Coasian Motion: Deforestation and the Central Tendency to Disperse

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Introduction

Tropical deforestation may contribute over 15% of annual greenhouse gas emissions. Any viable effort to mitigate climate change will have to address deforestation. International efforts to curb the rate of deforestation have thus far been composed of a series bilateral agreements, despite calls for a comprehensive, global mechanism. The United Nations has proposed the Reducing Emissions from Deforestation and Degradation (REDD) framework to directly address local incentives to convert forest to fiscally productive lands. This grand Coasian bargain, however, has been frustrated by many factors, including high transaction costs, discord among member countries, and poorly defined property rights. The number of frustrating factors is an increasing function of the number of relevant member countries. The devil is in the details, and the amount of details rises exponentially with the number of contracting agents. As with any network graph, the number of edges increases exponentially with the number of nodes. The UN REDD framework is effectively an attempt to consolidate negotiations; but this effort has met limited success due in part to a constantly shifting natural and political landscape for forest conservation.

This paper demonstrates that the basis for a comprehensive agreement is becoming more complex. Specifically, this paper utilizes satellite imagery to show that the dispersion of forest clearing across administrative units is increasing. The number of countries with a substantial share of forest clearing activities is increasing, potentially forestalling a truly comprehensive conservation framework.

Forest clearing detection

The data on forest clearing activity is based on the classification of stacked images from the Moderate Resolution Image Spectroradiometer (MODIS) sensor aboard NASA's Terra and Aqua satellites. Both time series and cross-sectional characteristics are extracted from the images, and then compared against historical (2000-2005) forest cover loss data (Hansen, 2008). The classification rule is derived from the comparison, and then applied forward to more recent imagery. The final output is a probability of forest cover loss between January 1, 2000 and the acquisition date of the most recent MODIS imagery. The resulting alerts are highly accurate when compared against other, production-level forest clearing alerts. A notable result is that a relatively simple algorithm can produce reasonably accurate alerts, especially to capture broad trends in forest clearing activity.
The algorithm to collect forest clearing alerts consists of four principal steps:

1. Time series characteristics from the derived Normalized Difference Vegetation Index (NDVI) are extracted for each 500-meter pixel in the humid tropics (MOD13A1). These characteristics include long-term trends and variation in the NDVI, along with short-term break detection. The techniques are common in time series econometrics, often in the context of financial indices. The established econometric techniques are repurposed to account for natural cycles.

2. Cross-sectional methods are employed on derived images to identify clusters of the extracted time dependent characteristics. This includes, for example, the largest detected drop in the NDVI series for

a cluster of pixels. The largest, neighborhood drop is ascribed as a pixel-level characteristic, acting as a smoothing operator across the image, much like a moving average over time.

3. The pixel-level attributes from the time series and cross-sectional analysis are compared against historical data on forest cover loss. The precise method of comparison is a logistic, ridge classifier, implemented in parallel to accommodate very large, distributed data.

The probability p_{it} indicates the likelihood of forest clearing activity within grid cell i for the interval between December 2005 and period t. The probability measure is the output from a logistic classifier, where the features are extracted from layered satellite imagery and compared against the Hansen (2008) data set. Additional description of the algorithm are presented in *Materials and Methods*. The spatial resolution for this study is 500-meters and the temporal frequency is 16-days. There are 191? periods during the study interval between 2008 and April 2013.
The algorithm to identify forest clearing activity for each 500m grid cell in the humid tropical biome is described in the *Materials and Methods* section. Let p_{it} indicate the probability of clearing activity for pixel i and the time interval between December 2005 and period t. The probability is the output from a logistic classifier, indicating the intensity of satellite signals that have historically been associated with deforestation. The deforestation rate for administrative unit j is the number of pixels that were tagged with deforestation for the first time in period t.
The incremental deforestation rate d_{jt} expresses the number of 500m grid cells tagged with clearing activity in administrative unit j during time interval t. The algorithm to identify pixel-level clearing activity from satellite imagery is described in *Materials and Methods*. The output from the algorithm is
The data used for this paper are the forest clearing alerts from Forest Monitoring for Action (FORMA), a pan-tropical forest monitoring system developed by Hammer et al. (2013). The data are derived from remotely sensed data, primarily from the MODIS sensor. FORMA reports the probability of forest clearing activity at 16-day intervals for each 500-meter, forest pixel in the humid tropics. Pixel time series are created by stacking satellite imagery, merging the spectral histories with ancilliary data, including rainfall. Non-forest pixels are removed from analysis by screening out pixels with VCF < 25 as done in Hansen (2008). The algorithm extracts characteristics from the pixel time series that correspond to unnatural patterns in data. The characteristics are, in turn, matched against the forest cover loss hotspots data set. The result is a continually updated characterization of clearing activity for each period, or a probability of forest clearing activity by the specified time interval.

The accuracy assessment in Hammer et al (2013) indicates that a confidence threshold of 0.5 produces a robust alerting system that minimizes false positives and successfully identifies the industrial-scale clearing activity that is the focus of this paper. The continuous probability range is valuable because it provides information on the relative intensity of clearing across pixels as opposed to a binary indicator. The aggregate measure of clearing activity in an administrative unit in this paper is calculated for each interval as the summed probabilities, conditional on the probabilities exceeding a confidence threshold of 0.5. Analysis of the dynamics of forest clearing acitivity are made possible by the high frequency of the updates. Higher resolution systems are suitable to focused areal assessments, but cannot adequately characterize the sub-annual dynamics at a time-scale commensurate with economic drivers of deforestation. The dynamics and geographic scope of FORMA data make this paper possible.

Definition of dispersion

Dispersion is the degree of spread of a phenomenon over space and/or time. In this paper, we consider dispersion of deforestation as characterizing the degree of concentration of clearing activity in a geographic area. The measure of dispersion of clearing activity at any particular time is based on an aggregated measure of clearing, given by FORMA. The geographic aggregations of interest in this paper - countries, provinces

and sub-provinces - are arbitrary, but important given that these units define the various levels of decision making that affect deforestation.
Let i be the pixel index, and cj be the set of pixel indices in administrative unit j. The aggregate level of clearing activity in administrative unit j and time period t is given by equation X.

$$D_{jt} = \sum_{i \in C_j} \mathbb{I}(p_{it} \geq 0.5) \cdot p_{it} \tag{1}$$

We characterize the spread of clearing activity across all administrative units in the sample by using Shannon's entropy criterion, defined in equation Y.

$$E_t = -\sum_{j=1}^{n} \frac{D_{jt}}{D_t} \log_2 \frac{D_{jt}}{D_t} \quad \text{with} \quad D_t = \sum_j D_{jt} \tag{2}$$

E ranges from 0 to 1, and larger values of E indicate higher dispersion across units. A value of 1 is a uniform distribution, with equal values for all units. A higher value of E across countries, for example, would indicate that clearing is less clustered at the the country level. More concretely, this would indicate that clearing is spreading beyond Brazil and Indonesia.

Geographic dispersion

At various levels of disaggregation, the patterns of forest clearing dispersion remain similar. We consider the country, provincial, and sub-province administrative units because that's where forest management policy is created or implemented.

Country

Upward trend. And seasonal. Is entropy low when deforestation rates are high, or vice versa? Plot the sd of clearing activity over the mean of clearing activity :: coefficient of variation. Find out whether CV trend is going up or down.
TODO: why seasonal? individual country's seasonality?

Province and sub-province level

TODO: do the same for prince and sub-province level.

Tree entropy

Look at the dispersion trends *within a country*. This corresponds with the scenario of countries being at international negotiations, who in turn deal with local provinces for actual conservation. How tenable are the promises made at the international negotiating table?
Consider Indonesia the world and look at the dispersion across sub-provinces. The question is whether the promises made by the big players are credible. Indonesia's position becomes more difficult, since they have to interact with more local leaders.

Implications for conservation

Our results indicate that tropical forest clearing is dispersing rapidly across countries, particularly in the regions near Brazil and Indonesia. This development may have significant implications for conservation strategy through its impact on the economics of negotiating, monitoring and enforcing international agreements. Since we focus on forest clearing as a carbon pollution problem, we provide a Coasian interpretation of the issue (Coase, 1960).[1] In the Coasian view, parties damaged by polluting emissions have three basic options

[1] We recognize that tropical forest clearing also entails grave risks for many endangered species, as well as large potential costs from the loss of local ecosystem services. Resolution of these problems may well require additional measures that are not discussed in this paper.

for redress: (1) receiving compensation for damage and/or reducing pollution through legal action against polluters; (2) reducing pollution via government regulation of polluters; (3) paying polluters to reduce their emissions.

As Coase and many others have noted, the appropriate choice depends on the relative benefits and costs of each option in a particular context, as well as the status of relevant legal and governmental institutions. In the case of forest policy, international donors have focused on Coasian option (3) — payment for pollution reduction — because global legal and regulatory constraints make options (1) and (2) infeasible. The traditional payment system has focused on direct support for protected areas in tropical forests. However, clearing has continued in many protected areas, and donors have responded by initiating programs that compensate countries for successful protection. These programs, coordinated by the United Nations, are collectively known as REDD+: Reducing Emissions from Deforestation and Forest Degradation in Developing Countries.

Unfortunately, our evidence suggests that the Coasian bargains envisioned by REDD+ are becoming less attractive as forest clearing disperses more widely. The essential problem resides in transactions costs. If pollution is concentrated in a few countries, compensation negotiations are not excessively costly because few parties are involved. As pollution disperses across countries, however, negotiation costs escalate even if total pollution remains constant. This is particularly true if weak governance in new entrants raises the cost of monitoring and enforcing compensation agreements.

From a traditional Coasian perspective, then, we are forced to conclude that the rapid dispersal of forest clearing has significantly raised the cost of tropical forest conservation. Fortunately, we believe that the Coasian prospectus can be expanded to a fourth option ("Coase+") that may provide an attractive alternative to REDD+ in some cases.

Coase+ shifts the locus of the pollution problem from production to consumption. It reflects the fact that pollution is a byproduct of commodity production for final delivery to consumers. In cases where products can be linked explicitly to polluting producers, the Coasian option set expands because damaged parties can seek redress through legal or governmental actions directed at polluters' products, or through selective promotion of products from "clean" producers. Coase+ measures can be enacted locally, because they do not depend on the assent of other countries. Such measures may be preferable to REDD+ programs in cases where consumption is highly concentrated (making single-country measures effective) and polluting production is widely dispersed (making compensation negotiations costly).

Is Coase+ an attractive alternative in the real world? The answer depends on assessment of at least five factors. The first is the concentration of consumption relative to polluting production in the tropical forest sector. Our evidence for rapid dispersion of forest clearing is striking, but consumption has also been de-concentrating internationally, as the global consumption share of low- and middle-income countries has increased. However, this process has been much slower than the accelerated dispersion of forest clearing during the past few years. On balance, the change in relative concentration has shifted the balance toward Coase+ measures.

The second factor is information. Can products be reliably linked to their polluting sources? "Pollution accounting" is feasible for bulk commodities whose value chains are relatively short, because product attribution is clear, only shipment in bulk lots is cost-effective, and transshipment in bulk through third countries to avoid detection is both expensive and futile. Many commodities produced on previously-forested tropical land fall into this category (e.g., palm oil, beef, soybeans).

The third factor relates to domestic politics in high-income areas where consumption is concentrated (e.g., North America, Western Europe). On balance, the political case for Coase+ measures seems favorable. For taxpayers, there is no immediately-clear distinction between Coase+ and REDD+ measures based on compensation or promotion of "clean" products, because both options involve public expenditure. Ceteris paribus, taxpayers should prefer the more cost-effective approach. Where product taxation is employed as a Coase+ measure, offsetting reductions in other taxes can be implemented. For products such as beef, soybeans and vegetable oil, where domestic (non-tropical-forest) producers compete with tropical forest producers, the domestic producers should support Coase+ taxation because it will improve their competitive status.

The fourth factor relates to international trade relations. Existing WTO rules can accommodate tariffs or regulatory controls for imported products that have negative production or consumption externalities, as long as these measures are not directed at specific countries. 2 In principle, this includes regulation or taxation of imported commodities produced in cleared tropical forest areas or, equivalently, subsidies for products that are not produced in those areas.

The fifth factor is the disposition of revenues from Coase+ taxation of imported products. In principle, the taxing country could rebate all revenues to the country whose products are taxed. This would preserve the basic rationale for Coase+ product taxation — raising the relative price of commodities produced on cleared tropical forest land — while ensuring overall revenue neutrality for the exporting country.

In summary, we believe that the rapid dispersal of clearing in tropical forests warrants a re- assessment of policies for reducing CO2 emissions from those areas. Two of the three traditional Coasian options are infeasible, because the international legal/regulatory regime will not supportthem. By default, protected-area programs and REDD+ policies have adopted Coasian option (3) – direct payments to polluters for reducing their pollution. However, as Coase and others have long noted, the transactions cost of option (3) escalates as the number of polluters increases. To address this problem, we propose an additional Coasian option set (Coase+) that focuses on transactions via consumption rather than transactions via production. Coase+ measures seem feasible for major tropical forest products, and they may well offer an attractive alternative to REDD+ in some cases.

Conservation negotiations rely on a series of joint arrangements. Each arrangement takes a significant amount of time to specify. Even if the number of relevant players in the negotiation rises linearly, the number of joint arrangements will rise exponentially. The complexity and barriers to a common conservation agreement increase exponentially as tropical deforestation becomes more dispersed. The basis for this observation is founded in both operations research and contract theory [find citations].

The increased dispersion also suggest the possibility of geographic leakage, given that deforestation has already begun to spread. Static coefficient of friction is much greater than the dyanmic coefficient of friction; and this analogy applies to economic processes with increasing returns to scale.

Appendix: Materials and Methods

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Figure 1: **Country**
subfigure[b][b]0.3

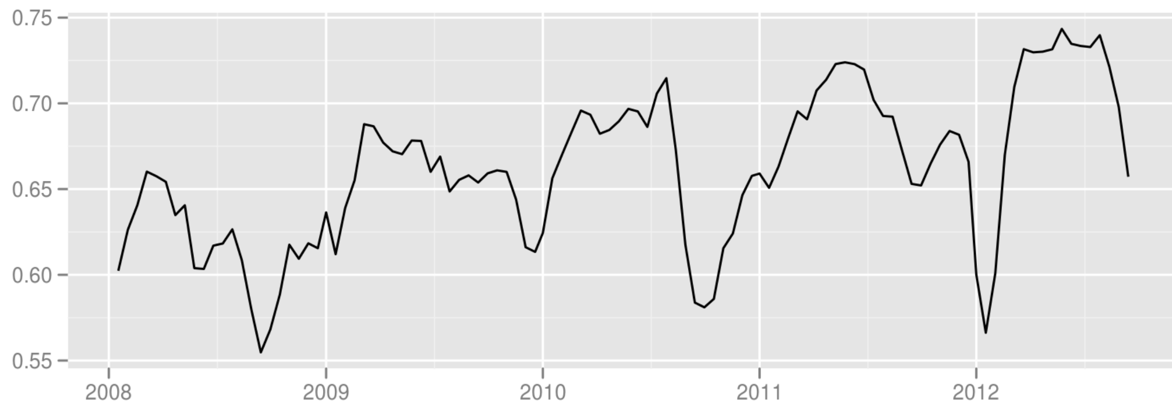

Figure 2: **Province**
subfigure[b][b]0.3

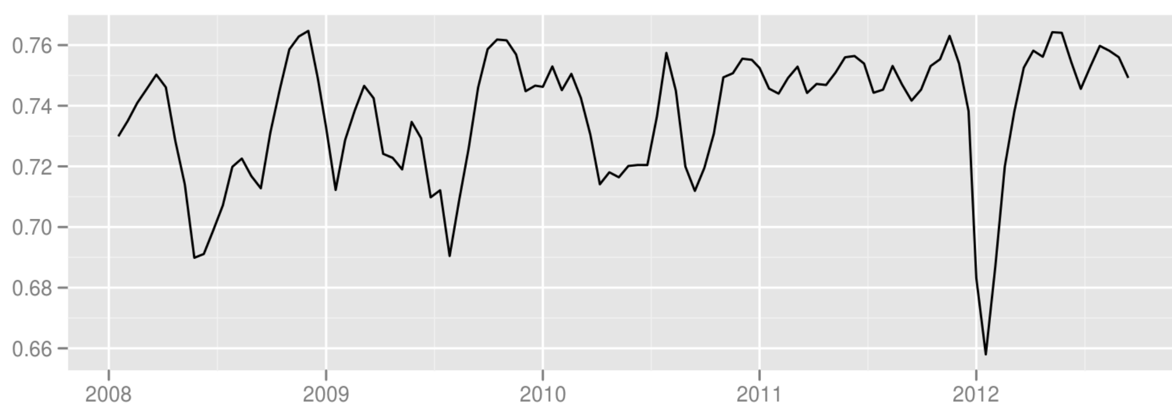

Figure 3: **Subprovince**

Figure 4: Entropy over time for three levels of administrative units