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Topographic restrictions on land-use practices: Consequences of different pixel sizes and data sources for natural forest management policies in the tropics

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ABSTRACT

Much of the tropical forest that will escape conversion is on steep slopes. Land uses in steep areas disproportionately affect environmental processes, especially hydrology (e.g., peak flows, suspended sediment loads). We use data from East Kalimantan, Indonesia, to demonstrate why slope measurements used for planning and regulatory purposes should be based on digital elevation models (DEMs) constructed with small pixel data and ground-based or canopy-penetrating remote sensing, and not just mean slopes calculated for large areas with passive remote sensing. For five logging concessions, the proportion of the forest on slopes > 40% (21.8°) ranged 35–85% with crown penetrating airborne lidar pixels of 1 m, but only 13–69% when pixel size was increased to 30 m. With passive satellite-based remotely sensed 30 m pixels, estimates of land on slopes > 40% were even lower (11–56%). Policies based on DEMs with underestimated slopes contribute to the misuses of steep areas and the consequent deleterious in-forest and downstream impacts. The energy costs of forest operations increase with slope, which decreases the financial costs of compliance with environmentally motivated policies for the protection of steep terrain.

1. Introduction

In response to seemingly inexorable growth in both global populations and *per capita* consumption, every possible effort should be made to satisfy human needs for food, fodder, and building materials through enhanced productivity, improved crop storage and handling, and more equitable distribution of critical commodities (e.g., Tilman et al., 2011). Nevertheless, even with our collective best efforts, agriculture, forestry, and other land uses will inevitably expand (e.g., Gibbs et al., 2010; Pirard and Belna, 2012; Phelps et al., 2013). Where arable land on level ground is already fully utilized, activities will expand onto still forested lands on increasingly steep slopes unless the associated risks are recognized and sloped lands are protected. With a focus on forestry practices on steep slopes in the tropics, we outline some of the biophysical and economic consequences of increased land-use intensity on steep terrain, explore how terrain is mapped, and consider the current and potential regulatory frameworks that govern land-use practices on slopes. Our data are from logging concessions in Indonesia, but the issues addressed are pertinent globally (e.g., Thees and Olschewski, 2017).

Slopes affect many physical processes due to gravitational acceleration (e.g., rates of surface water flow, energy needed to climb) and geometry (e.g., per unit ground surface area rates of incoming fluxes of precipitation and solar radiation, distances on maps versus on the ground). For example, with increased slopes angles, rates of soil erosion and the frequency of mass wasting events (i.e., slumps, landslides, and avalanches) increase, especially after trees are cut and soil-binding roots decay (e.g., Sidle et al., 2006, Lee and Pradhan, 2007). Insofar as soil depths typically decrease with increased slope, soil loss from sloped land can have substantial local as well as downstream consequences. Given these decreased soil depths coupled with increased rockiness, downhill extensions of tree crowns, and downhill tilts of tree stems (Berner, 1992), forests on slopes are more dynamic (e.g., treefall rates increase; Roberts, 2003), which is associated with slope-related changes in vegetation community structure and composition (e.g., Ferry et al., 2010).

2. Current policies that govern land-use practices on slopes

Whereas many government agencies and non-governmental bodies

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recognize the effects of slopes on the impacts of land-uses, many land-use regulations and their associated implementation guidelines intended to address slope-related issues lack clarity. Disregarding for the moment that many such regulations do not specify the minimum slope lengths considered, few set explicit limits on the maximum slopes on which different activities are allowed. In forestry codes of practice (i.e., best management practices for silviculture), instead of slope angle limits, changes in timber harvesting technologies are typically recommended for steep slopes. For example, the FAO Model Code of Forest Harvesting Practice (Dykstra and Heinrich, 1996) upon which many regional and national forest harvesting codes in the tropics were based suggests that "…slopes [> 30%] that are sustained over long distances should be harvested by cable or aerial systems that have the ability to suspend logs above the soil." Of the national codes of forest practices we examined, only those from Papua New Guinea and Vanuatu set a maximum grade for logging, both at 30% (Winkler and Nöbauer, 2001; Vanuatu Department of Forests, 1998). In temperate and boreal regions, regulatory emphasis is on avoidance of the deleterious environmental impacts of forest management activities, especially soil erosion, but logging is allowed on almost any terrain that grows trees. For example, in the State of Oregon in the USA, "slopes over 60 percent are subject to the requirements of Sections (4) through (9) of this rule", which specify how erosion should be controlled (www.oregon.gov/ODF/Working/Pages/FPA.aspx).

Slope-related rules in the agricultural sector are generally as vague as in forestry. For example, the Roundtable on Sustainable Palm Oil (RSPO) Principles and Criteria for Brazil require that "A management strategy should exist for plantings on slopes above a certain limit (needs to be soil and climate specific)" (http://www.rspo.org/en/document_local_indicators). While consideration of soil and climate qualifiers is justified, the lack of specificity is nonetheless worrisome. There are exceptions, such as in the Ivory Coast where the RSPO rules state that "…there will be no planting on slopes above 30° [57.7%] (i.e. unsuitable soils)."

Although slope angles are important, slope lengths also influence many biophysical processes, as captured in the "universal soil loss equation" (e.g., Toy et al., 2002). While there is no single slope length appropriate for all applications (e.g., Grohmann et al., 2011), it is too often disregarded in land-use regulations that calculated slope angles decrease with increasing reference area (i.e., pixel size and minimum slope length; e.g., Grohmann, 2015). An analogy in linear landscape measures is that to understand the meaning of a measurement of some landscape feature (e.g., coastline length), one needs to know the precision of the measurement device. This issue is well-discussed in the geomorphology and remote sensing literatures (e.g., Mukherjee et al., 2013), but is often overlooked by other disciplines. Given that most geographical information system (GIS) approaches based on remote sensing data calculate slopes as the maximum difference in measured elevations of adjacent pixels in digital elevation models (DEMs), the relevant dimension is pixel size. Slopes with lengths shorter than or equal to the diagonal of one pixel are missed unless they cross a pixel border, which can represent a major oversight in dissected terrain with short ridgetop-to-valley bottom distances. This simple geometry means that land-use analyses and plans based on large pixels deserve substantial scrutiny when they assume that slope effects are small.

The accuracy of topographic maps generated from remote sensing data from heavily forested areas depends on whether the sensors penetrate the canopy (e.g., Nelson et al., 2009). Under such conditions, DEMs constructed with passive remote sensing data that measure elevations at or near the canopy surface rather that than at the level of the forest floor underestimate slopes to the extent that valley trees are taller than their ridgetop counterparts (Berner, 1992). Where available, canopy penetrating data (e.g., lidar) are used to construct DEMs that more accurately represent changes in ground surfaces (termed Digital Terrain Models or DTMs; Hirt, 2015), but such data are not yet available for large areas in the tropics.

The problems with pixel sizes and the use of passive remote sensing data are evident in an otherwise excellent study on oil palm plantation expansion in Kalimantan, Indonesia, by Austin et al. (2015). Those authors reported that slope, as determined with a DEM constructed with passive remote sending data with 250 m pixels, was not related to where oil palm plantations were established during 2000–2010. Based on the preponderance of plantations and the scarcity of forests on relatively gentle slopes, we question this result. To explore in more detail the effects of pixel size and data source for DEM construction, we use data from five logging concessions in Kalimantan.

3. Current logging practices on steep slopes in Kalimantan, Indonesia

Logging practices and their impacts vary substantially in Kalimantan (e.g., Griscom et al., 2014), but the following procedures are typically employed for extracting timber from topographically heterogeneous cutting blocks. Felling and skidding operations often continue even during wet periods, but hauling is delayed when wet roads are impassable. Because most logging roads are on or near ridgetops, most skidding, which is typically done with tracked vehicles (e.g., D-7 Caterpillar or D85S Komatsu bulldozers/crawler tractors), is up hill. When log-dragging skidders encounter a slope that is too steep or slippery to ascend, they release the clutch on the winch to allow the cable to spool out as they climb as far as the cable allows, typically 20–25 m. They then drop their blade and use the rear-mounted winch to drag the log up next to the skidder and then repeat the process as necessary. Depending on log size (typically 4–6 Mg) and soil strength (i.e., trafficability), which decreases with moisture content and with each pass of the machine, slopes of < 10–15% are ascended in this way. If the same skid trail is used again, on the way back to the felling area, the driver scrapes off the damaged surface soil to improve traction. With this process, repeated passes often result in skid trails that are recessed 1–2 m below the former surface. Slopes of > 15%, especially if longer than about 25 m, are typically climbed at a sidewise angle (i.e., traversed). To keep the skidder more-or-less flat, a side cut is made into the hillside. Because this fill material is mechanically weak and skidder operators typically try to climb at as steep an angle as possible, skid trails that traverse hillsides are also often bladed on the way back to the felling area, which deepens the side cut with each pass. On slopes that are steep, wide, and long, switchbacks (i.e., connected traverses that zigzag on a hillside) are used. While cable yarding systems and even helicopters are reportedly used widely in the neighboring Malaysian states of Sabah and Sarawak, logging in Kalimantan is still overwhelmingly with bulldozers.

4. Consequences of different approaches to topographic analysis

We explore the effects of different slope mapping methods and regulatory limits on permitted land uses in five logging concessions in the topographically dissected terrain of East Kalimantan. We use topographic maps generated from DEMs generated with passive remote sensing data and those based on data from canopy penetrating airborne lidar to determine the proportions of the area classified as steep, which we assume as slopes > 40% (21.8°). We selected 40% (21.8°) slope as our cutoff to reflect its use in Indonesian land-use regulations (Ruslandi et al., 2014).

For each landscape we evaluate how using different pixel sizes influence the proportions of steep land. We also use passive remote sensing satellite data to extend the analysis to all remaining forests in Kalimantan. We conclude with policy recommendations related to slope restrictions in tropical forests in which we try to account for the complications related to governance as well as climates, soils, and alternative timber harvest technologies.