Structuring economic incentives to reduce emissions from deforestation within Indonesia

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We estimate and map the impacts that alternative national and subnational economic incentive structures for reducing emissions from deforestation (REDD+) in Indonesia would have had on greenhouse gas emissions and national and local revenue if they had been in place from 2000 to 2005. The impact of carbon payments on deforestation is calibrated econometrically from the pattern of observed deforestation and spatial variation in the benefits and costs of converting land to agriculture over that time period. We estimate that at an international carbon price of \$10/ tCO_2e, a "mandatory incentive structure," such as a cap-and-trade or symmetric tax-and-subsidy program, would have reduced emissions by 163–247 $MtCO_2e$/y (20–31% below the without-REDD+ reference scenario), while generating a programmatic budget surplus. In contrast, a "basic voluntary incentive structure" modeled after a standard payment-for-environmental-services program would have reduced emissions nationally by only 45–76 $MtCO_2e$/y (6–9%), while generating a programmatic budget shortfall. By making four policy improvements—paying for net emission reductions at the scale of an entire district rather than site-by-site; paying for reductions relative to reference levels that match business-as-usual levels; sharing a portion of district-level revenues with the national government; and sharing a portion of the national government's responsibility for costs with districts—an "improved voluntary incentive structure" would have been nearly as effective as a mandatory incentive structure, reducing emissions by 136–207 $MtCO_2e$/y (17–26%) and generating a programmatic budget surplus.

climate change | climate policy | land-use change | reducing emissions from deforestation and forest degradation

An emerging international climate policy mechanism called REDD+ would offer payments to developing countries that voluntarily reduce greenhouse gas emissions from deforestation below internationally agreed reference levels (1). Individual forested countries would decide upon the specific set of policies and measures to implement to achieve nationwide emission reductions. Accounting for these net emission reductions would ultimately take place at the national level, making national governments responsible for any internal geographical shifts of emissions (leakage), and providing incentives for systemic policy actions. However, although governments would receive payments under REDD+, it is actors at the regional, provincial, local, or household (subnational) scales who are directly responsible for many land-use change decisions. Thus, the effectiveness of REDD+ in reducing emissions and generating revenue will depend upon how national governments structure economic incentives so that subnational actors will be encouraged to reduce emissions and discouraged from increasing emissions.

Emission-reduction policy in the energy and industrial sectors of developed countries has commonly been approached through mandatory, market-based incentive structures, such as cap-and-trade or tax-and-subsidy programs. Such "mandatory" structures can be considered economically ideal in that all regulated actors at any emission level have an economic incentive to reduce an additional unit of emissions. However, in the land-use sectors of developing countries with decentralized land-use decision rights, national governments may instead prefer to structure incentives for emission reduction in such a way that subnational actors might voluntarily choose to maintain forests rather than convert land to agriculture or other uses. A voluntary incentive structure for REDD+ would be characterized by four policy decisions. (*i*) An "accounting scale" would determine the administrative level at which net emission reductions are calculated and payments made, thereby determining the de facto local decision makers for REDD+. (*ii*) A subnational "reference level" would be the level of emissions below which an actor could be rewarded for reductions. (*iii*) A "revenue sharing" arrangement would determine the portion of international income from carbon payments that would accrue to actors that reduce emissions, and the portion that would remain with the national government. (*iv*) A "responsibility-sharing" arrangement would determine the extent to which actors would be penalized for increasing emissions, and the extent to which the national government would bear the cost of these increases through reduced international payments.

A voluntary incentive structure for REDD+ would face design challenges that a mandatory incentive structure would not. In a voluntary system, the assignment of reference levels not only affects equity in the distribution of payments, as is the case with the distribution of allowances in a cap-and-trade system, but also affects the system's effectiveness in reducing emissions (2). Discrepancies between reference levels and counterfactual business-as-usual emission rates (3) can aggravate an adverse selection problem caused by information asymmetry between private actors and regulators in a voluntary system (4). Actors with reference levels above their business-as-usual emission rates could claim windfall payments beyond their actual emission reductions. Meanwhile, actors with reference levels below their business-as-usual rates could have insufficient incentive to participate in reducing emissions, and could even increase emissions above what they would have been in the absence of the REDD+ incentive system. As a result, a country's choice of economic incentive structure for REDD+ will critically impact the level of greenhouse gas emission reductions it can achieve, the cost-effectiveness of these reductions, and the distribution of costs and benefits within the country.

This article presents a spatially explicit land-use change model for Indonesia that allows us to estimate and map the expected

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impact of alternative economic incentive structures on reductions in emissions from deforestation and on the distribution of revenues and costs between the national government and local actors. While REDD+ in its entirety includes deforestation, forest degradation, conservation, sustainable management of forests and enhancement of forest carbon stocks, in this article we examine only emissions from deforestation.

We make several important methodological advances on previous models that have estimated the emission reduction potential of REDD+. First, most previous studies have relied upon a deterministic "opportunity cost" assumption that deforestation would be avoided entirely wherever potential carbon payments exceed net revenue from alternative land uses (5–14). In contrast, we calibrate the marginal impact of potential carbon payments on deforestation using the empirical relationship between the pattern of observed deforestation in a historical period and spatial variation in the benefits and costs of converting land from forest to agriculture. Using this "revealed preference" approach to estimate the impact of potential payments based on evidence from actual land-use decisions implicitly accounts for the richer set of factors that affect land-use in practice (15–18). Second, most previous studies have modeled land-use responses to variations in a single parameter: the carbon price. By modeling land-use response to variations in both the carbon price and subnational reference levels, and modeling participation decisions at multiple geographic scales, we are able to compare a wider range of potential policies for implementing REDD+ within a country. Third, as in global partial equilibrium (6, 9) or general equilibrium (12, 19) models, but unlike other opportunity cost (5) or regional (11) analyses, we model the "leakage" of deforestation (20) within the country, whereby reduced deforestation in one region produces market feedbacks that increase deforestation elsewhere. Finally, unlike previous qualitative discussions of multiscale REDD+ incentive policies (21–23), we are able to quantify and map the impacts of policy decisions within a particular country.

We select Indonesia as a case study because of its large forested area [94 million hectares in 2010 (24)], high greenhouse gas emissions from deforestation and peat degradation [1.46 $GtCO_2e$/y, or 3.3% of global emissions (25)], and globally significant commitment to emission reductions. In 2009, President Susilo Yudhoyono declared a national goal to reduce emissions by 26–41% below levels projected to 2020 (26). In May 2010, Indonesia and Norway signed a $1 billion agreement on bilateral cooperation to reduce emissions from deforestation and forest degradation, with payments in the final phase contingent upon verified emission reductions (27). Drivers of deforestation in Indonesia include large-scale conversion for industrial agriculture, small-scale conversion for community use, establishment of timber plantations, and planned and unplanned timber extraction (28). The national and provincial governments are responsible for allocating the forest estate between land uses, but the right to approve permits within certain land-use allocations was decentralized to district governments in 2002. Responsibility for monitoring and enforcement is shared by the national and district governments (29).

Indonesia is currently drafting a National Strategy for REDD+ (30) that will produce an economic incentive structure for reducing emissions from deforestation. The draft National Strategy envisions the "implementation [of REDD+] at the sub-national level, [with] the displacement of emission within the country territory boundaries handled at the national level". The Strategy considers development of national and subnational reference levels to be a prerequisite for REDD+, and recognizes that in the absence of an existing legal basis for carbon rights, elaborating benefit and responsibility-sharing mechanisms will create a clear delegation of responsibilities for reducing emissions. It is in the specific context of Indonesia and its National Strategy that we estimate the impacts of alternative economic incentive structures for REDD+. However, our policy analysis extends to any geographic region where emission reductions would be credited at an aggregate scale but land-use decisions are made locally.

We compare four scenarios for how a nationwide economic incentive structure for REDD+ could have been implemented in Indonesia over 2000–2005. First, as a point of departure for policy comparisons, we model counterfactual deforestation emissions in the absence of any carbon payment policies ("reference scenario") based on observable site characteristics and econometrically estimated parameters. Second, we consider a basic REDD+ policy framework ("basic voluntary incentive structure") consistent with standard payment-for-environmental-services (PES) programs, which offer voluntary incentives at the scale of the individual project or landowner (31). Specifically, we model payments based on 3-km × 3-km site scale reductions in emissions below reference levels equal to observed historical deforestation emissions, with no revenue-sharing or responsibility-sharing. Third, we sequentially add four potential policy adjustments to the basic voluntary incentive structure to produce an "improved voluntary incentive structure." In this scenario, payments are based on emission reductions at the district scale, below reference levels that are hypothetically able to perfectly match the business-as-usual emissions assumed under the reference scenario. In this scenario, the national government also shares 20% of the carbon revenue from districts' decreased emissions, and districts are responsible for paying 20% of the cost of lost international carbon payments because of their increased emissions. Finally, we consider a scenario that is consistent with a cap-and-trade or symmetric tax-and-subsidy program for deforestation emissions ("mandatory incentive structure"). In this scenario, districts are paid the full international carbon price for any reductions in emissions below a reference level that is 10% below assumed business-as-usual emissions; districts are penalized by the full international carbon price for any increase in emissions above the same reference level. Based on these national incentive structures, each of the 401 districts decide whether and by how much net emissions would be reduced within their borders.

Results

In the absence of any carbon payments, econometric modeling based on observable land characteristics generated a deforestation prediction (691,000 ha/y) that was within 1% of observed historical deforestation (687,000 ha/y), and an emissions prediction (809 $MtCO_2e$/y) within 6% of emissions estimated from observed deforestation (860 $MtCO_2e$/y). However, correlation between observed deforestation and deforestation predicted in the reference scenario was lower at the finer geographic scales of the province ($R = 0.81$; $n = 31$) (*SI Appendix*, Table S7), the district ($R = 0.68$; $n = 401$) (*SI Appendix*, Fig. S3 and Table S7) and the 3-km × 3-km "site" ($R = 0.34$; $n = 166{,}296$) (Fig. 1 *A* and *B*).

For every $1,000 per hectare increase in net present potential agricultural revenue, deforestation was estimated to increase by 1.4% (1.0–1.9%, with 95% confidence) at low-forest cover sites and 7.3% (5.6–9.0%) at high-forest cover sites, controlling for other factors (*SI Appendix*, Table S3). The regions with the greatest expected emission reductions in response to $10/$tCO_2e$ payments for site-level reductions below business-as-usual rates, assuming no leakage, were the peat-rich lowlands of Papua, Kalimantan, and Sumatra (Fig. 2).

At an international carbon price of $10/$tCO_2e$, a basic voluntary incentive structure for REDD+ would have reduced net national deforestation emissions by an estimated 62 $MtCO_2e$/y, or 8% below the reference scenario (45-76 $MtCO_2e$/y; 6–9%). In this scenario the national government would have paid $6.8

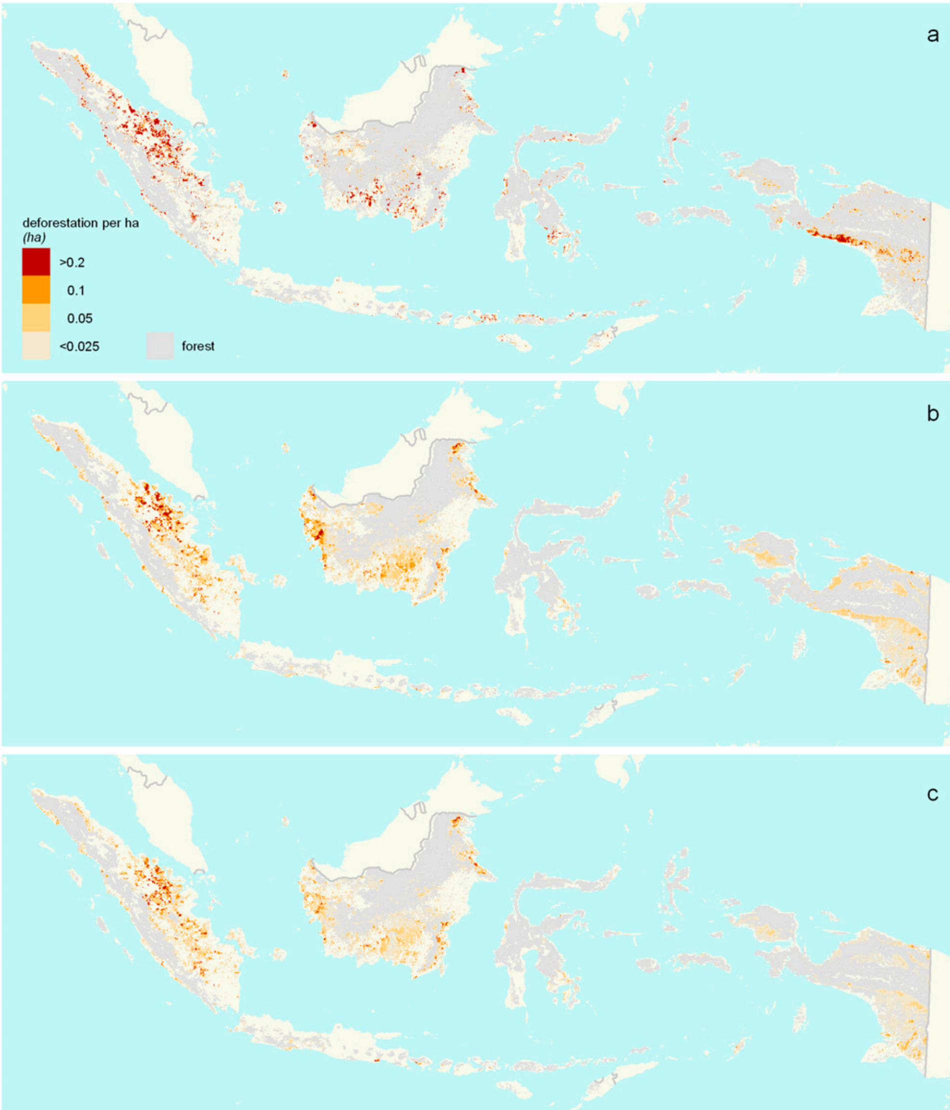

Fig. 1. Deforestation in Indonesia, 2000–2005. (*A*) observed deforestation (687 kha/y; 860 mtCO_2e/y); (*B*) modeled expected deforestation without REDD+ (691 kha/y; 809 mtCO_2e/y); (*C*) expected deforestation with "improved voluntary incentive structure" for REDD+ (597 kha/y; 633 mtCO_2e/y). Results are outputs of OSIRIS-Indonesia v1.5 assuming the following parameters: carbon price = \$10/tCO_2e; "effective" price elasticity = 3.8; exogenous agricultural price increase = 0%; peat emission factor = 1,474 tCO_2e/ha; social preference for agricultural revenue relative to carbon revenue = 1.0; start-up and transaction costs = \$0.

billion per year to local sites for gross reductions below historical reference levels, but would have received just \$610 million per year from international buyers for net reductions below a national reference level, resulting in a programmatic budget shortfall over that period (Fig. 3, column 1).

Implementing a series of four improvements to the basic voluntary incentive structure would have increased emission reductions while producing a programmatic budget surplus. First, aggregating accounting from the site scale to the district scale would have increased emission reductions to an estimated 105 MtCO_2e/y, or 13% below the reference scenario (72–123 MtCO_2e/y; 9–15%), while reducing the budget shortfall from \$6.0 billion per year to \$3.4 billion per year (Fig. 3, column 2). Second, setting district reference levels that perfectly match counterfactual emissions would have increased emission reductions to an estimated 202 MtCO_2e/y, or 25% below the reference scenario (160–229 MtCO_2e/y; 20–28%), while reducing the budget shortfall to \$77 million per year (Fig. 3, column 3). Third, sharing 20% of district revenues with the national government would have decreased emission reductions to an estimated 170 MtCO_2e/y, or 21% below the reference scenario (134–197 MtCO_2e/y; 17–24%), while producing a budget surplus of \$283 million per year (Fig. 3, column 4). Finally, sharing 20% of the costs of forgone income from international carbon payments with districts that increased emissions would have increased emission reductions to an estimated 175 MtCO_2e/y, or 22% below the reference scenario (136–207 MtCO_2e/y; 17–26%), while producing a budget surplus of \$331 million per year (Fig. 3, column 5).

At an international carbon price of \$10/tCO_2e, a mandatory incentive structure for REDD+ would have reduced net national deforestation emissions by 211 MtCO_2e/y, or 26% below the reference scenario (163–247 MtCO_2e/y; 20–31%), while producing a budget surplus of \$1.0 billion per year (Fig. 3, column 7). In this scenario, the allocation of reference levels to districts would affect the distribution of revenue between the national government and the districts, but unlike under a voluntary incentive structure, would not affect the amount of emission reductions achieved (Fig. 3, columns 5–8). Under the wide range of variable and parameter sensitivities explored (*SI Appendix*, Table S9), shifting from basic to improved voluntary incentives achieved 68–83% of the increased emission reductions gained by shifting from the basic voluntary incentives to a fully mandatory structure. Only with the addition of per-hectare transaction costs did the effectiveness of improved voluntary incentives fall greatly relative to the effectiveness of a mandatory system.

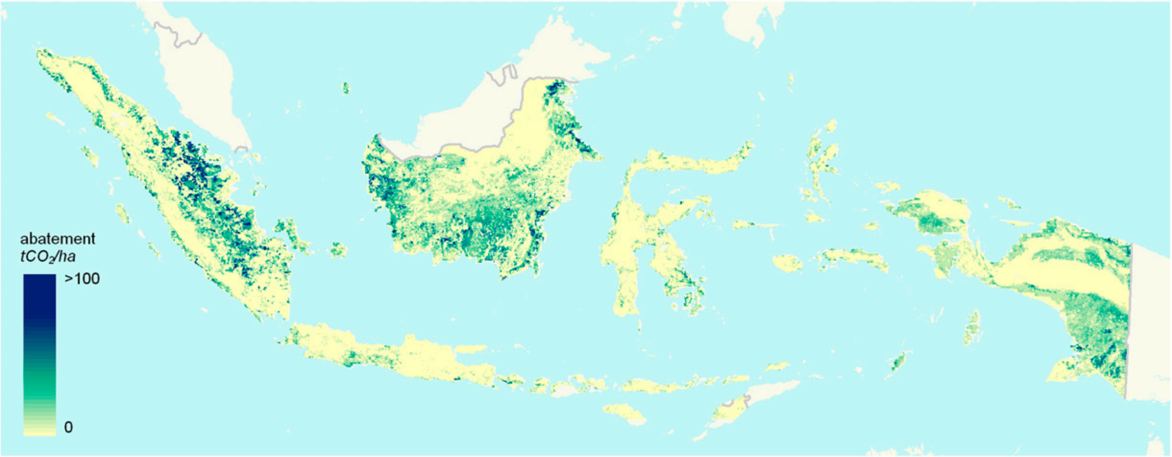

Fig. 2. Expected spatial distribution of abatement under REDD+, Indonesia 2000–2005. Expected abatement provided in response to a price of \$10 tCO_2e paid for voluntary site-level emission reductions below business-as-usual levels. Darker blue represents greater voluntary abatement of emissions from deforestation in response to incentive payments. Expected abatement is greatest where deforestation emissions would be high in the absence of REDD+ but low in the presence of REDD+. Results are outputs of OSIRIS-Indonesia v1.5 assuming the following parameters: carbon price = \$10/tCO_2e; "effective" price elasticity = 0.0 (no leakage); exogenous agricultural price increase = 0%; peat emission factor = 1,474 tCO_2e/ha; social preference for agricultural revenue relative to carbon revenue = 1.0; start-up and transaction costs = \$0; site-level accounting; national government share of revenue = 0%; national government share of responsibility for costs = 100%.

Discussion

Structuring REDD+ using mandatory incentives, such as a cap-and-trade or tax-and-subsidy program for deforestation emissions, would reduce emissions and bring in revenue more effectively than any other structure examined. Under a mandatory system, the level of emission reductions achieved would not be impacted by the allocation of reference levels; this is because local actors would have the same marginal economic incentive to reduce an additional unit of emissions to earn payments or avoid penalties, whether their emissions lie above or below their allocation of emissions under the policy.

Structuring REDD+ using only basic voluntary incentives targeted at individual actors, as in a standard PES program, would reduce emissions, but at a programmatic budget deficit because of adverse selection and leakage. Sites where historical reference levels greatly exceed counterfactual business-as-usual emissions would receive windfall payments beyond actual reductions. Meanwhile, some sites where historical reference levels are lower than business-as-usual emissions would opt out of participation in the REDD+ program, increasing emissions and undermining net national emission reductions. As a result, the national government would pay more for gross site-level emission reductions than it would receive from international buyers for net national-level emission reductions.

In principle a national program for REDD+ could be justified even with a programmatic budget shortfall, as net income from REDD+ to the country as a whole would be positive under such a program. However, a programmatic budget surplus would likely make national participation in REDD+ more politically palatable and easier to implement. Surplus revenue could be used as a performance buffer against leakage or reversals (23), and could fund systemic national policies and measures for reducing deforestation related to agriculture, infrastructure, land tenure, or governance (32, 33).

By implementing a combination of four policies that comprise an improved voluntary incentive structure for REDD+, governments could reduce emissions more than using basic voluntary incentives, and still produce a programmatic budget surplus. Setting reference levels with perfect foresight of future business-as-usual deforestation rates would lead to greater emission reductions and lower budget shortfall. Fewer windfall payments would be made to areas where historical emissions greatly exceed business-as-usual, and greater participation would be incentivized among areas where historical emissions are far below business-as-usual. Imperfections in predicting business-as-usual emissions could be partially ameliorated by aggregating the scale of accounting for net emission reductions from the site scale to the district or province scale; over- and underestimates of business-as-usual emissions at the site level would be progressively averaged by moving to higher spatial scales. However, jurisdictions at lower scales may have better information, more policy flexibility, and greater ability to directly influence local land use. Even with an aggregated scale of accounting, leakage of emissions would produce at least some budget shortfall in the absence of mechanisms for raising revenue for the national government. Sharing a portion of the revenue accruing from local emission reductions with the national government could enable a budget surplus from REDD+. However, unless the national government effectively redeploys these resources to reduce deforestation, too large a share of revenue retained centrally would reduce incentives for local actions, and correspondingly decrease national-scale emission reductions and revenue (*SI Appendix*, Table S8). Requiring local actors that increase emissions to share a portion of responsibility for the resulting costs of lost international carbon revenue would also reduce the national budget shortfall. A penalty for increasing emissions would make participating in REDD+ more attractive to local actors relative to converting forest to alternative land uses, and would increase national-level emission reductions and revenue.

In practice the ability to perfectly forecast business-as-usual emissions at either the site or district scale is likely to be limited and inherently unverifiable, given an unobserved counterfactual. Although we calibrated our econometric model of business-as-usual deforestation to provide the most accurate approximation of historical deforestation based on observable site characteristics, estimated emissions in the reference scenario still correlated only partially with historical emissions. Without multiperiod data on deforestation, we are unable to analyze whether econometric modeling outperforms extrapolation of historical trends in predicting future emissions. Future research should investigate what combination of historical trends, observable geographic characteristics, planned policies, and local insights provides the most accurate prediction of future emissions.

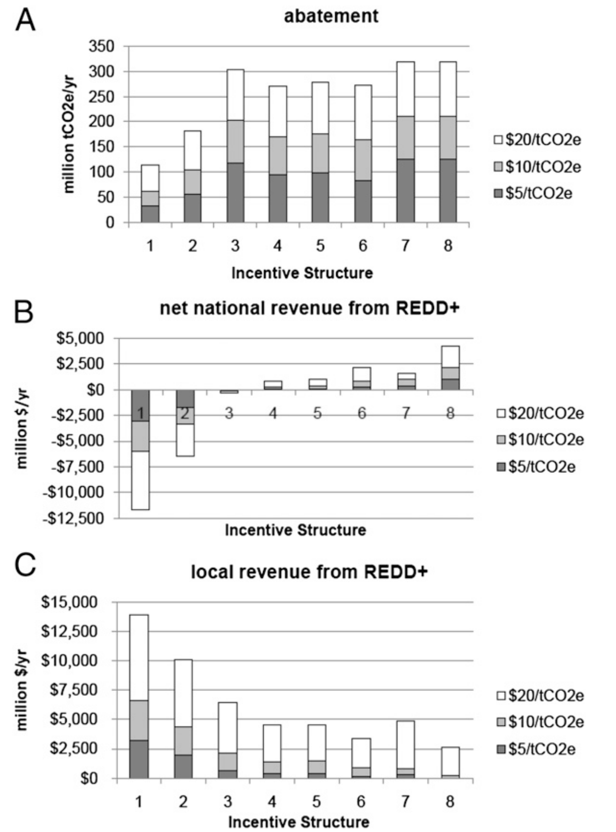

Fig. 3. Abatement (*A*), national revenue (*B*), and local revenue (*C*) under alternative national economic incentive structures for REDD+. (*A*–*C*) Incentive structures: Column 1: site-scale accounting; historical reference levels; no benefit sharing; no responsibility sharing ("basic voluntary incentive structure" or VIS). Column 2: Basic VIS + district-scale accounting. Column 3: Basic VIS + district-scale accounting + business-as-usual reference levels. Column 4: Basic VIS + district-scale accounting + business-as-usual reference levels + 20% revenue sharing. Column 5: district-scale accounting + business-as-usual reference levels + 20% revenue sharing + 20% responsibility sharing ("improved voluntary incentive structure"). Column 6: Improved VIS + 10% reduction to district reference levels; Column 7: District-scale accounting + business-as-usual reference levels + 0% revenue sharing + 100% responsibility sharing + 10% reduction to district reference levels ("mandatory incentive structure"). Column 8: Mandatory incentive structure + 26% reduction to district reference levels. For parameter assumptions, see the legend to Fig. 1.

The model's greatest value lies in enabling comparisons of the impacts of alternative incentive structures. A sensitivity analysis supports the robustness of our principal policy finding: an improved voluntary incentive structure for REDD+ can reduce emissions and bring in revenue much more effectively than standard site-scale payment programs, and nearly as effectively as a cap-and-trade or other mandatory incentive system. However, the absolute impacts of incentives are influenced by external factors (*SI Appendix*, Table S9). A higher carbon price from an international market or fund fundamentally motivates greater emission reductions. A national reference level, determined through international negotiations, would indirectly affect local actors' marginal incentives to reduce emissions. A higher national reference level would result in greater national revenue for any given level of net national emission reductions, which in turn would allow a national government to incentivize greater reductions from local actors by offering them a higher carbon price and higher subnational reference levels. Either higher agricultural prices or lower effective elasticity of demand for frontier agricultural products, associated with greater potential leakage within the country, would result in fewer net emission reductions and less national government revenue. This finding suggests the importance of coupling REDD+ with complementary agricultural policies (34), such as shifting agricultural expansion into low-carbon landscapes (35).

Conclusion

Previous studies have established the potential of REDD+ as a cost-effective climate-change mitigation option. However, how countries choose to structure economic incentives for REDD+ will critically impact the level of greenhouse gas emission reductions achieved, the cost-effectiveness of these reductions, and the distribution of costs and benefits within countries. We have developed a spatial land-use change model for Indonesia that is able to estimate and map the impacts of alternative incentive structures on emission reductions and national and local revenue.

Our analysis can guide the design of effective and equitable national and subnational economic incentive structures for REDD+. In theory, countries can achieve the full economic potential for emission reductions by implementing a mandatory incentive structure, such as a cap-and-trade or tax-and-subsidy program, which also has the advantage that effectiveness in reducing emissions and maintaining a programmatic budget surplus would not rely on accurately predicting future deforestation patterns. However, an approach to REDD+ in which participation is voluntary on the part of subnational actors may be more politically appealing. In this case, a voluntary incentive structure can be made much more effective than a standard site-level payment program, and nearly as effective as a mandatory structure, by aggregating accounting for net-emission reductions to higher jurisdictional scales, accurately approximating future business-as-usual emission rates for setting jurisdictional reference levels, and sharing revenues from emission decreases and responsibility for costs arising from emission increases between the national government and local actors.

Materials and Methods

Predicted Deforestation Without REDD+. We predicted site-level deforestation in the absence of carbon payments ("reference scenario") based on an econometric model of the observed percent deforestation from 2000 to 2005 (36–38), and spatial variation in estimated potential gross agricultural revenues (39) and the costs of converting land from forest to agriculture. Observable site characteristics used to proxy for costs included slope, elevation (40), distance to the nearest road, distance to the nearest provincial capital (41), and the percentage of cells contained within a national park, other protected area, logging concession, timber concession, or estate crop concession (42). The model was estimated with a Poisson Quasi-Maximum Likelihood estimator (43) for all 166,343 3-km $\times$ 3-km grid cells for which forest cover was present in the year 2000. Grid cells were stratified into four classes by starting forest cover. The combination of explanatory variables included in the regression was selected to maximize the district-level correlation between observed and predicted deforestation (*SI Appendix*, Table S7) without directly stratifying by geographic boundaries. Data and econometric methods are detailed further in the *SI Appendix*.

Expected Deforestation with REDD+. The expected equilibrium of deforestation at every 3-km $\times$ 3-km site with REDD+ was modeled based on the REDD+ participation decisions and land-use decisions made by districts in response to the economic incentive structure set by the national government. The district was selected as the subnational actor in the base case of the improved voluntary incentive structure because the district chief (*bupati*) controls the distribution of permits for use of forested land in Indonesia. Alternative accounting scales (3-km $\times$ 3-km site scale; province scale) were explored in a sensitivity analysis (*SI Appendix*, Table S8). Subnational actors received payments based entirely on their own performance in reducing emissions, consistent with either a REDD+ system in which the national government acts as an intermediary, buying emission reductions from subnational actors and selling to international buyers (21), or a system in which subnational actors sell emission reductions directly to international buyers, with the national government responsible for the cost of "truing

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up" to the balance of net national emission reductions [a "nested" approach (22, 23)]. For any structure of national economic incentives, a system of four equations—local land use, districts' participation, aggregate deforestation, and leakage—was resolved in equilibrium using OSIRIS v1.5 (46); model and dataset are available at http://www.conservation.org/osiris.

Local Land Use and Districts' Participation. In response to the national economic incentive structure, the expected amount of forest converted to agriculture was determined for every cell within every district in two possible cases (*SI Appendix*, Fig. S2). In the first case, the district "opts in" to the voluntary REDD+ program by reducing its deforestation emissions below its reference level. In this case, the expected deforestation at every site within the district shifts as predicted by the econometric model based on the marginal incentives provided by the carbon price, agricultural price and revenue sharing (*SI Appendix*, Eqs. **S4** and **S5**). In the second case, the district "opts out" by increasing its emissions above its reference level. In this case, the expected deforestation at every site within the district shifts as predicted by the econometric model based on the marginal incentives provided by the carbon price, agricultural price, and responsibility sharing (*SI Appendix*, Eqs. **S6** and **S7**). We did not explicitly specify the policy means by which each district would pass along the full price incentives to sites, but the model is consistent with districts imposing a mandatory incentive structure on local sites. Potential institutional start-up or transaction costs were addressed through sensitivity analyses (*SI Appendix*, Table S9).

Every district made a binary decision whether or not to participate in REDD+ based on which case would result in greater combined potential revenue from agriculture and carbon. That is, a district considered the aggregated net present costs and benefits summed across all sites within the district, and opted in if and only if the carbon revenue from opting in exceeded the forgone agricultural revenue from opting out, less any penalty from opting out because of responsibility sharing (*SI Appendix*, Eq. **S8**). In the "basic voluntary incentives structure" scenario, this participation decision was made at the site scale rather than the district scale. A parameter reflecting districts' preference for agricultural revenue relative to carbon revenue was initially set to 1.0, indicating that a dollar of income from carbon payments was considered equivalent to a dollar of income from agriculture. This parameter was allowed to vary in a sensitivity analysis (*SI Appendix*, Table S9).

Aggregate Impacts and Leakage of Deforestation. Expected deforestation at all sites, along with site-specific emission factors for biomass (46), nonpeat soil (47) and peat soil (48), was used to calculate district-level deforestation (*SI Appendix*, Eqs. **S9** and **S10**), district-level emissions (*SI Appendix*, Eqs. **S11** and **S12**), carbon revenue accruing districts that opt in to REDD+ (*SI Appendix*, Eq. **S13**), penalties to districts that opt out of REDD+ (*SI Appendix*, Eq. **S14**), and deforestation nationwide (*SI Appendix*, Eqs. **S15** and **S16**).

Any decrease in deforestation due to REDD+ raised potential agricultural revenue nationwide, which endogenously increased the pressure to deforest everywhere. The magnitude of leakage in our model was influenced through an "effective elasticity" parameter (*SI Appendix*, Eq. **S17**), which is functionally equivalent to the price elasticity of an exponential demand curve for frontier agriculture (9), but was calibrated using a separate general equilibrium model of the Indonesian economy (48) to also incorporate economy-wide feedback in the domestic labor and agricultural capital markets.

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