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Legacy Effects in Material Flux: Structural Catchment Changes Predate Long-Term Studies

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Abstract

Legacy effects of past land use and disturbance are increasingly recognized, yet consistent definitions of and criteria for defining them do not exist. To address this gap in biological- and ecosystem-assessment frameworks, we propose a general metric for evaluating potential legacy effects, which are computed by normalizing altered system function persistence with duration of disturbance. We also propose two distinct legacy-effect categories: *signal effects* from lags in transport and *structural effects* from physical landscape changes. Using flux records for water, sediment, nitrogen, and carbon from long-term study sites in the eastern United States from 1500 to 2000, we identify gaps in our understanding of legacy effects and reveal that changes in basin sediment dynamics precede instrumented records. These sediment dynamics are not generally incorporated into interpretations of contemporary records, although their potential legacy effects are substantial. The identification of legacy effects may prove to be a fundamental component of landscape management and effective conservation and restoration practice.

Ecologists have grown increasingly aware that land-use practices occurring decades or centuries ago may have residual influences on the biological composition and ecological processes of contemporary ecosystems (e.g., Moorhead et al. 1999, Franklin et al. 2000, Foster et al. 2003). Consider several historical legacy effects or ecological legacy effects (henceforth, *legacy effects*) evident in modern landscapes: Roman-era agricultural settlements continue to influence soil chemistry and vegetative community composition in contemporary French forests (Dupouey et al. 2002), basin land cover in the 1950s is a better predictor of southeastern US fish in-stream diversity than are contemporary or historic riparian land uses (Harding et al. 1998), and divisions between field and pasture continue to dictate how contemporary forest soils cycle nutrients in the eastern United States (Compton and Boone 2000, Fraterrigo et al. 2005). These ecological legacy effects have largely been detected in plot- or reach-scale studies in which historical data were effectively collected or creatively deciphered from human and environmental records. Therefore, our understanding of legacy effects generally applies to limited spatial areas. Here, we expand legacy-effect detection to broader spatial scales in an effort to understand the legacy effects on fluvial fluxes in modern landscapes.

The quantification of legacy effects at broad spatial scales can also have important implications for managing ecosystems in the face of global environmental change. Efforts to mitigate human strains on sensitive ecosystems and landscapes through the alteration of system dynamics require increasing certainty of ecosystem behavior (e.g., designing stream “restorations” to treat nutrient impairments; Craig et al. 2008). Although the importance of understanding historical conditions to design restoration targets is well established (e.g., Allen et al. 2002), the characterization of legacy effects also informs potential solutions to challenges in sustaining and maintaining contemporary ecosystems (table 1). This recognition echoes the recent calls for examination of press—pulse dynamics in socioecological systems (Collins et al. 2010); however, our emphasis on retrospective assessment of legacy-effect-causing processes is distinct and, moreover, represents an opportunity to generate data sets to test the conceptual model of presses and pulses.

Table 1.

Contemporary ecological management challenges and specific examples in which reconstruction of legacy effects can provide information that may increase the probability of management success.

Ecological management challenge or technique	Potential relevance of legacy effects
Habitat assessment	Identification of predictable landscape successional trajectories (e.g., historic property extents and therefore management history heterogeneity; Bain and Brush 2008), which provides the opportunity for habitat potentials to be incorporated into planning.
Riparian restoration	The aggradation of floodplains and channels incision are processes fundamental to successful floodplain management. Historical basin-scale sediment yield is a primary control on contemporary riparian processes (e.g., Jacobson and Coleman 1986).
Nutrient load reductions	Historic changes in soil and drainage network structure alter the ability of areas to assimilate, store, and transform nutrients (e.g., Groffman et al. 2002). Careful contemporary spatial apportioning of load in response to these historical changes may allow leeway in allowable loading and ultimately more successful management.
Water retention estimates	Alterations in flow path can reduce water retention time and bypass important biogeochemical processing hotspots (e.g., Claessens et al. 2006). Reconstruction of these changes in structure through time can improve our understanding of retention process in particular watersheds or across landscapes.
Forecasting land cover changes	Historic land uses can ease or inhibit subsequent transitions (e.g., Bain and Brush 2008). An understanding of past land uses may allow improved prediction of sprawl patterns and the eventual planning of regional corridor networks.

Nevertheless, challenges remain. Extrapolation of observations from plots to landscapes introduces substantial uncertainty in legacy effects at larger scales, particularly the heterogeneities in human activity. As was noted above, much of the literature on ecological legacy effects has been focused on plot- or reach-scale changes, because land-use histories and long-term manipulations are more tractable at these scales. Yet, ecological patterns are often scale dependent and so too may be our interpretations of them (Wiens 1989). The spatial integration of patterns across catchments remains an important challenge for understanding legacy effects (Pijanowski et al. 2007). The characterization of the processes that govern legacy effects will require a synthesis of information from systems ranging across a wide range of scales and may ultimately improve our ability to manage complex biotic dynamics.

In the present study, we examined legacy effects on fluxes at the catchment scale because catchment fluxes are often used to monitor and assess ecosystem function (Likens and Bormann 1995), because some of the best time-series records are available for catchments (Lovett et al. 2007), and because catchments are studied by complementary disciplines (e.g., fluvial geomorphology and hydrology). Here, we address two central issues that have limited the formulation of a general conceptual model for examining legacy effects on contemporary watershed biogeochemistry and hydrology: poor documentation of past watershed land use or disturbance and the lack of quantification or conceptualization of disturbance events (human caused or otherwise) to incorporate differences in severity, duration, and legacy impacts. We then illustrate these ideas using watershed-based data to evaluate the legacy effects on material fluxes (e.g., carbon, nitrogen, water, sediment) among six long-term study sites in the eastern United States (figure 1). This comparison revealed both the existing strengths in data holdings and the additional data needed to establish a conceptual framework of legacy effects. A conceptual framework will allow the improved detection of legacy effects and a formulation of strategies to address these effects in environmental analysis and management.

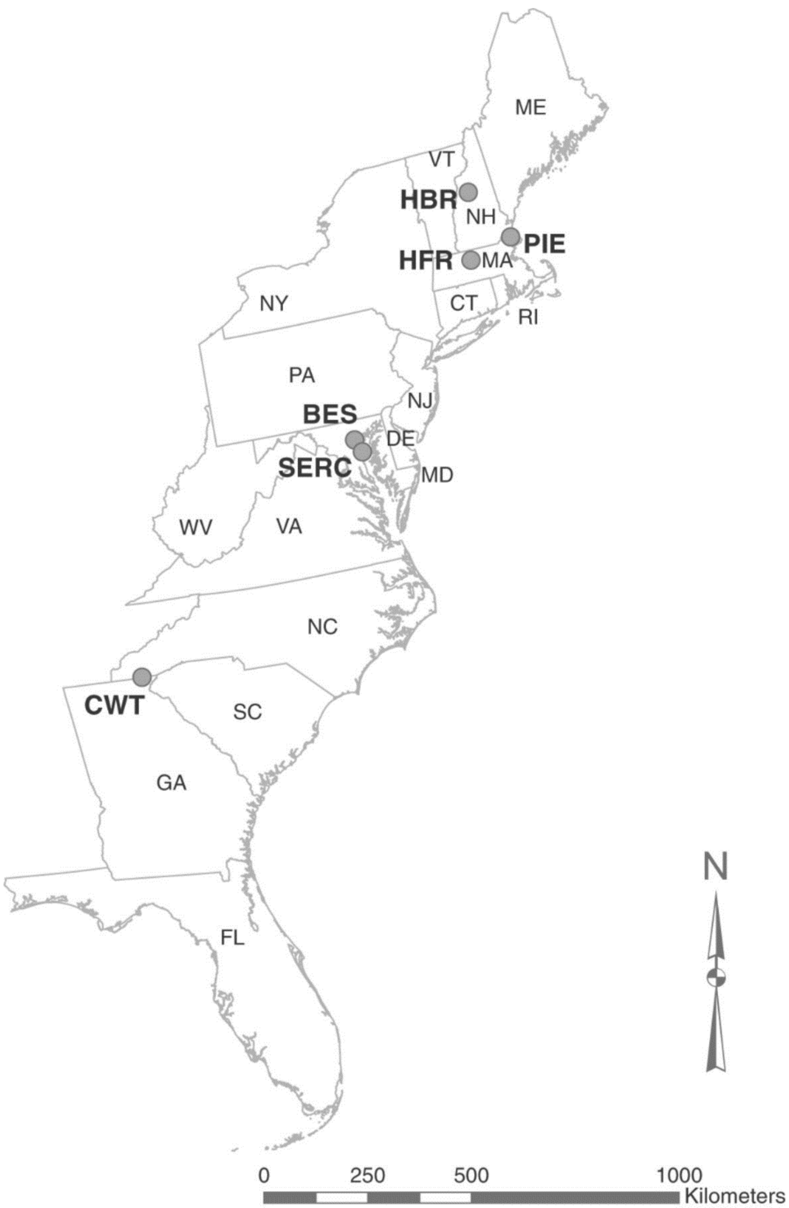

Figure 1. Locations of study sites. Abbreviations: BES, Baltimore Ecosystem Study; CWT, Coweeta Hydrologic Laboratory; HBR, Hubbard Brook Experimental Forest; HFR, Harvard Forest; PIE, Plum Island Ecosystem; SERC, Smithsonian Environmental Research Center.

Legacy effects: Refining our language

Meaningful discussion of legacy effects calls for a more precise definition, one that distinguishes effects on functions from the functions themselves and also differentiates between disturbances and their lasting influences.

Legacy-effect time ratio

What is a legacy effect? In the most general of terms, it is a persistent effect on contemporary function from a definite and identifiable past ecosystem perturbation. This definition is useful in theory but lacks the quantitative precision necessary to help ecologists compare and contrast ecosystems with a range of historical disturbances and a range of contemporary ecological responses to these past events. A more-precise definition of *legacy effects* must address material storage and the complex distribution of materials among hydrologic flow paths—particularly, long, slow paths such as groundwater. The definition should also differentiate between legacy effects that alter material transport in the existing system and those that directly alter the biotic or abiotic components of the system. However, if the definition of *legacy effects* remains too broad, most processes could be labeled a legacy effect (because they follow a sequence of events). Effects that remain more persistent and influential on long-term function, often beyond typical time-scales of cultural memory, are legacy effects. Clarification of this level of persistence and influence allows the identification of legacy effects and, therefore, facilitates the incorporation of such effects into our understanding of ecosystem function.

Given two equally intense disturbance events—one rapidly attenuating and one causing persistent altered function—the persisting event is a legacy effect. We propose that legacy effects must persist longer than the relevant period of disturbance—that is, the period of effect persistence, when it is divided by the duration of disturbance, must be greater than one (legacy-effect time ratio = persistence time/disturbance time > 1; figure 2). The separation of legacy effects from simple recovery processes with a legacy-effect time ratio value of one is a preliminary criterion, and the value will probably grow as additional data are gathered and actual thresholds are revealed. When applied to previously reported and proposed legacy effects, this metric provides a range of values stretching across several orders of magnitude (figure 2). However, the legacy-effect time ratio cannot be precisely calculated for currently persisting effects, although we can make reasonable estimates. For example, the legacy-effect time ratio for Roman agricultural disturbance (8.8; Dupouey et al. 2002) is higher than those of similar disturbances in Massachusetts or Rhode Island (0.5–0.8; Compton and Boone 2000, Hooker and Compton 2003). The legacy effects still persist in both cases, but the long persistence of Roman activities results in a higher ratio. In addition, the ratio is sensitive to disturbance period characterization. For example, although in studies from the Adirondacks (Goodale et al. 2000) and Rhode Island (Hooker and Compton 2003) in which the persistence of legacy effects from human disturbance in soil nutrient pools were evaluated, the legacy-effect time ratio values differed by orders of magnitude (0.75 for Rhode Island, 80–110 for the Adirondacks). Although some of this difference may arise from different resiliencies in the systems or from contrasting disturbance intensities, the relatively short disturbance period reported in the Adirondacks seems to cause disproportionate variation in the index. Despite these limitations, this legacy-effect time ratio provides a means to objectively evaluate the legacy impacts of historical human activities—particularly in cases in which careful and consistent characterizations of the historic time scales have been generated.

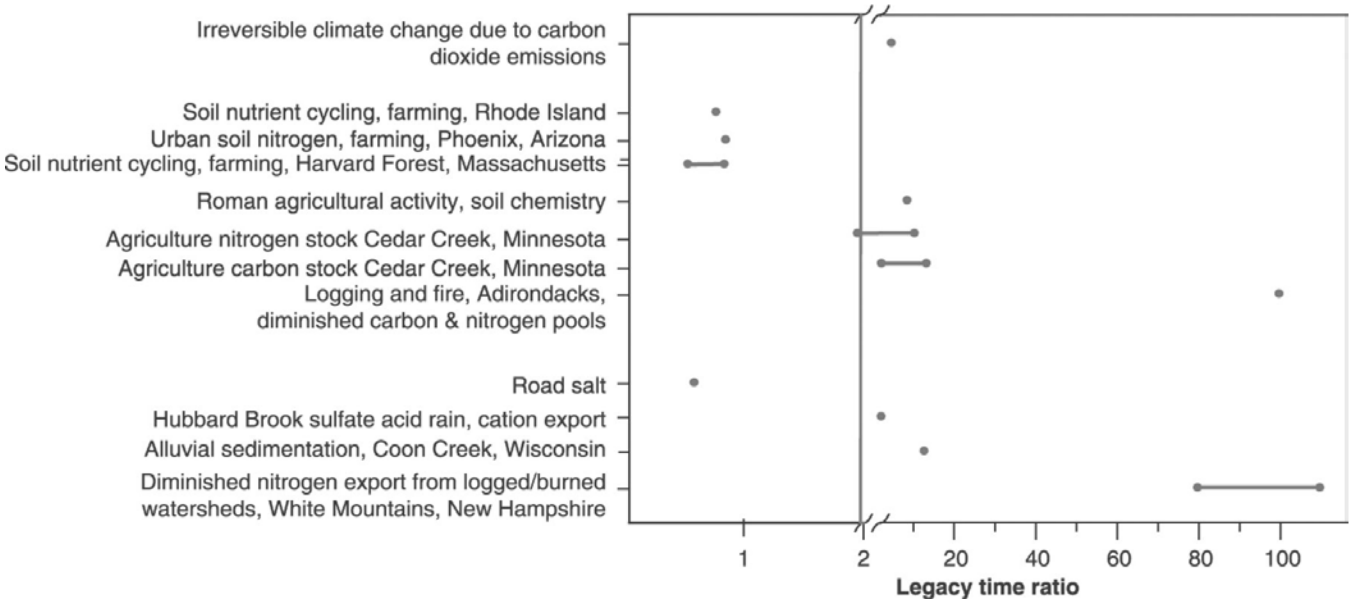

Figure 2. Legacy effects plotted as the ratio of effect persistence time to disturbance time (the legacy-effect time ratio). The legacy-effect time ratio is calculated by dividing the time of the observed effect by the time period of disturbance. For example, in the "Soil nutrient cycling, farming, Rhode Island" example, the following data are from Hooker and Compton (2003): Persistence time is the end of disturbance (1884) through the period of data collection (1999), or 115 years. Disturbance time is the period between initial European settler activity (1731) and the end of disturbance (1884), or 153 years. The resulting ratio is 0.75. We propose a threshold for legacy effects that the legacy-effect time ratio should be at least greater than one. The x-axis is broken into two regions (at the vertical line) to present all data on a linear scale. The legacy effect, disturbance, and location (where appropriate) are indicated on the y-axis. The data sources are, from top to bottom, Solomon and colleagues (2009), Hooker and Compton (2003), Lewis and colleagues (2006), Compton and Boone (2000), Dupouey and colleagues (2002), Knops and Tilman (2000), Knops and Tilman (2000), Latty and colleagues (2004), Kaushal and colleagues (2005), Likens and colleagues (1996), Trimble (1999), Goodale and colleagues (2000).

As additional potential legacy effects are identified and characterized, it is likely that additional criteria—particularly criteria that address spatial scales and disturbance intensity—may be necessary to refine the classification scheme. The use of characteristic scales, including ratios of area, helps in the conceptualization of complex phenomena (Fraterrigo and Rusak 2008, Turner et al. 1993), and therefore, also incorporating a spatial ratio in which the spatial scale of impact is compared with the spatial scale of disturbance could facilitate the measurement and comparison of legacy effects. To achieve this, a more sophisticated approach for comparing spatial extents would be necessary (e.g., Reiners and Driese 2001). Potential legacy-effect-imparting events such as contaminant leaks to groundwater systems have a large spatial impact relative to the point release of a pollutant (i.e., the ratio approaches infinity), whereas the impact of nonpoint pollution on lakes tends to have a contrasting spatial signature (a much larger spatial scale of impact than area impacted; the ratio may approach zero). Integration of a legacy intensity metric may help overcome the challenge inherent in spatial scale ratios, which would allow comparisons of the relative magnitudes of disturbance and legacy effect. In the point-source and nonpoint-source pollution example, inclusion of the pollutant mass could contribute to a characterization of the potential impact, with larger quantities being more intense. Formulation of characteristic measures incorporating the intensity of ecosystem disturbance should clarify the classification of legacy effects. However, even simple metrics such as the legacy effect time criteria can only be applied to a small subset of our accumulated understanding of ecosystems. Generation of additional criteria for legacy-effect characterization relies fundamentally on continued retrospective assessment to confront the criteria with data.

Structural versus signal legacy effects

Legacy effects can be classified into two categories: signal and structural effects. *Signallegacy effects* arise from lags in material transport along relatively slow and long flow paths. For example, the agricultural nitrogen transported to estuaries by way of groundwater generally arrives later than that transported in surface waters (Meals et al. 2009). In contrast, *structural legacy effects* rearrange physical systems to alter material interactions within the ecosystem, fundamentally altering material transformations and transport (e.g., tillage, stream entrenchment). These structural changes are widespread, and they are often effectively irreversible over management time scales, which requires the forces of landscape evolution to act in a particular combination or in a specific sequence to truly reset the system (Phillips 2006). For example, the European settlers' clearance of the North American landscape led to substantial erosion and valley deposition in areas with relatively thick soils (Trimble 1999). In these areas, streams have entrenched, which has lowered local water tables and isolated floodplain sediments from hydrologic systems (Groffman et al. 2002). These legacy impacts reduce nitrogen assimilation relative to that in pristine systems, and this loss of assimilation capacity complicates strategies for managing high nitrogen inputs (Erisman et al. 2008).

Although both legacy-effect types are important, signal legacy effects are more straightforward to quantify. The characterization of catchment water-residence-time distribution (McGuire and McDonnell 2006) relative to material input histories can illustrate potential deleterious temporal lags (e.g., Pijanowski et al. 2007). Structural legacy effects are harder to characterize, since reconstructing historic landscapes and historic material fluxes with fine-scale specificity is demanding. A compelling challenge arises because structural legacy effects often cause changes in material transport pathways and therefore the potential for attenuation in the system, which makes the strict separation of structural and signal legacy effects difficult. For example, how can nitrogen impacts be partitioned between excessive inputs and regionally reduced nitrogen-assimilation capacity? These challenges in legacy-effect characterization probably require the integration of hydrologic, geomorphologic, and other associated information for it to be possible to discern the dominance of competing processes in systems affected by both structural and signal legacy effects and to guide management efforts. This effort logically begins with our best extended records of material flux.

Legacy effects or cumulative impacts?

The classification of legacy effects into structural and signal components remains a challenge because of the limitations in our understanding of historical conditions. Given this data gap, we compiled available historical time lines from long-term study sites along the eastern seaboard of the United States: the Hubbard Brook Experimental Forest (HBR), the Plum Island Ecosystem (PIE), the Harvard Forest (HFR), the Baltimore Ecosystem Study (BES), the Smithsonian Environmental Research Center (SERC), and the Coweeta Hydrologic Laboratory (CWT) (figure 3). A cross-comparison of land-use histories at these sites revealed fundamental differences among the locations.

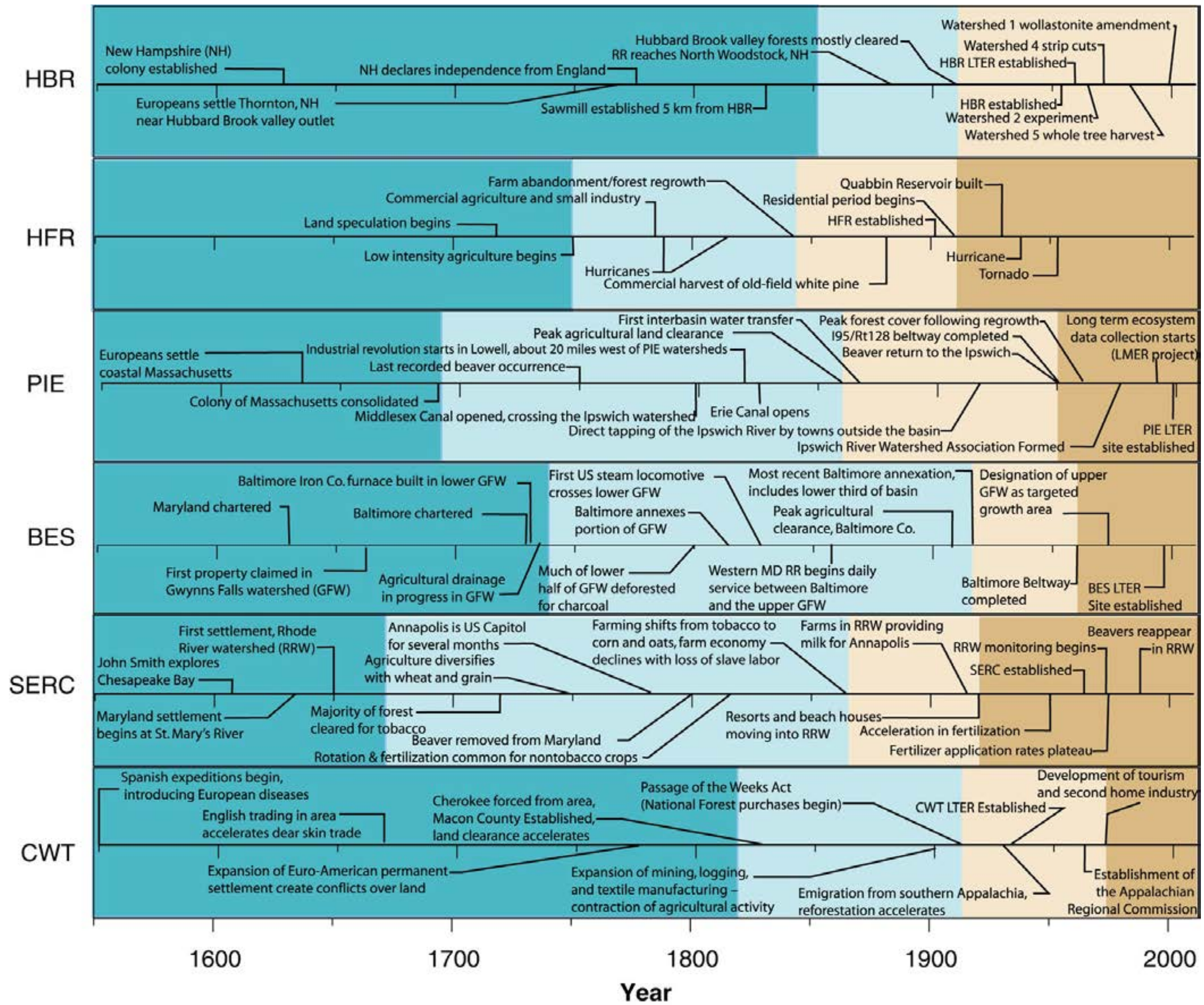

Figure 3. Time line showing significant historic events and transitions at each site. The time lines are color coded to indicate important transitions. The blue-green portions of the time lines indicate periods before substantial European disturbance, the light blue portions indicate periods of agriculture and resource extraction, the light tan portions indicate recovery, and the dark tan portions are the times of urban and suburban development. Abbreviations: BES, Baltimore Ecosystem Study; Co., county; CWT, Coweeta Hydrologic Laboratory; HBR, Hubbard Brook Experimental Forest; HFR, Harvard Forest; km, kilometers; LMER, Land Margins Ecosystem Research; LTER, Long Term Ecological Research Newtork site; MD, Maryland; PIE, Plum Island Ecosystem; RR, railroad; SERC, Smithsonian Environmental Research Center.

All six sites accumulated land-use changes; however, there was limited coherence in these time lines, even in a region of relatively consistent history. The chronology started in year 1500 to capture the landscape interactions after European colonization. In doing so, we ignored pre-European human—landscape interactions that may have imparted important legacy effects (Mann 2005); however, an evaluation of the interactions among legacy effects within and across sites is possible for more-recent, data-rich periods. For example, were the structural legacy effects arising from roughly equivalent periods of agricultural disturbance at SERC and BES diminished or amplified by the much more intensive urbanization in the BES? Or conversely, were the distinct legacy effects inherited from tobacco cultivation (historically common at SERC and uncommon in the BES) detectable after urbanization? Similar comparisons can be drawn among the other sites. Although this is not the first such compilation of long-term data (e.g., Sylvester and Gutmann 2008), the transitions were based on landscape shifts that might impart distinct structural changes and were therefore an important first step in the identification and analysis of legacy effects.

In addition, this analysis suggests logical and important extensions of the legacy-effect framework. How do we incorporate special long-term study sites, such as experimental watersheds affiliated with both the Long Term Ecological Research Network and US Department of Agriculture Forest Service research, into these cross-site characterizations of legacy effects? Experimental watersheds are generally located in areas beyond the reach of typical contemporary human land-use change. Human-driven land-use changes do occur in areas surrounding these experimental watersheds (e.g., the suburbanization noted at CWT), although these areas remain undisturbed relative to their landscape context. Although large manipulations produce powerful insights (Likens and Bormann 1995), this body of knowledge could be extended when it is coupled with adjacent areas that are more likely to inherit structural legacy effects. Understanding the structural legacy effects common in the central New Hampshire landscape would allow findings from places such as the HBR to be applied to wider landscape-management questions. For example, how do septic systems function in systems with a continuum of historic forestry-practice intensity? Pairing human-dominated watersheds with experimental watersheds seems an underuse of our long-term data and therefore of our understanding of the implications of historical activities for contemporary management.

Finally, two other research gaps emerge from comparative histories. First, material flux from the eastern United States during periods of afforestation following declines in agricultural activity is poorly understood. What happened to material fluxes from the working landscape as it transitioned to a period of reduced human forcings? Was this a period sufficiently long that some structural effects faded before urbanization began? This question is particularly important because the advent of monitoring during this period creates a temptation to use period data as a baseline. We probably need to reconstruct the landscape resilience during this period from less traditional data sources in order to answer such questions (Redman and Kinzig 2003). Second, a great deal is obviously missing from these time lines (figure 3). For example, although the removal of the beaver from the landscape was mentioned in the time line, the ensuing effects on geomorphic and aquatic ecosystem reorganization were not well characterized. An understanding of the legacy impacts on the system requires laborious retrospective assessment, which the researchers at most sites have not pursued.

Ultimately, as we manage our landscapes with increasing intensity, concepts such as *cumulative impacts*, or the grouping of legacy effects into a single bottom-line effect, are not precise enough. We need to be able to identify and prioritize the legacy effects that are tractably dealt with in our management systems. For those that are relatively intractable, we must adapt our management tools and frameworks to address these legacy effects. The variety of landscape histories across long-term study sites is daunting, even among sites within a relatively limited area. However, this variety, when it is exploited with careful retrospective analysis, can enhance our understanding of legacy effects. This information is essential to emerging systems-based strategies of adaptation (Nicholls 2002).

Fluvial flux histories

Under ideal circumstances, the identification of legacy effects in material flux records would include the recognition of a historical event and a clear change (step or otherwise) in the temporal material flux record. However, as we emphasized in the previous section, our understanding of long-term site histories is strongly biased toward more recent events. Furthermore, our instrumented records rarely cover more than a quarter of the relevant time period for European legacy effects (post-1600, figure 4). Hence the repeated call for additional retrospective reconstruction of historical events in all systems but particularly in long-term study systems.

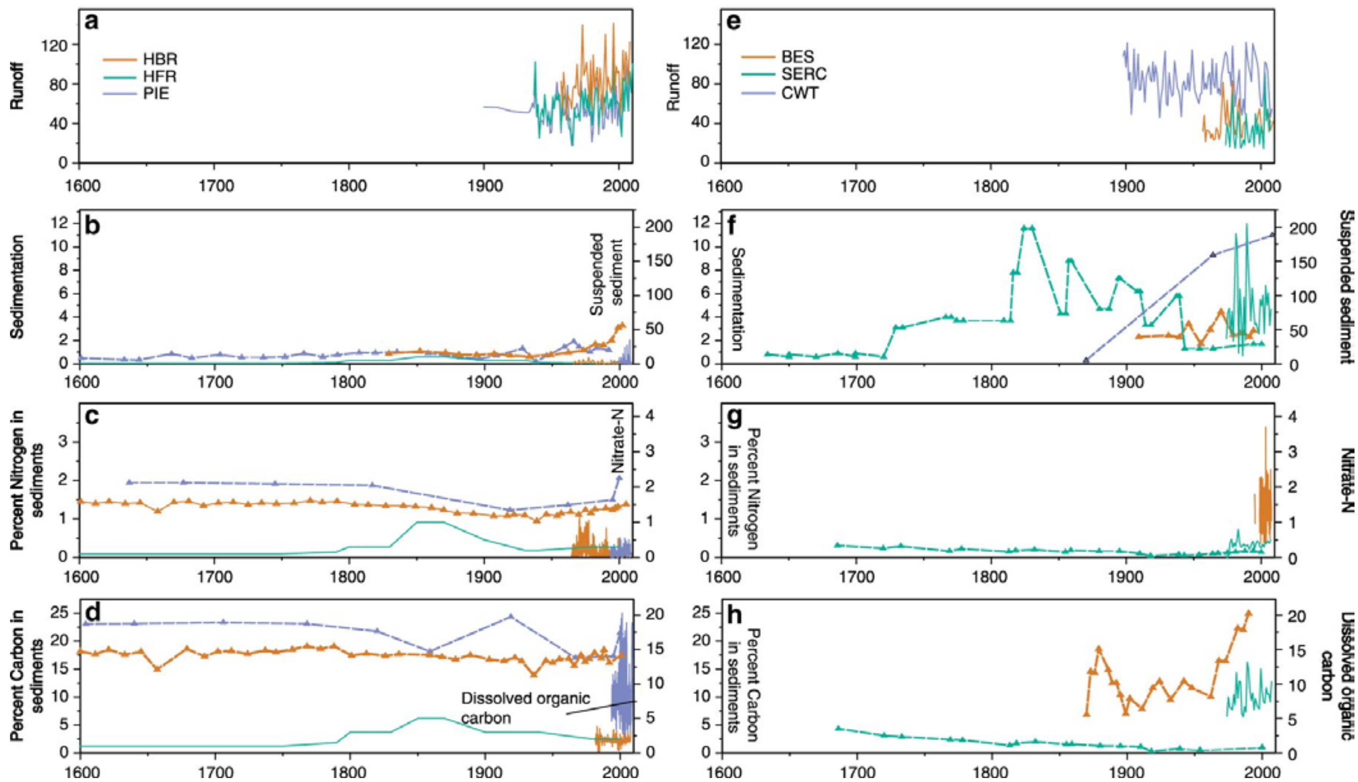

Figure 4. *Cross-site comparison of material flux. Panels (a) and (e) show the runoff in centimeters per year at each site (data sources: CWT, US Geological Survey [USGS] gauge no. 03513000; SERC, Weller et al. 1986, Jordan et al. 1997, 2003, Correll et al. 1999a, Breitburg et al. 2008; BES, USGS gauge no. 01589300; PIE, USGS gauge no. 01102000; HFR, USGS gauge no. 01174500; HBR, Bailey et al. 2003). Panels (b) and (f) show two series where they were available: sedimentation rates in millimeters per year (the dashed lines with triangles) and contemporary suspended sediment concentrations leaving the watershed in milligrams per liter (the solid lines). (Sedimentation rate data sources: CWT, Leigh 2010; SERC, Elliott and Brush 2006; BES, Mason et al. 2004; PIE, Köster et al. 2005; HBR, McLauchlan et al. 2007. Suspended sediment data sources: SERC, Jordan et al. 1997, 2003, Correll et al. 1999b, Gallegos et al. 2005, Breitburg et al. 2008; PIE,*http://ecosystems.mbl.edu/pie/data/wat/WAT-VA-Inputs.html; *HFR, estimated as was described in the text). Panels (c) and (g) show nitrogen concentrations, both in the sedimentary record (as the percentage nitrogen, the dashed line with triangles) and in surface waters (the level of nitrate-nitrogen in milligrams per liter, the solid line). The SERC data is depicted as the percentage organic nitrogen, not the total nitrogen. (Sedimentary nitrogen data sources: SERC, Elliott and Brush 2006; PIE, Köster et al. 2005; HBR, McLauchlan et al. 2007. Surface water nitrate data sources: SERC, Weller et al. 1986, Jordan et al. 1997, 2003, Correll et al. 1999c, Breitburg et al. 2008; BES*, www.beslter.org/frame7-page_1_verbose.html*and historic USGS water-quality data for gauge no. 01589300; PIE*, http://ecosystems.mbl.edu/pie/data/wat/WAT-VA-Inputs.html; *HFR, estimated as was described in the text; HBR, Jordan et al. 1997, 2003, Hong et al. 2005). Panels (d) and (h) show carbon data, both in the sedimentary record (as percentage carbon, the dashed line with triangles) and in surface waters (dissolved organic carbon in milligrams per liter, the solid line). The SERC data is depicted as the percentage organic carbon, not the total carbon, and the BES data are depicted as the percentage of organic matter. (Sedimentary carbon data sources: SERC, Elliott and Brush 2006; BES, Mason et al. 2004; PIE, Köster et al. 2005; HBR, McLauchlan et al. 2007. Dissolved organic carbon data sources: SERC, Jordan et al. 1997, 2003, Correll et al. 2001, Breitburg et*

al. 2008; PIE, http://ecosystems.mbl.edu/pie/data/wat/WAT-VA-Inputs.html; *HFR, estimated as was described in the text; HBR, Johnson et al. 2000).*

Plotting relevant material flux data from these long-term study sites does allow insight (figure 4). Instrumented flux data, sediment-core data, and modeled fluxes were combined to produce a time series of long-term fluxes. With one exception, the long-term records used here represent actual data. Routine collection of biogeochemical data at HFR began only very recently (i.e., in 2007). These values would barely appear in plots, given the period of interest. Therefore, the recorded values from all of the available data were used to set a fixed recent value and were coupled with existing detailed land-cover history (Motzkin et al. 1996) to generate the expected fluxes retrospective to 1600. The periods of maximum deforestation are predicted to be the periods of maximum material flux, and the three estimated series are therefore closely associated. To address the limitations in the temporal coverage of actual or estimated water-chemistry records, we have included relevant sediment-core data (figure 4). These sediment records are not necessarily immediately comparable to contemporary data without additional calibration; therefore, these data should be interpreted cautiously. However, sediment records are the only data with a time scale that is routinely long enough to conceivably capture the spectrum of legacy effects in material flux (e.g., valley burial or changes in biotic communities) across the long-term sites. Despite these potentially available and important data, we do not routinely incorporate such records into our thinking about how ecosystems have worked during recent periods.

Stream runoff from the sites generally follows expected hydrologic patterns, increasing northward (or with elevation in the case of CWT) because of similar precipitation and diminishing evaporative demand (figure 4a, 4e). The interannual variation of runoff ranges by a factor of roughly three across the periods of record, which varied between 34 and 110 years. Most of the records began in the interval after peak agricultural disturbance and before significant urbanization (figure 3)—that is, after periods of maximum regional land clearance. Clear hydrologic legacy effects on annual runoff are not immediately apparent in figure 4a and 4e, possibly because the duration of measurement was too short to capture confounding changes such as water withdrawal and climate change (Claessens et al. 2006), and a discharge baseline does not exist. Extending these records further back is fundamental to improving the understanding of contemporary water budgets and of the structural changes that have an impact on them.

Sediment flux shows clear differences in responses among study sites, which is probably driven by an interaction between land use and glaciation history (figure 4b, 4f). For example, although pre-European sediment deposition was roughly equivalent at PIE and SERC, in the early 1700s, a threshold was reached at SERC that began a period of rapid sediment accumulation. In contrast, there were no clear changes in sedimentation at PIE over this period, despite regional land-use changes that were similar to those at SERC (figure 2). Similarly, the southern sites (BES, SERC, and CWT) all had historical and contemporary sediment fluxes that were substantially larger than those of the northern sites, despite similar historic land use. Although the deposition and storage of eroded materials at the bottoms of hillslopes and in floodplains is a signal legacy effect in its own right (Meals et al. 2009), the structural changes that resulted in altered local soil moisture and vegetation dynamics were arguably the more pertinent legacy effect to managers of water quality and in-stream biota. Buried riparian systems with entrenched streams do not have the capacity to assimilate nutrients or to provide in-stream habitat that systems not imparted with structural sedimentation legacy effects provide (Groffman et al. 2002).

Nitrogen fluxes seem to be a story of urbanization and the associated accumulation of structural legacy effects (figure 4c, 4g). Rapid increases in nitrogen fertilization occurred largely before the measurement periods began, which precludes the establishment of a baseline and of the early catchment response without additional retrospective reconstruction. However, these sites do not necessarily capture agricultural landscapes and their associated changes in post—World War II agricultural landscape inputs. The sediment records that are available seem to record relatively consistent nitrogen values over time. This is not surprising, since sediment nitrogen records are notoriously dependent on water-column processes, which limit our ability to simply compare concentration values. However, the contemporary nitrate concentrations are unambiguous. BES clearly has the highest nitrate concentrations of any of the long-term study sites along the Eastern Seaboard, which probably resulted from the population density and contemporary land use in the BES. The question remains of how much of this flux results from increased human inputs (signals) and how much results from legacy structural changes (e.g., flows bypassing nutrient processing hot spots). The relative values of nitrate concentrations observed at SERC indicated that some nitrate flux may result from the structural changes associated with basin sediment dynamics (e.g., SERC is relatively less urban than PIE, but SERC has higher nitrate values). Although a simple comparison must be replaced with a consistent material budget approach in order to advance our understanding, coupling these initial findings with enhanced site histories highlights the possible role of legacy effects.

The cross-site carbon flux data are difficult to interpret because many sites lack significant changes across the record, which forces the interpretation of subtle patterns in the time series. For example, the carbon content in cores from the northern sites remained relatively consistent through time. SERC (organic) carbon content decreases over time. Although organic matter in a core from BES was not precisely comparable with the percentages of carbon measured in other cores, the variability—and, in particular, late-1800s peaks in organic matter—points to important events in the catchment—possibly the Baltimore annexation of 1880 and the resulting land-use changes in the watershed. In contemporary waters, dissolved organic carbon concentration data are less commonly collected across sites, but they seem to be influenced by their geography, sampling locations, and catchment structures (e.g., coarse coastal plain sediments are drained through SERC), which probably influence the relative concentrations. Ultimately, although the level of dissolved organic carbon should reflect structural landscape changes, the existing long-term monitoring data have not yet captured these signals.

These analyses remain limited by the available data. Other material fluxes, such as major cations, might provide clear indications of the advent of structural legacy effects or the recovery from signal legacy effects (Likens et al. 1996). However, such additional data are not collected consistently at the studied sites. The historical time lines at all of the sites remain relatively crude, given the “long-term” ambitions of our research networks. Despite these data limitations, the cross-site comparison points to important landscape-scale structural legacy effects resulting from the erosion and sedimentation that followed early European settlers' activities. Although the time-series data suggest that some differences in nitrate flux may arise from this structural legacy effect, understanding the effects on the riparian systems—including shifts in vegetative community and dramatic alterations of in-stream habitat—cannot be achieved with the fluvial fluxes alone. However, such intersite contrasts in reach-scale function arising from structural legacy effects are fundamental to the function of catchments throughout this region. The cross-site examination of material fluxes and landscape histories is probably one of the only ways to determine the contributions of structural legacy effects to regional patterns in ecosystem function.

Conclusions

We recommend that the evaluation of legacy effects should be a fundamental, first-order exercise in advance of any ecological research, conservation, or restoration initiative. This exercise may prove frustrating in some cases because of limited historical data or knowledge on the extent and severity of disturbance or because of limited historical data on ecological metrics that might document a change. We recognize that these limitations prevent legacy effects from becoming an instantly robust area for ecological analyses, but we have provided the basic concepts for quantifying and classifying these effects. The incorporation of legacy effects into the management of ecosystems remains in its infancy and may transform some management efforts. Most systems with data records extending to historic endpoints before the advent of modern processes (e.g., nitrogen fertilization or urbanization) generally only extend back to periods of temporary recovery or redisturbance (e.g., figure 3). Furthermore, these best records arise from thoroughly studied landscapes. Although reconstructing data at this level of detail for historic periods and at the regional scale is probably infeasible, the clear understanding of the ecosystem's trajectory and of the legacy effects that can be discerned in less-studied locations are an absolute minimum for effective management. This cross-site comparison emphasizes this need to reconstruct and understand system histories to inform contemporary investigations. A synthesis of the data from our long-term research networks, when it is coupled with land-use histories and sedimentary records, provides a way to begin this vital work. Nonetheless, landscape management that does not incorporate these legacy effects into a sustainable and resilient design of human-dominated landscapes may risk fundamental errors in the development of future ecological scenarios. For example, the “restoration” of nitrogen-removal capacity through the removal of reach-scale legacy sediment does not address catchment-scale sediment and impervious surface legacy effects, which ultimately increases the chances of short-term management failures (Bain et al. 2008). In closing, ecologists and environmental scientists working in human-influenced areas need to at least consider the potential for legacies and their effects and the types of creative data sets that could be gathered for the proper analysis of these legacy effects. We believe that this approach should be encouraged and shared widely throughout the biological sciences.

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