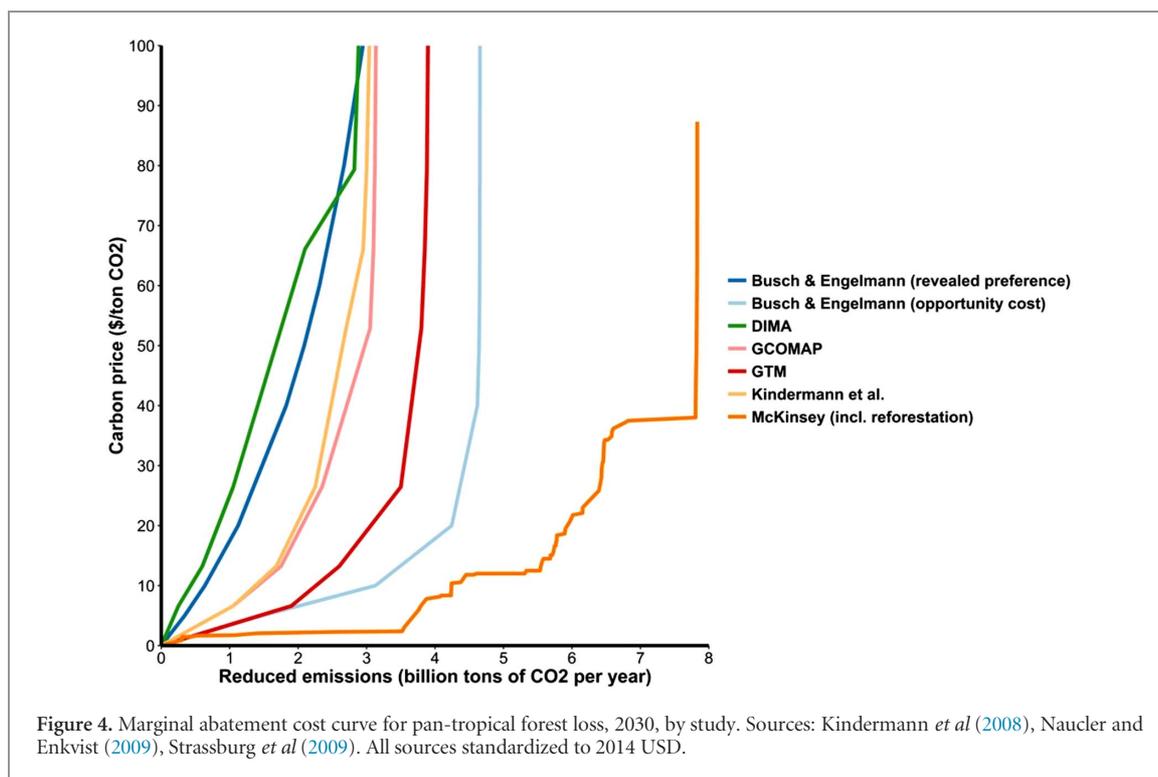
Our projection of near-term low-cost abatement (e.g. 0.92 GtCO₂ avoided in response to a price of \$20/tCO₂ in 2020) was toward the lower end of the range of previously published MAC curves for reduced tropical deforestation (0.8–4.4 GtCO₂ avoided in response to a price of \$20/tCO₂ in 2020) (figure 3). This is in part because our newer data accounted for reductions in deforestation made by Brazil after 2004, but also because land users reduced their observed deforestation in response to historical changes in prices by less than assumed under the opportunity cost approach used in previous analyses. Applying to our data the approach used by Grieg-Gran (2006), Strassburg *et al* (2009), and Busch *et al* (2009), in which a 15% profit margin was applied uniformly regardless of potential geographic variation in input and startup costs, resulted in 3.8 GtCO₂ avoided in response to a price of \$20/tCO₂ in 2020. The functional form of our model also contributed to the difference in price responsiveness across studies; allowing the effect of agricultural prices on deforestation to vary quadratically rather than linearly in our model nearly doubled the amount of emission reductions available in response to a price of \$20/tCO₂ (supplementary appendix table S4). We projected that the amount of emission reductions available at any given price would increase into the future (figure 4, supplementary appendix figure S8) as business-as-usual emissions from deforestation increase through time. This finding is at odds with the partial equilibrium models presented in Kindermann *et al* (2008)

which project that the amount of emission reductions available at a given price will fall between 2020 and 2030.

Brazil's restrictive policies substantially reduced deforestation in the Amazon; without them forest loss in the Brazilian Amazon from 2005–2012 would have been 86% higher than it was (26.7 million hectares rather than 14.3 million hectares) and associated emissions would have been 90% higher (11.0 GtCO₂ rather than 5.8 GtCO₂). Our estimate of emissions prevented by Brazil's policies (5.2 GtCO₂ from 2005–2012) is higher on a per-year average basis than the 2.7 GtCO₂ from 2005–2009 estimated by Assunção *et al* (2015). It is considerably higher than another recent 'tentative' estimate (0.65–1.96 GtCO₂ from 2005–2013, achieved at a budgetary cost of \$2.1 billion to federal, state, and local governments; Fogliano *et al* (2016), since our model predicted that in the absence of restrictive policies deforestation would have increased after 2005, as it did elsewhere, rather than remaining stable at average pre-2005 levels.

We projected that if Brazil fails to sustain its policies and instead reverts to the pre-2004 policy environment, then pan-tropical forest loss from 2016–2050 would be 26% higher than it would be otherwise (365 million hectares rather than 289 million hectares), with associated emissions that are 33% higher (224 GtCO₂ rather than 169 GtCO₂). Negating the additional emissions from undoing restrictive policies would require a carbon price across the Brazilian Amazon of \$86/tCO₂.

On the other hand, if all tropical countries were able to replicate the impact of Brazil's 2004–2012 restrictive policies with equivalent effectiveness in their own policy settings, then pan-tropical forest loss and associated



emissions would be 34% lower (192 million hectares and 111 GtCO₂ respectively), avoiding 7.2 GtCO₂ from 2016–2020 and 57.8 GtCO₂ from 2016–2050. This is equivalent to the effect of enacting a carbon price of \$47/tCO₂ throughout the entire tropics outside the Brazilian Amazon. If all tropical countries, in addition to replicating the effectiveness of Brazil's policies, enact a carbon price, then emissions from 2016–2050 would be 50% lower (85 GtCO₂) at a price of \$20/tCO₂ and 63% lower (63 GtCO₂) at a price of \$50/tCO₂.

Results were sensitive to a variety of data set choices, parameter assumptions, and modeling decisions. The most significant of these was assumed future agricultural prices, with the range between constant (low) 2001 prices and (high) 2012 prices presented in figure 2. Results were more sensitive to carbon pools considered in emission factors, peat emission factor, land users' responsiveness to prices, and quadratic treatment of prices, and less sensitive to the use of alternative carbon stock data sets, the use of a Tweedie functional form, the inclusion of cattle revenue, other-order polynomials on forest cover, basing potential agricultural revenue on the most lucrative crop of the twelve-year rather than one-year period, and a single pan-tropical model (supplementary appendix table S4). The addition of uniform per-hectare costs representing transaction costs and management costs reduced emission reductions, while the addition of uniform per-hectare co-benefits increased emission reductions. Introducing leakage to the model reduced the available abatement at any given price by raising agricultural prices faced by land users, bringing MAC curves inward (supplementary appendix

figure S7). Introducing selective participation within countries also reduced available abatement, especially at low carbon prices, underscoring the importance of national-level programs and participation by many countries in deforestation-reduction efforts.

Discussion and conclusions

In the absence of new forest conservation policies, we project that tropical deforestation will persist for decades and even accelerate. Projected business-as-usual tropical forest loss of 289 million hectares between 2016–2050 would release 169 GtCO₂, curtailing the likelihood of limiting global temperature rise to well below 2 °C, as intended by the 2015 Paris climate agreement.

Areas of the tropics with high forest cover and historically low levels of deforestation (da Fonseca *et al* 2007) should be expected to experience rising levels of deforestation while areas with intermediate forest cover that are currently experiencing high levels of deforestation should be expected to experience falling levels of deforestation. This projection results from applying the robust inverted-U-shaped relationship between forest cover and deforestation observed in this study. Factoring this inverted-U shaped relationship into projections of future deforestation can improve the accuracy of reference levels for payments for reducing emissions from deforestation and forest degradation (REDD+), relative to extrapolating average historical rates (e.g. Forstater *et al* 2013) or applying ad hoc adjustments to historical rates (e.g.

Gutman and Aguilar-Amuchastegui 2012). Controlling for this relationship can also reduce potential omitted variable bias in spatially explicit econometric analyses of determinants of deforestation.

Our revealed-preference model corroborates the findings of previous opportunity cost-based partial equilibrium models that reducing emissions from tropical deforestation is a cost-effective action for mitigating climate change relative to actions in other regions and sectors. A carbon price of \$20/tCO₂ would avoid 923 MtCO₂ of emissions from tropical deforestation in 2020. While this is toward the low end of the range projected by earlier studies, this is still 4.5 times the 206 MtCO₂ available at the same price in the European Union (Kim *et al* 2006, JGCRI 2015), and 55 times the 17 MtCO₂ available at the same price in California (Air Resources Board 2010)—two regions with carbon pricing policies already in place. Incorporating the MAC curves from this study into multi-sector integrated assessment models would be useful future research.

As an alternative to carbon pricing, governments of forested countries could reduce emissions from deforestation by implementing restrictive policies, as Brazil did post-2004 in the Amazon where potential agricultural revenue was decoupled from deforestation. For example, we find that if all tropical countries could enact restrictive anti-deforestation policies with equivalent effectiveness to those in the Brazilian Amazon, one-third of emissions from tropical deforestation from 2016–2050 would be avoided—a greater amount than the one-quarter of emissions that would be avoided from a carbon price of \$20/tCO₂. Unlike carbon pricing, enacting restrictive policies could be accomplished without having to establish new institutions for assigning and monitoring land users' emission rights, which could be complicated or expensive across much of the tropics because of unclear property rights over forest lands (Clements *et al* 2010). Furthermore, restrictive policies might well have lower budgetary costs than carbon pricing (e.g. Fogliano *et al* 2016). However, because restrictive policies would push opportunity costs onto current and would-be land users, they lack the potential of carbon payments to create winners from policy as well as losers (Borner *et al* 2015b, Nepstad *et al* 2014). Combining restrictive policies with carbon pricing allows for even greater emission reductions while achieving a desired distribution of winners and losers from policy.

That so much more abatement is available at a given price in tropical forests than in developed countries suggests the need to find ways to pay for the relatively modest costs of reducing deforestation in developing countries. One method with great potential is international carbon payments for REDD+, with performance in reducing deforestation monitored and verified by satellite (Seymour and Busch 2016). Such payments could provide ex post finance for the successful results of either domestic carbon pricing

policies or restrictive policies. The 2015 Paris climate agreement endorsed this concept by codifying a framework for REDD+ and sanctioning 'internationally traded mitigation outcomes.' However, international finance for REDD+ hovers around just \$1 billion per year, of which less than half is paid for ex post results (Norman and Nakhouda 2014). This leaves considerable room to grow, for example through bilateral agreements, the Green Carbon Fund, the Forest Carbon Partnership Facility, linkage to carbon markets such as California's, purchases by members of the International Civil Aviation Organization, or other channels.

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