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Forest–flood relation still tenuous – comment on 'Global evidence that deforestation amplifies flood risk and severity in the developing world' by C. J. A. Bradshaw, N. S. Sodi, K. S.-H. Peh and B. W. Brook

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Abstract

In a recent paper in this journal, Bradshaw and colleagues analyse country statistics on flood characteristics, land cover and land cover change, and conclude that deforestation amplifies flood risk and severity in the developing world. The study addresses an important and long-standing question, but we identify important flaws. Principal among these are difficulties in interpreting country statistics and the correlation between population and floods. We review current knowledge, which suggests that the removal of trees does not affect large flood events, although associated landscape changes can under some circumstances. Reanalysis of the data analysed by Bradshaw and colleagues shows that population density alone already explains up to 83% of the variation in *reported* flood occurrences, considerably more than forest cover or deforestation (<10%). Feasible explanations for this statistical finding – whether spurious or causative – are not difficult to conceive. We, therefore, consider the conclusion of Bradshaw and colleagues to be unsupported. However, their study is a valuable first step to show how these or similar flood data might be used to further explore the relationship between land cover and flooding.

Keywords: conservation, damage, flooding events, forest loss, generalized linear mixed-effects models, generalized linear models, human displacement, projected costs, rainfall

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Introduction

In a recent paper in this journal, Bradshaw *et al*. (2007a) use country statistics derived from various sources in an analysis that seeks to test whether deforestation has an effect on flooding frequency and severity. Flood frequency, duration, and the number of people killed or displaced and economic damage associated with floods were derived from the Dartmouth Flood Observatory (2007a, b) data base. The authors make *a priori* assumptions about likely explanatory variables, and use these in alternative generalized linear mixed-effect and generalized linear models to decide on the optimal model using an information criterion. The authors conclude that country area, annual precipitation, slope, degraded area, natural and nonnatural forest cover collectively account for over 65% of the variation in flood frequency. A subset of these factors also explains some of the variation in flood duration (45%), number of people killed (42%), number of people displaced (44%) and economic damage.

The effect of deforestation on flooding is a hotly debated issue. Evidence to date is partly inconclusive, and therefore new data sources and analyses provide an important opportunity to further our understanding. Laurance (2007) considered the paper by Bradshaw and colleagues 'a landmark study (that) provides strong

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correlative evidence that natural forests do reduce the frequency and severity of floods in developing nations'. We welcome the effort that Bradshaw and colleagues have made to address this question, but cannot agree that the correlative evidence presented is strong. In particular:

1. The country statistics used hide such a variation in climate, land use, population and hydrological conditions that it is impossible to draw any conclusions about cause and effect.
2. A strong correlation between floods reported in the database with population is to be expected – and indeed exists – as a consequence of observation bias and because of the various human influences on flooding and flood damage.

To put these issues into perspective, we first provide a brief summary of current knowledge about the influence of deforestation on flooding, before demonstrating why the findings of Bradshaw *et al*. are not supported by their data and analysis[1].

Current knowledge about the influence of deforestation on flooding

The link between deforestation and the frequency and severity of flooding has been one of long-standing debate but with little evidence to go on, as also noted by Bradshaw *et al*. (2007a). The debate is perhaps even more intense in the public arena than it is in the scientific arena, fuelled by the implications for human security, forestry industry, economic development and nature conservation, particularly in developing countries, and is occasionally distorted for political, institutional and policy purposes (Calder & Aylward, 2006; Van Dijk & Keenan, 2007).

The debate goes back at least to the nineteenth century and probably before that. Since the 1920s, some systematic field research has been done, but the idea that a good forest cover reduces or even prevents floods remained largely unchallenged until the 1980s, when the late J. D. Hewlett demonstrated that the presence or absence of forest did not appreciably influence the magnitude of the largest flow events (Hewlett, 1982).

Perhaps, the debate has continued for so long in part due to varying definitions of what constitutes 'deforestation' and a 'flood'. Here, we define 'deforestation' as the clearance of natural forest, without any assumptions about the manner by which this occurs or the land cover that replaces it (which may be forest regrowth). By 'floods', we refer to infrequent inundation events that negatively impact on human livelihoods: floods and peak flows are a natural phenomenon. An indicative definition could be, for example, a flood that under historic circumstances would be expected to occur once every one or more decades (i.e. return interval ≥ 10 years). Following Bradshaw *et al*., we further limit the definition of floods to those caused by large rainfall events, rather than those associated with storm surges, snow melt, mass wasting, geological events, infrastructure failure or other possible causes. Even narrowed down in this way, complicating factors remain that prevent blanket statements about the link between deforestation and floods.

Firstly, rainfall events give rise to floods because of a variable combination of unusually high intensity, spatial extent and/or duration, and these interact with the area that contributes to flows at a location. Thus, a convective summer storm may cause local flooding, but not have any effects further downstream. Conversely, a particularly wet monsoon may not cause floods in the headwaters, but the accumulation of runoff downstream can cause flooding there. The effects of climate variability and climate trends are difficult to separate from terrain effects in case studies. For example, Tu *et al*. (2005) could not demonstrate a terrain effect in flooding in the European Meuse basin after accounting for rainfall variability. Similarly, Gentry & Lopéz-Parodi (1980) were quick to ascribe increasing water levels in the Amazon River to deforestation, until Nordin & Meade (1982) and later Richey *et al*. (1989) demonstrated that climate variability provided a more feasible explanation.

Secondly, tree clearing is often – but not always – associated with a reduction in soil infiltration rates (e.g. as a consequence of logging, postclearing agricultural or urban land use, land degradation, road construction), enhanced drainage (e.g. via roads, drains and river levees) and greater sediment generation (which can lead to downstream channel sedimentation, loss of channel capacity and hence overbank flows). In other cases, logging may be followed by secondary growth and in such cases, hydrological landscape functions may rapidly return to prelogging conditions. Therefore, it is difficult if not impossible to single out tree clearance *per se* as a cause of flooding, except in strictly controlled, small-scale experiments.

Thirdly, there are many factors besides rainfall, catchment size and land surface condition that can affect the generation of floods. Soils, geology, catchment and river morphology, and antecedent conditions (e.g. catchment wetness) all influence catchment hydrological processes

[1]There are some incongruities in the data used, and we would question some choices in data treatment and analysis (e.g. the exclusion of China, the use of mixed-effect models for a relatively small dataset), but we do not seek to argue that these elements by themselves affect the conclusions of Bradshaw *et al*.

to varying degrees. Essentially, floods occur when more water has entered a river channel than can be stored or passed on downstream (Rodríguez-Iturbe & Rinaldo, 1997). This is a function of the nature and storage volume of the river channel, the rate of entry and the rate of outflow. All these three can be influenced by land use and human activity. This makes inter-comparison between catchments difficult, regularly even when they are adjacent, and also affects comparisons between countries.

Despite this, a wide range of studies on plots, in small catchments and in large basins have contributed to what appear to be some reasonably well-tested theories about the role of forests in hydrology. Reviews of such studies include, for example, Bruijnzeel (1990, 2004), Bowling *et al*. (2000), Brooks *et al*. (2003), Calder (2005), Eisenbies *et al*. (2007) and Van Dijk & Keenan (2007); and a science digest was prepared by FAO/CIFOR (2005). The mechanisms by which forests can influence rainfall-induced flood generation are thought to be through changes in interception loss (direct evaporation of rainfall intercepted by the canopy), infiltration into the soil and retention of infiltrated water. A few general principles may be formulated:

- The difference in interception loss between forest and short vegetation (e.g. grass or crops) is typically in the order of 15% of rainfall over longer periods, but varies as a function of storm size, weather conditions and canopy characteristics. Local floods in tropical regions (e.g. an event of 1 or a few days with >10 years return period) are likely to be caused by a rainfall event well in excess of 100 mm. For such storms, the difference in interception loss between forest and nonforest vegetation is unlikely to exceed a few percent of rainfall and therefore is not likely to be a significant factor. Effects could be somewhat greater for large-scale floods caused by a number of successive storms if the canopy dries up in between storms.
- As mentioned, deforestation can be (and frequently is) associated with a reduction in soil infiltration capacity. This causes more rainfall to runoff over the surface, and particularly where drains and roads enhance the accumulation and transfer of water into the stream, this can increase peak flows considerably.
- If soil infiltration and surface runoff are not affected, the amount of rainfall that enters the soil would be expected to be very similar between forested and nonforested conditions. In that case, flood generation downstream might be enhanced after forest removal if the soil can retain less of the infiltrated water, provided that the excess water rapidly finds its way to the stream. Soil water use rates tend to decrease after deforestation (though depending on the characteristics of the replacing land cover) and, therefore, this 'forest sponge' effect cannot be discounted. It is more likely to affect smaller, brief and local flooding events than extreme, prolonged and large-scale events, however.

A peak flow enhancing effect of forest removal has been observed in small-scale (normally $<10\,km^2$) experimental studies. Small to medium peak flows (i.e. the more common, less damaging ones) appear affected most, while the largest events do not change noticeably (e.g. Hewlett, 1982; Bowling *et al*., 2000). To date, studies in larger basins have not usually found any changes after deforestation of up to 50% of the catchment, and where changes did occur, these were not directly attributed to deforestation (reviewed in Bruijnzeel, 1990; Wilk *et al*. 2001). For example, Costa *et al*. (2003) inferred an increase in wet season discharge of 28% after 19% of the $175\,460\,km^2$ Tocatins River Basin in Amazonia was cleared, but attributed these to reduced infiltration associated with settlement. Yin & Li (2007) identified silting up of the Yangtze River as the main reason for increasing flood severity. It can reasonably be argued that deforestation was part of a process that led to reduced infiltration and greater sediment generation, respectively. However, the absence of trees *per se* was not the determining factor. This is not just a semantic but also a practically important distinction; it means that enhanced flooding does not necessarily occur as long as the soil is protected and settlements, roads and drains are designed and maintained well (cf. Bruijnzeel, 2004). It also means that reforestation does not necessarily reduce flooding (for example, if soil properties do not recover, river bed morphology does not change, and settlements, roads and drains remain unaltered).

In summary, our understanding of the influence of deforestation on hydrology is far from complete, but to date, there has not been convincing empirical evidence or theoretical argument that removal of trees is likely to exacerbate severe flooding in developing countries (or elsewhere). In principle, the data used by Bradshaw *et al*. could provide new, more convincing evidence, but below, we will argue that it is very difficult to interpret the data in their current form.

The difficulty with country statistics

The country statistics used include an accumulation of very different events and conditions. The data can include flash floods in small catchments as well as large-scale seasonal floods in the world's largest rivers. They can range from entirely expected floods to extreme events. Some countries are three orders of magnitude larger than others (e.g. China or India vs. Trinidad or Jamaica). Between and even within countries, vastly different climate, terrain, settlement and land cover characteristics exist. In some cases, floods predominantly originate from another country (e.g. Bangladesh; Brammer, 1990). While this does not prevent a statistical analysis of country totals, it does confound an inter-country interpretation of the results. The authors also exclude some flood events from the analysis because they were 'too large'. It is not clear what definition of floods was used and why the size of these inappropriately large events warranted their exclusion. In any case, it suggests that the analysis may not provide any evidence on the role of forests in the most devastating of floods (cf. Laurance, 2007).

The relationship between population, floods and flood records

The authors use flood records from the Dartmouth Flood Observatory website. A disclaimer to the data states that they 'are derived from a wide variety of news and governmental sources. The quality and quantity of information available about a particular flood is not always in proportion to its actual magnitude, and the intensity of news coverage varies from nation to nation. In general, news from floods in low-tech countries tend to arrive later and be less detailed than information from 'first world' countries' (Dartmouth Flood Observatory, 2007a). The website also states that the data cannot be totally consistent and that 'Usually this question of consistency is avoided or quickly presented. The originality of this project is to acknowledge the data inconsistency' (Dartmouth Flood Observatory, 2007b). These upfront caveats should lead to great caution when trying to make inter-country comparisons.

Relationships between flood occurrence, flood recording and people are many and complex. A number of links between human settlement and flood frequency, and damage exist. Floodplains tend to be fertile land and have historically led to high population densities, along with locations at the mouth of a river where maritime trade was feasible. Without adequate design of storm flow systems, rapid urbanization increases the likelihood of local flash flooding (e.g. Barnolas & Llasat, 2007). Increasing population pressure can also lead to increased settlement in floodplains without adequate flood protection (Plate, 2002). There are also links between population and the fraction of occurring floods that are recorded. Floods in sparsely populated areas (e.g. natural forests) are more likely to go unreported in media and official records.

Bradshaw *et al*. tabulate country population numbers but did not use these numbers as an explanatory variable for flood frequency. We performed a correlation analysis on the data tabulated in their paper (we included China). Where meaningful, we also calculated the same numbers but after dividing by country area. Strong statistical correlation was indeed found between population and flood frequency, for country totals ($r^2 = 0.82$) as well as after dividing by area ($r^2 = 0.70$; Table 1). There is some evidence that the maximum flow of rivers tends to scale with area to the power 0.7 (Rodríguez-Iturbe & Rinaldo, 1997); applying this to flood frequency led to a minimally enhanced correlation of $r^2 = 0.83$.

Conversely, correlation between forest cover or cover loss and flood frequency appears absent ($r^2 < 0.10$). The land cover parameter that accounts for most of the variation in flood frequency is the 'degraded lands' fraction (including all urban and agricultural land; $r^2 = 0.30$–0.61; Table 1). This may or may not be a spurious correlation introduced by the relationship between population and land degradation ($r^2 = 0.64$ for country totals and $r^2 = 0.41$ when divided by country area, but in both cases log-normalized). In any case, deforestation should not be equalled to land degradation for reasons discussed.

After accounting for the correlation with population, forest cover or deforestation appeared to explain less than 1% of the remaining 17–30% of variation in country statistics. However, even if these factors explained any significant variation, the observational bias and scale differences in the data would need to be addressed before such a finding can be interpreted. Subsequently, several alternative explanations would have to be eliminated before it could be concluded that deforestation amplifies flooding. Our correlation analysis merely intended to demonstrate these points.

Conclusion

Reanalysis of the data presented by Bradshaw *et al*. does not provide evidence that deforestation amplifies flooding in the developing countries studied. It does suggest a correlation between population density and the flood records used in the analysis, and the reasons behind this can be many. We speculate that Bradshaw *et al*. may have derived their erroneous conclusions by intuitively assuming, as has been done for a long time, that forests necessarily protect us from floods. Current scientific evidence does not support their assumption, however. In another article, the authors contend that 'An excessive dumbing down of conservation science for the masses is, in our opinion, naïve because it risks further distancing lay people from the real and often harsh

Table 1 Coefficients of correlation between selected country statistics for 56 developing countries and indicators of the frequency and severity of floods; for (a) country totals and (b) with variables divided by country area where applicable

	Number of floods	Total average damage ($US)	Number of people killed	Average number of people displaced
(a)				
Area (km^2)	0.40	0.10	0.08	0.28
Rainfall (mm yr^{-1})	0.00	0.00	0.01	0.02
Slope	0.05	0.00	0.00	0.01
Population number	0.82	0.74	0.21	0.87
Degraded area (km^2)	0.61	0.43	0.13	0.55
Number of floods	n/a	0.82	0.17	0.80
Natural forest cover (km^2 2000)	0.04	0.01	0.00	0.01
Natural forest cover (km^2 1990)	0.04	0.01	0.00	0.01
Natural forest lost (km^2)	0.00	0.16	0.00	0.00

	Number of floods per km^2	Total average damage ($US km^{-2})	Number of people killed (per km^2)	Average number of people displaced (per km^2)
(b)				
Area (km^2)	0.05	0.00	0.01	0.00
Rainfall (mm yr^{-1})	0.10	0.02	0.00	0.01
Slope	0.02	0.00	0.01	0.00
Population density (per km^2)	0.70	0.73	0.14	0.52
Degraded area fraction	0.30	0.14	0.02	0.21
Number of floods per km^2	n/a	0.39	0.07	0.35
Natural forest cover fraction (2000)	0.07	0.05	0.01	0.04
Natural forest cover fraction (1990)	0.10	0.04	0.00	0.05
Natural forest lost (fraction)	0.01	0.02	0.00	0.03

natural world ecologists work to understand.' (Bradshaw *et al*., 2007b). We suggest that a similar comment can be made about the impacts of land use change on hydrology in general, and flood risk in particular. We agree with Bradshaw *et al*. that intact natural forests provide many and important benefits, and that there are powerful arguments for forest conservation. Some of the most powerful arguments may be ethical or religious. However, flood protection would seem a utilitarian, anthropocentric argument. This forces us to consider that there are real and often very substantial cost implications and tradeoffs between one type of public good (e.g. flood protection) and another (e.g. poverty alleviation), and requires us to assess the factual veracity of the argument. Deforestation can set the stage for activities that lead to further environmental degradation, but so far, the evidence does not suggest a strong role of trees in floods, even if there are many questions still to be answered.

Despite our criticism, we appreciate the attempt by Bradshaw *et al*. to address the forest–flood question from a different angle, and so demonstrate the potential for new data sources. Satellite observations are already being used to analyse land cover condition and change. Satellite observations of flood occurrence, duration and extent such as those from the Dartmouth Flood Observatory, as well as global observations of rainfall (e.g. Hong *et al*., 2007) are valuable new source of information when interpreted carefully. We applaud Bradshaw *et al*. for realizing this opportunity.

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