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Reply to comment by Birkinshaw on "A paradigm shift in understanding and quantifying the effects of forest harvesting on floods in snow environments"

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> "The vitality of a branch of science is a reflection of the magnitude or importance of the questions on which its students are applying their effort."
>
> *Leopold and Langbein* [1963]

1. Introduction

Green and Alila [2012] focused on forests and floods in snow environments. We thank Steve Birkinshaw for providing us with the opportunity to illustrate further why we remain opposed to the use of chronological pairing even in rain environments. *Green and Alila* [2012] insist that the science of how forest harvesting is affecting floods must be guided by the question: (1) what is the change in magnitude (frequency) for a flood of a specific frequency (magnitude)? *Birkinshaw* [2014] argues that this question should be extended to include (2) what is the change in magnitude for a flood generated by a specific rainfall event?

The first question examines the difference in magnitude between preharvest and postharvest discharges of the same frequency (frequency pairing or FP). The second question examines the difference in magnitude between preharvest and postharvest discharges of the same storm (chronological pairing or CP). Consequently, FP and CP refer to different experimental designs for testing hypotheses whereby the former uses the frequency of the flood while the latter uses the storm as one of the controlling factors to isolate the effects of forests on the magnitude of floods. We illuminate below how the CP-based change in flood magnitude for specific storm event is misleading because it stems from an uncontrolled experiment, i.e., fixing the storm input does not fully or properly isolate the effects of forests on the magnitude of floods. *Birkinshaw*'s [2014] CP-based research question is, hence, inappropriate and must not be used to guide, in part or in totality, the science of how forests affect floods.

2. CP Leads to Erroneous Conclusions on How Forests Affect Floods

The CP-based change in magnitude, originating from the paired watershed experimental design, has always been assumed to isolate the effects of tree removal on the magnitude of the flood—but does it? An experiment designed to fully isolate the effects of forests on the magnitude of a flood must control for all factors affecting such flood. So, what are the factors affecting the flood response? The magnitude of the flood is affected by, among other factors, not only the storm and its characteristics but also by the antecedent moisture conditions at any given time in the watershed; this is true with or without a forest cover [*Hewlett et al.*, 1984; *Buttle*, 1994]. A CP-based change in magnitude seemingly controls for the effects of the storm input but leaves the effects of antecedent moisture conditions uncontrolled. Therefore, CP is flawed because, as we further explain below, it leads to a change in magnitude that stems from an uncontrolled experiment that does not fully or properly isolate the effects of forests on the magnitude of floods.

If the storm input and antecedent moisture conditions are the two hydrometeorological factors responsible for the flood, it is the effects of these hydrometeorological factors and not just the meteorological input alone that would have to be simultaneously controlled to isolate the effects of forests on floods. However, this is not possible, since forests affect the antecedent moisture conditions and, as a consequence we argue, may even change the type of storms that generate floods of a given magnitude. Tree removal suppresses evapotranspiration which in turn may result in some medium size storms that never caused some large preharvest floods of a certain magnitude, to start generating such postharvest floods. Therefore, and perhaps to the surprise of most, even the storm could not be fixed as an attempt to isolate the effects of forest cover on the magnitude of floods. In other words, forest harvesting changes the two hydrometeorological factors responsible for producing floods and hence neither can be used as a controlling factor in an experiment meant to isolate the effects of forests on such flood response.

How can the combined effects of the antecedent moisture conditions and storm input be controlled to isolate the effects of forest cover on the magnitude of the flood? Frequency, which is determined by considering the full posttreatment time series of floods concurrently, captures the simultaneous effects of the hydrometeorological factors responsible for the flood. The designation of a rank (a surrogate of frequency) to a specific event in a time series of floods, for instance the 15th largest observation, is determined by how its magnitude compares in relation to all other flood observations in the time series. But the magnitude of this 15th largest flood event is affected, as discussed earlier, by the antecedent moisture conditions and the storm input. This is why, by fixing the frequency, it is possible to control the combined effects of the two hydrometeorological factors responsible for the flood and hence fully isolate the effects of tree removal on the magnitude of such a flood.

We offer a second different but related explanation of how CP is flawed, which may help readers better understand why the pairing must be by equal frequency. Some medium size storms falling on wet antecedent conditions may produce floods large enough in magnitude to become equal to or even larger than floods generated by some bigger storms, a phenomenon exacerbated by suppressed evapotranspiration caused by tree removal. This can change the rank order or frequency of postharvest floods generated by storms with a wide range of sizes including those produced by these bigger storms that otherwise might not have been affected much by harvesting from a CP view point (see *Green and Alila* [2012], Figure 5 for an illustration of this rank order change in snow environments). Consequently, the probability density function of postharvest floods might shift rightward including its upper tail. However, this upper tail is now only partly formed by these bigger storm-induced floods. Although a CP-based investigation may reveal that the magnitude of some large storm-induced floods may not have been affected much by forest harvesting, an FP-based investigation will reveal that they have become more frequent in comparison to their preharvest counterparts simply because some medium-size-storm-induced postharvest floods have increased in magnitude. Consequently, conclusions stemming from the CP-based investigation—that the magnitude of large floods is not affected by forest harvesting is irreconcilable with those of the FP-based approach—that large floods are becoming more frequent. This is because postharvest floods cannot become more frequent unless they are larger in magnitude than preharvest floods. This is yet another reason why the science of forests and floods must only be guided by the FP-based research question for evaluating simultaneously the change in magnitude and frequency of floods.

Birkinshaw [2014] states that "*Green and Alila* [2012] do indeed show that harvesting increases the magnitude and frequency of most events." Following such admission, the question we have is: what is the effect of such increases in the frequency of large postharvest floods on the variance of the flood frequency distribution? If harvesting increases the variability of the floods around their mean value, preharvesting and postharvesting flood frequency distributions must diverge at the upper tails, challenging an age-old hydrological precept still being taught to students in hydrology textbooks [e.g., *Jeffrey*, 1970; *Lee*, 1980; *Calder*, 1992; *Brooks et al*., 2012; *Chang*, 2012] that the effect of forest harvesting must always decrease with an increase in event size. Although a change in the variability of floods, a proxy for flood responsiveness or flashiness, may not come as a surprise to most of us it is rarely invoked in the forest hydrology literature, at least not quantitatively, and hence its effects on the frequency and magnitude of larger floods have been concealed by the dominant use of the CP-based framework. This issue is of paramount importance, since the magnitude and frequency of floods, making up the upper tail of a flood frequency distribution, are sensitive to even small changes in the variability of the floods around their mean value.

Our arguments against the use of CP in this reply are conceptual in nature but have been corroborated in a few FP-based studies that are rarely cited by forest hydrologists or land use policy advocates. *Svoboda* [1991, Figures 5 and 6], *Reynard et al*. [2001, Figure 5], and *Brath et al*. [2006, Figure 8], for instance, used FP to illustrate that even in rain environments forest harvesting can increase the magnitude across a much wider range of return periods than ever reported in decades of CP-based studies. Such increase in absolute terms is larger as the event size increases and the larger the flood the more frequent it becomes with no apparent threshold beyond which forests have no effects, at least not before the 50 and 100 year return periods. These findings run counter the prevailing "wisdom" in hydrological science, but are consistent with the conclusions of *Green and Alila* [2012], *Kuraś et al*. [2012], and *Schnorbus and Alila* [2013] in snow environments, despite the totally different processes underlying the two hydro-climate regimes.

Birkinshaw [2014] confuses the FP-based convergence of preharvest and postharvest flood frequency distributions with the CP-based convergence of preharvest and postharvest regressions when he states "However, almost the same results [convergence] can be obtained in a chronological pairing (CP) approach. For example, *Birkinshaw et al*. [2010] at La Reina catchment in Chile found a reduction in the relative change for higher discharges (and hence return period) but little variation in absolute change." *Birkinshaw et al*. [2010] used CP to test the hypothesis that the effects of forest cover on the magnitude of flood peaks become less important as the size of the hydrological event increases. We reiterate that if investigated using a CP framework such hypothesis tells us nothing about the correct change in magnitude and equally important it does not recognize the fact that floods could also be greater in frequency, i.e., more frequent. A CP-based change in magnitude may be decreasing, in relative or in absolute terms, as the size of the preharvest flood or its generating storm increases, but this is irrelevant and does not necessarily translate into forest harvesting not affecting floods of any size, especially larger floods.

3. Should the Physics of Forest Effects on Floods Be Investigated via CP or FP?

Birkinshaw [2014] argues that CP should not be abandoned because it provides "some insights into the physics of the catchment." We remain opposed to the use of CP for understanding the physics, because CP leads to a change in magnitude that does not fully or properly isolate the effects of forests on the magnitude of floods and because CP and FP can provide diametrically opposite conclusions on how forests affect floods, in which case they cannot be both right. Additionally, by leaving the CP door open for explaining the physics we also leave ourselves vulnerable to the misleading claims of convenience that forests will always have no effects on large floods [*Alila et al*., 2010].

The use of CP in forest hydrology has for decades forced a deterministic way of explaining the physics of the purely stochastic relation of forests and floods and in the process created a physical understanding for a seemingly related but inappropriate research question. If the flood frequency distribution framework, which allows for fixing the frequency, must be used for predicting the effects of forests on the magnitude of floods, it becomes an absolute necessity for explaining the physics of forests and floods. The research question that we argue must guide the science of forests and floods constrains us to compare two events of equal frequency that do not necessarily belong to the same hydrometeorological event, which incidentally has long been hinted to by the most luminous of Forest Hydrology [*Hewlett and Helvey*, 1970, pp. 779]. We assert that the understanding of a change in the inextricably linked magnitude and frequency of a specific flood must be conducted using FP by addressing the questions: how do the effects of forest harvesting on hydrologic processes change the peak flow frequency distribution? Does harvesting shift the mean only, or does it simultaneously affect the mean and variance? Does it change the form of the frequency distribution altogether? Only this sort of understanding that links physical hydrology to the frequency distribution [e.g., *Green and Alila*, 2012] (Figure 7) can help us quantify the changes in magnitude of, for instance, a 20 year flood. Such approach to understanding the physics is common outside the forest hydrology literature [e.g., *Eagleson*, 1972; *Lamb*, 2005; *Sivapalan et al*., 2005], and therefore should not be the subject of much resistance.

4. Hydrologic Recovery Can and Should Be Investigated Using FP

Green and Alila [2012] demonstrated how and why CP leads to erroneous answers to questions related to the immediate effects of forest harvesting before any hydrologic recovery caused by forest regrowth using either recovery-adjusted field measured or model simulated stationary time series of peak flows. In this reply, we further illustrate that CP-based study outcomes are invalid, because CP does not fully and properly isolate for the effects of forest cover on the magnitude of floods. Investigating hydrologic recovery involves the use of a nonstationary time series of peak flows and was outside the scope of our published work to date. Hydrologic recovery questions can have the form of: (1) when would the watershed flood response return to its preharvest conditions (full recovery)? or (2) what is the stage of recovery at any point in time postharvesting (partial recovery)? *Birkinshaw* [2014] defends CP using a flawed argument when he claims that it is impossible to use FP for investigating questions related to hydrologic recovery, because the time series of peak flows is nonstationary. This argument of "nonstationarity in peak flows" has been used before to justify CP [*Beschta*, 1978, pp. 1015] but it is in our opinion a serious misconception with long lasting consequences. Misconceptions in archival science are often not easily or quickly corrected and need wide recognition if they are to be overcome [*Kiang*, 1995, pp. 347].

Although it may be more challenging to investigate hydrologic recovery in a frequency pairing framework when a time series is nonstationary, it is not impossible. There are newly emerging flood frequency analysis methods that can accommodate nonstationarity caused by forest regrowth [*Katz et al*., 2002; *Katz*, 2013]. An advantage of FP in the context of recovery is that it invokes concurrently the effects of forest regeneration on magnitude and frequency which incidentally may be recovering at different rates because of their highly nonlinear relation (recall how only modest changes in magnitude are needed to observe surprising changes in frequency). *Alila et al*. [2009, Figure 6b] FP-based analysis of the borderline stationary time series of recovery-unadjusted peak flows points to the possibility that hydrologic recovery at the 25% patch cut and fully roaded watershed (WS3 of the HJ Andrews Experimental Site, Oregon, USA, dominated by a rain and rain-on-snow environment) may have mitigated some of the effect on the magnitude of peak flows, but the effect on peak flow event frequencies appear to have persisted for decades after harvest. Perhaps these findings should not be surprising, since roads cause more permanent physical changes to watersheds, and therefore their effects should not be expected to recover at the same rate as forest stands [*Gucinski et al*., 2000]. Our FP-based work is only hinting that FP can lead to a much slower hydrologic recovery than reported in previous CP-based studies using the same data sets and more FP-based work is urgently needed on this topic.

Birkinshaw [2014] claims we are being contradictory in insisting that forest hydrologists must abandon CP while still using it in our FP-based analyses, but we disagree. *Birkinshaw* [2014] is referring specifically to our use of the CP-based calibration equations for estimating the expected posttreatment period peak flows had there been no logging in the treatment watershed at the two paired watershed study sites. The use of CP to establish a pretreatment calibration equation is entirely different than the use of CP to isolate the effect of forest removal during the posttreatment period. *Green and Alila* [2012, paragraphs 11 and 12] clearly stated that there is nothing wrong in such use of CP-based regression equations relating peak flows of two similar (i.e., paired) catchments for estimating expected flows in neighboring gauged watersheds. During this pretreatment (fully forested) calibration period the paired catchments are, in theory, behaving in an identical manner. However, we remain adamantly opposed to the use of CP as a means of isolating the effect of forest cover on the magnitude of floods during the posttreatment period, because the hydrometeorological processes driving peak flows have become decoupled between the two paired watersheds.

5. How Rare Must Floods Be for Forest Harvesting to Have No Effects on Floods?

Green and Alila [2012] considered the FP-based zero or negative change in magnitude of the largest event at each catchment an artifact of sample size and therefore not real. *Birkinshaw* [2014] argues that this change in magnitude is real—but is it?

It is the power of meta-analysis that allows us to consider the lack of an effect of harvesting on the largest flood an artifact of sampling. The pre and postharvest flood frequency curves at Camp with 19 years of record intersect at around 20 year return period. Considering Camp alone, i.e., not part of a meta-analysis, this intersection may lead one to hastily conclude that harvesting has no effects on floods with return period larger than 20 years. However, considered collectively, our FP analyses at the four snow sites with approximately similar harvest levels, but progressively larger posttreatment record length, suggest an emerging pattern of no clear upper limit return period to the effect of harvesting. As record length increases, the apparent "no-effect" threshold return period shifts from the 20 year for Camp (19 years record) to the 50 year for Fool (48 years record) and to beyond the 100 year for 240 and Redfish Creeks (95 and 99 years record, respectively) [*Green and Alila*, 2012, Figure 2].

Our meta-analysis is trading space for time but what happens to the largest event as sample size increases at the same site and within an FP framework? Although it is true that the magnitude of the largest event in a sample of any size is fixed, an increase in sample size also means that this same large event may now have an equal rank with a totally different flood and hence the change in magnitude for this large event and its return period will change with an increase in sample size. The rightward shift of the no-effect

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threshold with increasing sample size at the same site was also demonstrated by *Alila et al*. [2009] when they compared the FP analysis outcomes using the first 27 years and then the entire 48 years of postharvest record of the same Fool Creek data set. The largest two events in both samples are the same, yet the flood at which the pre- and postharvest frequency curves intersect has a return period in the range of 17 to 48 years when using 27 years of data and in the range of 30 to 80 years when using 48 years of data. This illustrates how sensitive the frequency, and hence the FP-based change in magnitude, of the largest few events is to sample size. This is why *Green and Alila* [2012] considered the FP-based negative or zero change in magnitude of the largest event at each site an artifact of sample size and therefore not real. *Green and Alila* [2012, Figures 6 and 7 and related discussions] physical process investigation, which *Birkinshaw* [2014] choose to remain silent about, lend more support to our conclusion of a no clear upper threshold return period to the effects of forest harvesting in snow environments. This conclusion runs counter the conventional “wisdom” repeatedly echoed in elite journals, forest hydrology textbooks, and influential United Nations policy documents (*Alila et al*., [2009] paragraphs 3 and 67 and *Green and Alila* [2012] paragraph 5 for references) that larger floods are not affected by tree removal due to an “overwhelming” of the interception capacity of the forest canopy and storage capacity of the forest soils. To the contrary, regardless of the relative role of forests on evapotranspiration, *Green and Alila* [2012] illustrated how the mitigating effects of the forest canopy on snowmelt, the primary process controlling peak flows, are maintained over the full postharvest peak flow sample [*Green and Alila*, 2012, Table 3, Figure 6]. This physical process interpretation is also consistent with multiyear stand level investigations that found melt rates to be consistently higher in cut blocks relative to the forest regardless of the seasonal variability in meteorology during the study period [*Green and Alila*, 2012, and references therein].

Birkinshaw [2014] argues against our finding of no clear upper threshold return period to the effects of forest harvesting in snow environments but without the benefit of providing the readers with a physical explanation to the contrary. *Birkinshaw* [2014] only claims that a CP-based approach could be used to explain physically why forest harvesting may be reducing instead of increasing the magnitude of the largest peak flows. We again caution that a decrease in magnitude under the CP framework is misleading, because it is not necessarily equivalent to a decrease in magnitude under the FP domain. We, therefore, stand firm behind our original claim that the effect of forests on floods has no clear upper no-effect threshold return period in four snowmelt catchments, at least within the range of the observed or simulated record of 19–99 years. *Kuraś et al*. [2012] and *Schnorbus and Alila* [2013] came to the same conclusion that there is no clear upper threshold to the effects of forest harvesting on floods using 100 years of simulated flows in snow environments. *Svoboda* [1991], *Reynard et al*. [2001], and *Brath et al*. [2006] using an FP analysis showed similar patterns of no apparent threshold return period beyond which forests have no effects even in a rain environment.

Birkinshaw [2014], while suggesting the FP-based effects on the largest flood event on each site may be real, disagrees with our conclusion that our CP-based analysis suggests that the largest floods are either not affected much or are reduced relative to the preharvest conditions or control catchments [*Green and Alila*, 2012, Figures 3 and 4]. However, our conclusion is valid because unlike the stochastic FP analysis, CP is deterministic and hence does not involve the sampling uncertainties induced by ranking and the estimation of return periods. Previously published independent studies by other researchers using CP-based analysis of the same data sets at Fool and Camp Creeks led to the same conclusions [*Alila et al*., 2009 and *Green and Alila*, 2012 and references therein].

6. Conclusion

The unrelenting often intense debates on the topic of forests and floods have been fueled by misconceptions related to the basics of the scientific method: setting the right research hypotheses or questions and designing the right experiments to test such hypotheses or answer such questions. The CP-based research questions defended by *Birkinshaw* [2014] are inappropriate, because they stem from an experiment that does not fully and properly control for all factors needed to isolate the effects of forest harvesting on the magnitude of floods. The forest hydrology community has been misguided by these CP-based research questions for over a century and as a consequence forced a flawed deterministic process understanding on what should have been purely stochastic research questions. Deterministic approaches where peak discharges can be predicted based on CP-derived regression relations between two similar catchments and may have some role to play in hydrology, but forests' effects on the magnitude and frequency of floods can only be physically understood and predicted within the stochastic frequency-based framework. In order to move beyond the widespread confusion on this topic, we must accept that FP- and CP-based research questions lead to different conclusions on how forests affect large floods; they cannot be both right. We maintain that the CP-based questions defended by *Birkinshaw* [2014] lead to scientifically unfounded conclusions on how forests affect floods and therefore must be abandoned and supplanted by their FP-based counterparts.

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