Report to LTER Network Office on Long Term Hydrologic Change: Disturbance Legacies in Material Fluxes Working Group Meeting

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New England Center – Durham, NH

Submitted by Dan Bain and Mark Green (March 12, 2009)

Working Group Participants and Affiliations

Working Group: *(Front Row, Left to Right)*: John Chamblee (UGa, CWT Information Manager), Jon Duncan (UNC Chapel Hill), John Campbell (USFS, HBR Information Manager); (Sitting, Left to Right): Caroline Hermans (CCNY), Sherry Martin (Michigan State U.), Mark Green (CCNY), Tom Jordan (Smithsonian Environmental Research Center -- SERC), Jen Fraterrigo (UIUC), Sayo Chaoka (UIUC); *(Standing, Left to Right)*: Gretchen Gettel (UNH), Bill Sobczak (Holy Cross), Don Weller (SERC), Dan Bain (U Pitt), Emery Boose (HFR, Information Manager), Tony Parolari (MIT), Brian Hall (HFR), Sujay Kaushal (U Md, Chesapeake Biological Lab), Jonathan Thompson (HFR), Jim Vose (CWT); *(Not Pictured)*: Praveen Kumar (UIUC), Wil Wolheim (UNH)

MAJOR OUTCOMES

Defining Legacy Effects

One of the first orders of business during the working group meeting was trying to arrive at a working definition of "legacy effect." The term legacy has been applied to a variety of human induced changes across scales. For example, the recent fluvial geomorphology literature tends to refer to the floodplain deposits that have accumulated following the European forest clearance in North America as "legacy sediments." The stream ecology literature tends to use legacy in the sense of Harding et al. (*PNAS*, **95**, 14843-14847), who noticed interesting patterns in stream biodiversity that are better explained by land use 50 years in the past than contemporary land use. In time series analysis, legacy effects are roughly equivalent to "system memory," the long-term ramifications of system perturbation throughout the subsequent time series record. Some legacies in the uplands are associated with divergent management practices and the associated impacts on soil nutrient status (e.g., *Ecology* **81**, 2314-2330). With such a wide variety of scales and potential processes, we spent the initial part of the meeting focusing on what exactly a legacy is, particularly in terms of material fluxes.

In the end, we agreed that legacies can be divided into two groups: legacies that fundamentally change the structure of the watershed system (e.g., erosion of the top 10 cm of soil following deforestation) and legacies related to signal storage in the watershed (e.g., excess fertilization stored in groundwater). These groups were dubbed (respectively) "structural" and "storage" legacies. In addition, our discussion focused almost entirely on legacies arising from human activity and rarely considered other disturbances (e.g., glaciers).

In addition, as most geophysical and ecological processes occur in dynamic systems, these processes are all subject to a wide variation in both storage and structure. Therefore, if legacy effects are simply alterations in storage or structure, almost anything could be defined as a legacy effect. However, the term legacy implies continued impacts to systems for a much longer time period than the characteristic time period of the perturbation. So, one of the first post-meeting charges of the working group is to assemble a range of potential legacies. Using these examples, we will ratio the time of sustained impact against the time of disturbance to generate a

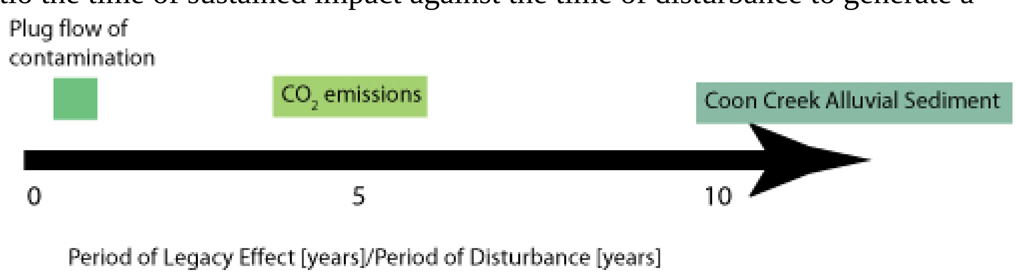

Figure 1 Dimensionless time criteria for identifying legacy effects. Normalizing characteristic time periods of legacy effects by the time scale of the disturbance allows evaluation of what constitutes a legacy effect. While plug flow (left) is clearly not a legacy effect, the criteria is a lower limit of values we are likely to see, at a value of one. The CO_2 emissions box uses the estimate of the longevity of the “irreversible climate change effects” of carbon emissions (i.e., 1000 years, *PNAS* **106**, 1704-1709) normalized by the period of accumulated carbon emissions (roughly 200 years). The legacy sediment example on the right uses data from Coon Creek Wisconsin (*Science* **285**, 1244-1246) and normalizes the increased sediment efflux by the period of severe erosion in the basin. While we have placed it with a lower bound of ten, it is likely much larger. Ultimately we expect that the legacy threshold will lie somewhere between one and five.

dimensionless index allowing clear temporal criteria for legacy effects. It is assumed that clear demarcation will be possible using these criteria (see Figure 1.)

While many processes have been described as legacy effects, this working group meeting produced important groundwork for formalizing and standardizing the concept of legacy effect.

Characterizing Legacy Effects

With some consensus on what we mean when we say legacy effect, we proceeded to create a list of criteria with which to understand and describe these effects. These criteria were: residence time, flowpath, reactivity/metabolism, connectivity, and material source. The working group anticipates that these criteria will evolve and be refined as work progresses. For example, the group was somewhat ambiguous about including connectivity because the meaningful changes in connectivity are strongly associated with changes in flowpath and residence time. However, activities clearly causing a legacy effect, such as dams, can cause permanent changes in connectivity and therefore flux (in the case of dams, anadramous fish migration and the associated riparian nutrient enrichment). Likewise, most changes in flowpath would result in changes in residence time.

We agreed that “storage” legacies can be explained by the fact that water residence time in a watershed is a distribution – often a heavy-tailed distribution – thus, flow paths with long residence times store materials from past disturbances. In other words, materials transported through a watershed may be present in the watershed for a very long time due to the possible fractal nature of watershed transport.

One proposal that emerged late in the meeting and garnered a great deal of support was to examine “structural” legacy effects by simplifying the catchment to a batch reactor. In a continuous stirred tank reactor (CSTR), the transport of material through the reactor is predicted by equation 1:

$$J = s(e^{-k\tau})$$

In this case J is material flux [mass per time], s is the material source [mass per time], k is the first-order rate constant [per time], and τ is the residence time in the reactor [time]. We suggest that a change in flux due to a structural change to the watershed can be explained as:

$$\Delta J = s_1(e^{-k1\tau 1}) - s_2(e^{-k2\tau 2})$$

where the flux is altered by a change of source, reactivity, or residence time (changes in connectivity and flowpath are lumped into residence time). In essence, a change in ΔJ is a candidate legacy effect. The use of this simple framework is particularly useful in catchment approaches where things are more complicated than a simple stirred vessel, but CSTR theory explains the fundamental processes in a parsimonious way. This framework is very promising for understanding legacy effects both conceptually and quantitatively.

Cross-Site Historical Trajectories

With at least a working consensus on a conceptual model and the terminology for describing the model, we proceeded toward using the model to understand observations made at long-term ecological research sites. One of the first tasks was characterizing the differences in intensity, duration, and timing of human disturbances to each site. This analysis was conducted with a simple parallel timeline approach, summarizing the history of human disturbance to each site. This immediately captured the range of disturbance histories with Hubbard Brook and Coweeta occupying one end and Baltimore the other.

However, two important similarities for all sites quickly became evident. Both went through a period of recovery following initial disturbance, generally coinciding either with westward expansion and the consequent changes in agricultural economics or the failure of substantial regeneration following initial clearance. In addition, all sites are experiencing build out in second homes or exurban homes, providing a great opportunity for future cross-site research. For example, how do systems with contrasting legacies react to modern suburbanization?

Cross-Site Data Comparisons

One of the more exciting tools to emerge from the working group meeting was what has been dubbed "the Jordan Plot" (after Tom Jordan). As we spent time considering the various histories of the sites and the resulting legacies in a range of biogeochemical systems, the idea was put forward to plot flux time series (i.e., water, carbon, nitrogen, and sediment) against each other (please see Figure 2). This organization not only gives us the opportunity to outline conceptual ideas, once populated with a combination of instrumented and proxy data from the paleorecord, it will provide an effective means to structure the inter-site comparison as this working group continues to pursue the questions laid out during this first meeting.

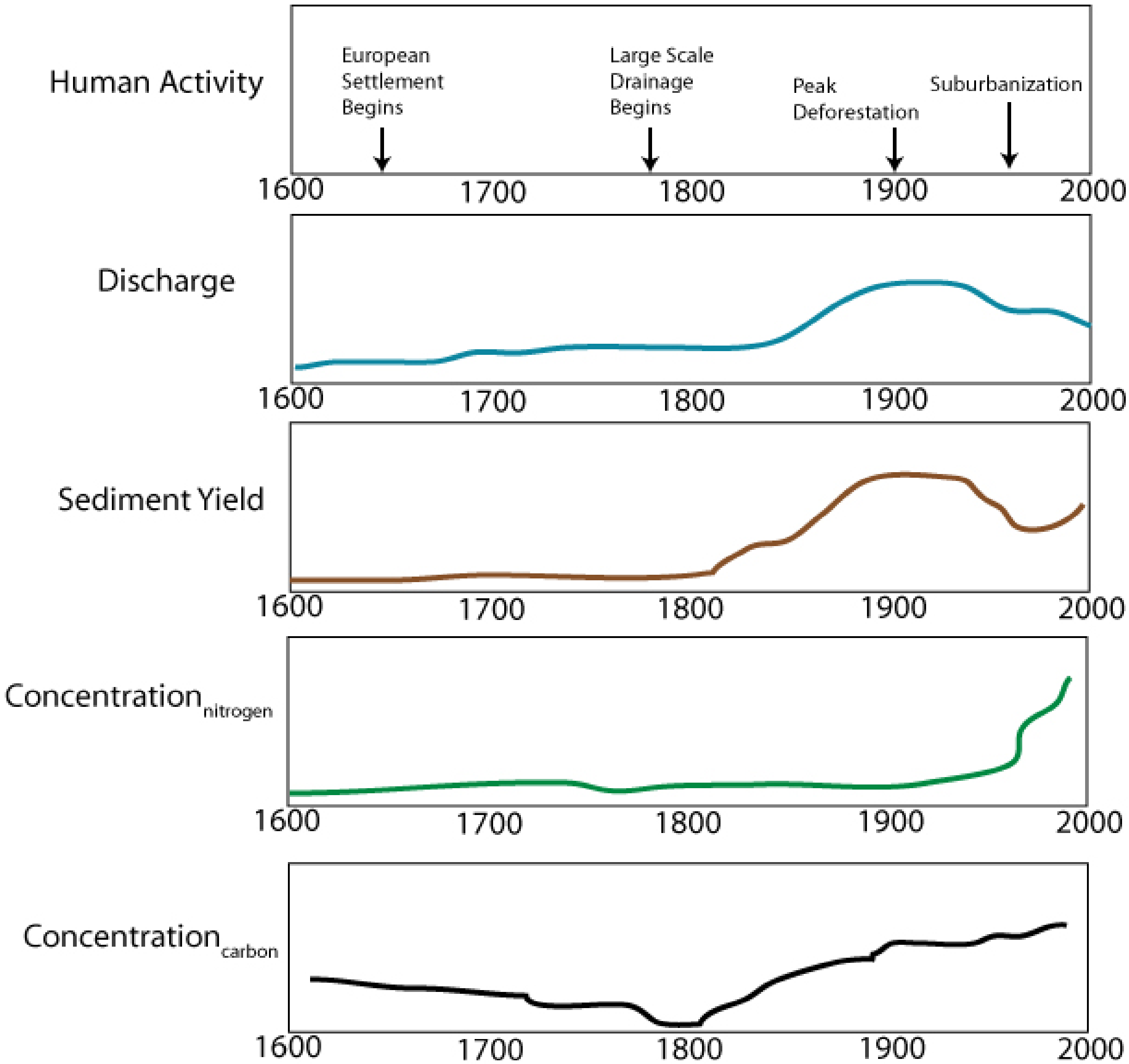

Figure 2 A hypothetical Jordan plot showing a rough approximation of what one might find at any given site. The peaks in water and sediment flux correspond roughly to the period of maximum deforestation, nitrate to the widespread adoption of chemical fertilizer application and carbon to periods of wetland rich landscapes and more recent inputs of human and animal waste. This plot will be confronted with available data at each site to ensure it reflects reality.

PRODUCT PLANNING

Based on the progress outlined above, it is clear to see that this working group will be productive. While a discussion of planned and potential products generated a long list, we find the following products to be realistically achievable in the short-term:

- *A Concept Paper to Bioscience*: This paper will contain much of the material described above, in addition to:
    - Case studies from each long term ecological site to illustrate the concepts outlined above
    - Populated Jordan Plots--Not only will we include the conceptual Jordan plot sketched above, we will, to the fullest of our ability, populate the Jordan plots will all available data from each site. It is likely this exercise alone will generate multiple hypotheses that will guide continued subject matter for the working group to pursue.
    - This paper will be submitted within a year of the workshop.
- *ESA Symposium 2010 Pittsburgh*: The group plans on submitting an organized symposium on legacy effects to the 2010 meeting in Pittsburgh. This symposium will not only highlight the important working group results, but interesting aspects of legacy effects from throughout the ESA membership.

FEEDBACK TO THE LTER NETWORK OFFICE

As first time synthesis working group organizers**,** there are a number of successes and failures we wanted to relate to the network office so that future working groups might be even more effective:

1. Once we were nearing the end of the working group meeting, we realized that we had not established a means to evaluate the effectiveness of the meeting. For example, the Network Office's feed back regarding data management was very helpful. If similar advice, perhaps universally, regarding evaluation metrics were passed on early, we think that meetings would ultimately improve as a result of this feedback.
2. Similarly, a list of communication tools that have been successfully used in these working groups would be helpful. Two collaborative tools that we employed for this working group were a wiki (GoogleSite; http://sites.google.com/site/legaciesinmaterialfluxes/) for sharing literature and data; and a collaborative mind mapping website to organize the ideas from the meeting (http://www.mind42.com). Ultimately, these two tools will allow us to maintain coherence as we transition from face-to-face discussions to collaborative writing and analysis from a distance.
3. Inclusion of scientists from the Smithsonian Environmental Research Center was an important part of successful synthesis. While we understand the Network Office serves the LTER network, we strongly recommend that, in synthesis exercises, the network encourage inclusion of researchers from non-NSF funded initiatives.
4. It was clearly and repeatedly demonstrated that Harvard Forest's land use database provides significant increases in the ability of an LTER site to provide data on legacy effects beyond the instrumented record. As we believe these legacy effects are important and can be invoked to explain many contemporary observations, the elevation of spatially explicit historical data to "core data" status for all sites is inevitable. We recommend creating incentives such that this process begins now.