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Meeting Current and Future Conservation Challenges Through the Synthesis of Long-Term Silviculture and Range Management Research

Hydrologic Influences of Forest Vegetation in a Changing World: Learning From Forest Service Experimental Forests, Ranges, and Watersheds

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Abstract

The importance of forests in providing reliable sources of clean water cannot be underestimated. Therefore, there is a pressing need to understand how hydrologic systems function in forested ecosystems, in response to a variety of traditional and novel stressors and environments. Long-term watershed research on Experimental Forests and Ranges (EFRs) of the Forest Service has provided many examples of how vegetation management affects streamflows. New challenges and new stressors will require a deeper understanding and novel research and synthetic activities to help ensure sound forest management for a variety of end uses, included reliable supplies of clean water. In this paper, we discuss the potential role of EFRs for addressing new and challenging issues in forest hydrology.

Introduction

The effective management of forests requires a sound understanding of the structure and processes of forest ecosystems and the ability to predict changes precipitated by planned and unplanned disturbances. Because silviculture provides the primary means for managing forests, there is a need to examine the effects of silvicultural activities on various forest ecosystem properties and components. One component of particular importance is water. Forest lands provide 52 percent of the U.S. drinking water as well as a high proportion of water used for agriculture; forests support abundant opportunities for water-related recreation and they provide habitat for freshwater aquatic organisms. Therefore, it is vitally important that we understand how to manage forests to sustain this role as a reliable source of high-quality water. An understanding of the influence of vegetation on streamflows can help managers plan silviculture activities to be compatible with the needs of downstream water users and of other water-related ecosystem services and values (Kochenderfer et al. 2007).

The Forest Service, U.S. Department of Agriculture (USDA), network of EFRs and experimental watersheds provides unique opportunities to improve our understanding of the effects of silviculture on hydrology. Since the early 20th century, EFRs have been sites for long-term experiments on hydrologic response to vegetation manipulation, usually involving some degree of removal and regrowth. Several thorough reviews have evaluated the hydrologic influences of forest vegetation (Bosch and Hewlett 1982, Huxman et al. 2005, NRC 2008, Stednick 1996), and much of the data those reviews rely on was provided by EFR experiments.

Most EFRs were established decades ago, and since then, new causes of vegetation change have become important, new resources are being threatened, and new research questions have arisen. The most prominent among these are related to global change. Shifts in climate are changing the patterns of water supply and distribution that human cultures rely on at the same time that increasing populations are creating new demands for water. Meanwhile, stresses on water-dependent resources and values are also increasing due to the cumulative influence of climatic shifts and increasing human populations. Society's

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capacity to adapt to these changes will depend strongly on the ability to understand and predict future changes and to modify land management practices to compensate for those changes.

Innovative approaches for analysis and synthesis will be needed if the emerging issues in forest hydrology are to be adequately addressed at the spatial and temporal scales required. Developing an understanding of global change requires large-scale approaches. Although each EFR is relatively small, its distribution across North America enables regional- or continental-scale syntheses (Lugo et al. 2006). With the accumulation of completed studies across a variety of ecoclimatic zones, ongoing long-term data collection, and introduction of new approaches to data management, the construction of useful syntheses across continental transects is becoming increasingly feasible.

This paper discusses the potential role of EFRs for addressing new issues in forest hydrology. We first outline interactions between vegetation and hydrology to provide a context for understanding the problems, then identify issues likely to be of particular importance in coming decades, and finally describe analytical strategies that could be used to address the issues using data from EFRs.

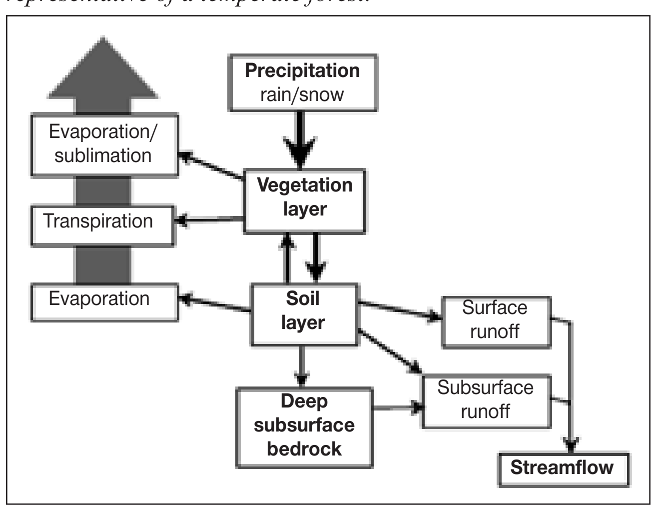
Stand-Scale Interactions Between Vegetation and Water

In forests, vegetation influences each step in the pathway linking precipitation and runoff (fig. 1). A portion of a storm's rain or snow encounters foliage, where it may be stored until it evaporates ("interception loss"), drains as stemflow, or drips to the ground. Rates of interception loss are influenced by canopy conditions and climatic setting and can be appreciable in some forests. Second-growth redwood forests at the Caspar Creek Experimental Forest in coastal California were found to intercept and evaporate 20 to 25 percent of the annual rainfall, for example, with greater than 16-percent loss rates observed even during high-intensity storms (Reid and Lewis 2007). Interception rates tend to be lower in continental climatic settings and in hardwood forests relative to conifers. For example, estimated interception rates at Coweeta Hydrologic Laboratory ranged from a low of 2 percent of annual precipitation to 13 percent in hardwood catchments to 15 to 26 percent in white pine (Helvey and Patric 1988). In some areas, forest canopies have been found to collect water from fog, leading to precipitation beneath the canopy during nonrain periods (Harr 1982). Discussion of rainfall interception in subalpine western forests is largely academic because the snow-dominated hydrologic regime is heavily impacted by wintertime interception and subsequent sublimation loss in these forests. Summertime interception losses are a small percentage of the annual subalpine water balance and most rainfall is consumed on site before reaching a stream.

Interception and sublimation of snow can result in significant losses of wintertime precipitation in mature subalpine forests. At the Fraser Experimental Forest, snowfall accounts for about 70 percent of the annual precipitation (Alexander et al. 1985) and more than 90 percent of the annual runoff, so canopy losses directly through sublimation represent a significant portion of the annual potential water yield. Montesi et al. (2004) gave a conservative estimate of 20- to 30-percent loss of total snowfall to sublimated interception. Studies on the effect of timber removal on water yield have shown that about one-third of the increased yield following clearcutting can be attributed to savings from canopy sublimation, while the other two-thirds can be relegated to the removal of growing season evapotranspirational losses (Troendle and King 1985).

After rainfall or snowmelt encounters the ground surface, it may infiltrate or—if input rates are greater than infiltration rates or the ground is saturated—run off across the surface

Figure 1.—*Diagram of hydrologic fluxes. The strength of the fluxes is indicated by arrow thickness and is broadly representative of a temperate forest.*



as overland flow. Infiltration is promoted by the presence of porous soils and by surficial materials, such as forest litter, that slow surface flows. Overland flow usually increases where soil is compacted and can be particularly extensive where hydrophobic soil layers are formed by fire or exposure of dry soil. Where soils have become saturated, overland flow also occurs through both exfiltration and direct precipitation onto the saturated area. Increased rates of overland flow often generate high erosion rates and increased peak flows, increasing storm runoff at the expense of long-term moisture storage on hillslopes. Vegetation strongly influences soil structure, organic content, litter composition, and the generation of hydrophobic soil conditions, and so can affect the distribution of overland flow.

Water that infiltrates into the soil becomes available for uptake by roots and evaporation through transpiration. Uptake and transpiration rates vary considerably by species, season, and stand age. Rates are generally highest during seasons of maximum growth, and riparian stands tend to sustain high transpiration rates both because species with high water-use requirements grow there and because water is consistently available for transpiration near streams. Soils with high water storage potential—deep soils and those rich in clays or organic matter—can support higher rates of transpiration for longer periods between storms. At a given site, soil moisture is more rapidly depleted between storms when transpiration rates are high, increasing the volume available for moisture storage at the onset of the next storm and thus reducing the potential for overland flow during the storm. Transpiration accounts for about 25 percent of the annual precipitation in the redwood forest at the Caspar Creek Experimental Forest (Reid and Lewis 2007), while potential evapotranspiration is about 51 percent of precipitation in the mixed deciduous hardwood forests at the Fernow Experimental Forest (Adams et al. 1994). Kaufmann (1985) showed large differences between tree species in the central Rocky Mountains; however, average values of around 50 percent of annual precipitation consumed by evapotranspiration agree with those values of Leaf (1975).

Water draining downward through soil or fractured bedrock during and immediately after storms may be diverted to flow downslope along less-permeable horizons and so reach streams, adding to stormflows already enhanced by overland flow inputs and by direct precipitation into the streams. The remaining water eventually reaches the water table and accumulates as ground water. Streamflow between storms and during dry seasons is sustained through the drainage of ground water. At Caspar Creek, about 50 percent of the annual rainfall of 1,165 mm reappears as streamflow, with 63 percent of the flow occurring as stormflow. The Caspar Creek forest thus strongly influences the disposition of one-half the annual precipitation through interception and transpiration and also affects the relative importance of baseflow and stormflow through its influence on hillslope flow paths during storms. At Fernow Experimental Forest, streamflow averages 710 mm per year, or about 48 percent of precipitation. Fool Creek in Fraser Experimental Forest had a pretreatment runoff efficiency of about 37 percent with 760 mm precipitation and 280 mm streamflow (Goodell 1958). South-facing basins at Fraser tend to produce more runoff with close to 50-percent efficiency. These values vary locally with aspect and elevation of individual basins but are generally representative.

Water flowing through streams is also strongly influenced by forest vegetation. Riparian vegetation moderates stream temperatures through shading, and large woody debris not only provides habitat for aquatic biota but also modifies channel hydraulics by increasing channel roughness. Flow slows in debris-laden reaches, increasing in-channel storage of water and sediment and hyporheic exchange including nutrients.

Interactions between hydrology and forest vegetation are by no means unidirectional. Forest species composition, growth rates, and susceptibility to environmental stresses are strongly influenced by the availability of water and nutrients that are primarily stored in soils. For example, sugar maple growing on summit and upslope sites in northwestern Pennsylvania, with poorer nutrient and moisture status, were more likely to demonstrate decline symptoms than those growing in more moisture- and nutrient-rich toeslope positions (Horsley et al. 2000).

Emerging Issues Regarding Forests and Water

Past issues in forest hydrology centered primarily on the effects of logging on water yield, flooding, and water quality, with the intent of reducing impacts to domestic water supplies and downstream infrastructure. Now attention is shifting to new causes of vegetative change, such as air pollution, invasive exotic species, introduced pathogens, and climate change, and to different downstream resources, such as ecosystem integrity. The influences of forests on hydrology are known mainly from small-scale experiments carried out over relatively short periods (NRC 2008), but relationships between intensities of vegetative stress and magnitudes and durations of hydrologic response now need to be evaluated at larger temporal and spatial scales if the kinds of hydrologic influences that occur over the landscape are to be adequately understood.

Many new stressors, such as climate change and exotic pathogens, are lower in intensity than some direct land use practices but are more pervasive and represent chronic disturbances. Climate change alters the effects of land use and disturbances on ecosystem processes and services and requires managers to evaluate and manage for cumulative impacts in new ways to take these influences into account. Because of the scales over which the chronic disturbances act, impact predictions now need to address the basin or landscape scale and must encompass time scales for impact expression that are far longer than have been evaluated in the past.

Global climatic change can alter the volume, timing, and type of precipitation, which, in turn, can influence vegetation. Shallow snowpacks may begin melting earlier in the spring and melt more rapidly, leading to increased peak flows and creating prolonged summer drought. Warmer temperatures may foster the spread of pathogens and insect pests that otherwise are suppressed by cold winters (Negron and Popp 2004). Wildfires may increase in size and frequency (Westerling et al. 2006), altering vegetation and soils and further influencing the amount and quality of runoff. A change in climate can alter the availability of soil moisture and modify forest disturbance patterns, leading to pervasive changes in forest species composition and age distribution. Influences on the hydrologic regime are then compounded, reflecting both the climate shift and the change in vegetation.

Increased human populations at the wildland-urban interface modify both the potential for wildfire and the strategies used to fight wildfires and often entail increased water extractions from wildland streams. Increased populations are also associated with increased atmospheric deposition of contaminants in particulate or dissolved form and with increased concentrations of gaseous constituents of smog. Atmospheric deposition and exposure to smog can affect vegetative health and its ability to perform hydrologic functions (Schaberg et al. 2000), and atmospheric constituents may accumulate in soils and affect water quality (Driscoll et al. 2001). Any changes in environmental conditions that influence the health and distribution of forest vegetation can potentially alter the volume, timing, and quality of runoff from forest lands.

In addition, human influences on hydrology are becoming more complex as new impacts increasingly overlie previous impacts. For example, we may understand the short-term effects of clearcutting on forest land hydrology; however, there is little research on the hydrologic effects of repeated harvesting. Several studies suggest that the hydrologic response to repeated disturbance differs from that for a single disturbance (Adams and Kochenderfer, in press; Hornbeck et al. 1993), and that some kinds of disturbances have very long recovery times (Compton et al. 1998).

In a recent review of the current state of knowledge in forest hydrology, the National Research Council (NRC 2008) identified high-priority questions that need to be answered if emerging issues are to be adequately addressed (table 1). Answering questions such as these will require considerable interdisciplinary cooperation and must involve a wide variety of research approaches. Notable as an underlying theme across the range of questions is the need for increased understanding of hydrological responses at larger spatial and temporal scales than usually have been addressed in the past.

Applying EFR Research To Address Emerging Issues in Forest Hydrology

The Forest Service EFR network appears to be uniquely positioned to provide the kinds of information needed to address issues at large spatial and temporal scales due to the existence of long-term data from the sites, the multidisciplinary breadth of research topics explored at such sites, and the diverse climates and physiographies sampled by the network (Lugo et al. 2006). Although EFRs are distributed widely across the Nation, most are small relative to the bioregional and physiographic provinces they represent. If information from EFRs is to contribute to broad-scale integrated analyses, innovative strategies for synthesis will need to be applied.

Table 1.—*Key questions regarding emerging issues in forest hydrology (from NRC 2008).*

1. What are the magnitude and duration of hydrologic effects due to timber harvest?
2. What are the hydrologic effects of removing or retaining riparian forests over the long term and in large watersheds?
3. What are the cumulative watershed effects of forest cover loss in large watersheds?
4. How do past forest cutting patterns affect water quantity and quality?
5. How have changes in grazing of both domestic and native grazers affected forests, and what are the indirect effects of those changes on water quantity and quality?
6. How do the legacies of road networks on forest land affect peak flows and sediment movement?
7. What are the hydrologic effects of forest fires and firefighting (such as fire breaks, soil disturbance, and application of fire retardants)? What are the hydrologic effects of high- versus low-severity fires, including considerations of long-term effects and larger spatial scales?
8. How do insect outbreaks affect water quantity and quality? How can future hydrologic effects of insect outbreaks be understood or predicted as indirect effects of climate change?
9. What are the hydrologic effects of nonnative species' presence and nonnative species' removal treatments in forests?
10. What are the hydrologic responses to climate change?
11. How do changes in ownership affect forest management, and how do these changes affect water resources?
12. What are the effects of the expansion of human settlements into forested areas and the consequent changes in forest management, such as thinning for fuel reduction, on water quantity and quality?

Use of Process-Based Understanding

Fundamental to all synthesis strategies is the establishment of a sound understanding of process mechanisms. Our current level of understanding of hydrologic process has been produced largely through studies carried out at the scale of laboratory benches, study plots, hillslopes, and small instrumented watersheds. EFRs have been the location of many such studies.

EFRs have been particularly useful in providing sites for paired-basin research. Such work allows controlled experiments to be carried out at spatial scales that encompass a range of site conditions, permitting the implications of site-specific process-based information to be tested in settings where a realistic array of potential influences is present. Work at the paired-basin scale provides the basis for our ability to predict streamflow responses to vegetation changes. Because paired-basin studies require that relatively large tracts of land be set aside expressly for experimental manipulation over lengthy periods, such work is rarely feasible on lands not managed by public agencies. Even land managed by agencies must often be protected by an explicit charter prioritizing its purpose for research activities. As a result, much of our basic understanding of watershed responses to vegetation change in U.S. forests applies to conditions represented by EFRs.

Extrapolating results from EFRs to other areas requires knowledge of system performance. An EFR offers a reference not so much because it represents a certain stand condition (e.g., old growth) but because enough knowledge has been acquired at such sites to develop an understanding of how particular components of the system function and of how those components affect one another (Lisle et al. 2007). Knowledge of system performance improves the ability to transfer research results to other areas having different landscape histories and background conditions. For example, to predict how peak runoff will respond to fire in a particular area, one might seek information from EFRs that brackets the background conditions of the area of interest, but interpolation between the outcomes at those EFRs would not be sufficient to solve the problem. Rather, analysis would rely on the understanding of how peak runoff is generated at each EFR and how vegetation and fire affect peak flow generation processes. Responses for the site in question would then be estimated according to the extent to which controlling variables at that site are likely to produce the outcomes observed at the EFRs. The value of the research is not only related to the outcome of the site-specific study but also more importantly to the knowledge gained of the processes involved.

The application of process-based understanding for predicting hydrologic responses requires interdisciplinary efforts because no part of the hydrologic system is isolated from direct or indirect influences of biological systems. Understanding of hydrologic outcomes of either acute or chronic forest disturbances first requires an understanding of the initial vegetation response. At that point, it becomes possible to determine which components shown in figure 1 will be directly or indirectly affected by the change and to assess how changes in those components will influence the response of others. A greater understanding and transferability is gained by analyzing system function than by simply comparing inputs (precipitation) and outputs (runoff).

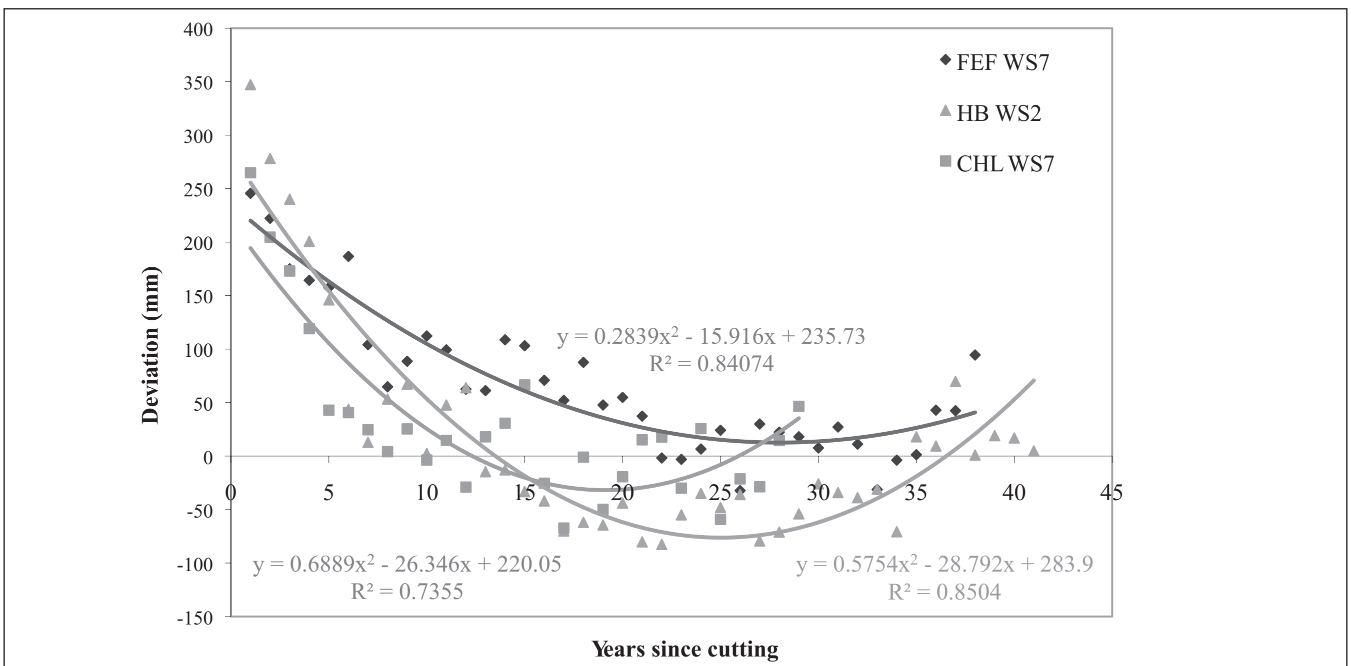
Use of Cross-Site Comparisons

The utility of paired-basin studies is increased when results are compared at multiple sites. Such work allows evaluation of hydrologic response patterns at scales much broader than those of the original experiments.

As an illustration of this approach, consider an example from three experimental forests within the Appalachians: Hubbard Brook, Fernow, and Coweeta. All three sites are mountainous watersheds dominated mostly by hardwood forests, and the paired watershed approach has been used to evaluate the hydrologic responses to clearcutting at each site (Hornbeck et al. 1997, Kochenderfer et al. 1990, Swank et al. 2001). The responses of annual water yield to clearcutting were qualitatively similar among the three sites (fig. 2). In each case, short-term increases in annual water yield were observed immediately after clearcutting, and these increases rapidly declined to or below pretreatment levels as natural revegetation of the site progressed, generally requiring less than 10 years before the differences between pretreatment and posttreatment were not statistically significant. This reduction was then followed by an increase to levels slightly greater than pretreatment. Although the general shape of the curves is common to all sites, the intercepts and the levels of the minimum flow differ among sites.

Hornbeck et al. (1997) ascribed the decrease in predicted flow at Hubbard Brook to the presence of pioneer species such as pin cherry (*Prunus pensylvanica* L.) in the regrowing forest. Pin cherry has lower rates of stomatal resistance and higher rates of transpiration than some tree species present before treatment, so streamflow was reduced while pin cherry was present. Pin cherry is a relatively short-lived species, however, and flow then began to increase as the pin cherry was replaced by maple and other later successional species. A similar explanation was offered for the responses at Coweeta and Fernow (Kochenderfer and Lee 1973, Swank et al. 2001), but the early successional species differ at those sites, with black cherry (*Prunus serotina* L.) most common at Fernow and black locust (*Robinia pseudoacacia* L.) most common at Coweeta. The differences in hydrologic responses shown in figure 2 thus are likely to reflect the different successional pathways. Such results suggest that information on species composition and successional trajectories might provide a basis for predicting hydrologic responses to management activities over wide portions of the Appalachians. Results may also be applicable to predicting effects of climate change because climate change is expected to provoke shifts in species composition in eastern hardwood forests (Iverson and Prasad 2001).

Figure 2.—*Deviation from predicted annual water yields after clearcutting Appalachian watersheds on the Fernow Experimental Forest (FEF), Hubbard Brook Experimental Forest (HB), and Coweeta Hydrologic Laboratory (CHL).*



At the regional or continental scale, Jones and Post (2004) carried out cross-site comparisons of EFRs in Pacific Northwest coniferous forests and eastern hardwood forests to explore the seasonal effects of logging on streamflow and to evaluate the influence of forest age on the hydrologic response. They reported that both relative and absolute streamflow changes after forest removal were significantly and positively related to the age of the forest at the time it was cut, although there were some differences among coniferous and hardwood forests.

Using Experimental Results To Explore Unprecedented Changes

In some cases, shifts in climate or land use may alter hydrologic regimes beyond the range of responses observable in a region. Experimental manipulation of vegetation at EFRs may reveal the potential for major shifts in process regimes in response to pervasively altered conditions. A vegetation conversion experiment at the San Dimas Experimental Forest, for example, demonstrated that hillslopes there are considerably less stable under grassland than under the native chaparral vegetation (Orme and Bailey 1970). Such results suggest that climatic shifts or land use changes that expand grasslands in the area may well be accompanied by major changes in sediment regime.

The structure of the EFR network permits an additional strategy for exploring responses to unprecedented conditions. By substituting space for time, information from a larger area can be used to expand the range of variation considered. Attention must be paid, however, to the role of background variables that govern basic process relations. Comparisons across regions are most likely to be valid when variation between important background variables is minimized or when their influence can be accurately evaluated. If the disturbance is both catastrophic and ubiquitous, then the signal-to-noise ratio of well-designed studies is high and site differences may be ignored to some degree to extrapolate or interpolate important results. The current epidemic of mountain pine beetle across western North America is a good example. More than 90 percent of the lodgepole pine *(Pinus contorta* Douglas ex Louden*)* trees in many basins are dead or dying. With impact of this magnitude, there may be hydrologic impacts or lessons learned that are applicable across wide areas, regardless of significant site differences.

Making Use of Geographic Gradients

Small changes in climatic conditions may have disproportionate effects on forest species composition, so changes to the hydrologic regime may be far greater than those expected solely from the direct influences of the climatic shift. Resulting changes from biophysical interactions are difficult to predict, but comparing vegetation, hydrology, and their interactions across carefully selected continental gradients can provide realistic scenarios of the effects of climate change. Because of their wide distribution, EFRs provide important data sources for gradient analysis.

As an example, one critical gradient reflects the range of precipitation that causes water to be stored in the rooting zone of soils (Huxman et al. 2005). If vegetation can tap this water long enough to produce growth, precipitation will strongly influence productivity, and interception and transpiration by plants will strongly influence runoff. The critical range in which this interaction varies steeply with precipitation is in semiarid climates. In arid climates, overland flow is the only contribution to surface flow during intense precipitation. Vegetation is sparse and has little influence on surface runoff. In wet climates lacking a seasonal drought, vegetation generally has more water than it can use, so variations in precipitation do not affect plant growth, and plants transpire the same amount of water regardless of precipitation. Climatic changes that shift rainfall into the critical range would entail much stronger hydrologic and vegetation responses than would climatic changes of similar magnitude in drier or wetter contexts. In this case, an understanding of the nature of the gradient would allow the prediction of nonlinear hydrologic responses. The presence of EFRs across this gradient enables a space-for-time approach to this problem.

In other cases, gradient analysis provides a basis for broad-scale extrapolations by defining ranges of variability of attributes across large areas. A series of experimental watersheds is distributed along the Pacific Coast from San Dimas in Southern California to near Juneau in Alaska (fig. 3). Annual precipitation increases from 700 mm at San Dimas to 4,000 mm on Vancouver Island, then decreases again to about 2,500 mm near Juneau. Foliar interception of rainfall has been measured in coniferous forests at or near four of these sites, and average interception in each area was found to be between 22 and 32 percent of annual rainfall, irrespective of the amount of rain. The consistency of interception rates across this broad climatic gradient provides reasonable assurance that similar values might be expected in similar mature coastal coniferous forests along the sampled gradient. The shifts in conifer species composition that might be expected from a climate change thus are unlikely to cause large changes in interception loss in mature Coast Range forests. Measurements at the San Dimas Experimental Forest, however, show annual interception losses of 7.9 percent in grassland and 12.8 percent in chaparral (Corbett and Crouse 1968), suggesting that climatic or land use changes strong enough to cause a change in cover type might induce a strong shift in hydrologic regime.

Another critical climate-related gradient exists in areas with seasonal snowpacks. EFRs spanning a wide elevation range, such as the Fraser Experimental Forest, or multiple sites spanning a latitudinal range, such as the Fraser, Tenderfoot, and Priest River Experimental Forests, all offer possibilities for examining the role of climate in snow-dominated hydrologic regimes. The Fraser site shows no statistically significant change in annual mean or daily maximum temperature at low elevation (2,750 m at sea level); however, daily minimum annual temperature does show a significant increase (Elder and Porth, unpublished data, fig. 4). (As an aside, this temperature record may be valuable in quantifying causal factors related to the current mountain pine beetle epidemic, which is having a profound impact on Fraser area forests.) Long-term runoff records from Fraser Experimental Forest gauged watersheds show that daily maximum discharge and instantaneous peak flow are occurring a week to 10 days earlier when post-1985 data are compared to historical pre-1985 records, with some variation depending on physiography and historic land use (logging). Records also show no change in high-elevation snow accumulation (fig. 5) but show a decrease at the lowest elevation snow course (fig. 6). All these details are interesting

Figure 3.—*Variation of annual foliar interception and annual precipitation along a latitudinal gradient on the Pacific coast of North America. Letters identify research watersheds. All watersheds except San Dimas are dominated by coniferous forests.*

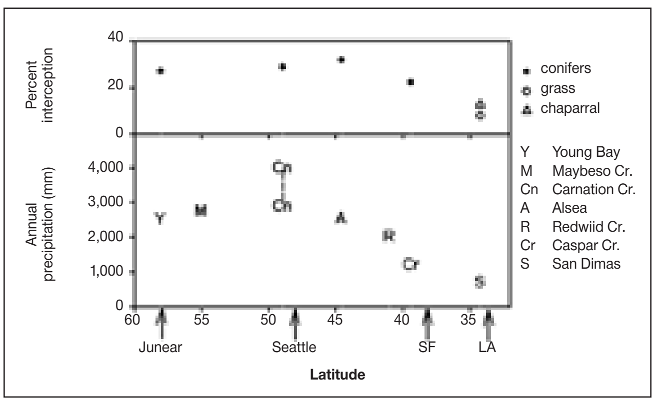


Figure 4.—*Year of observation versus temperature.* T_{max} *is the warmest mean daily temperature for a given year.* T_{min} *is the coldest mean daily temperature for a given year, and* T_{mean} *is the mean temperature for the entire year indicated.*

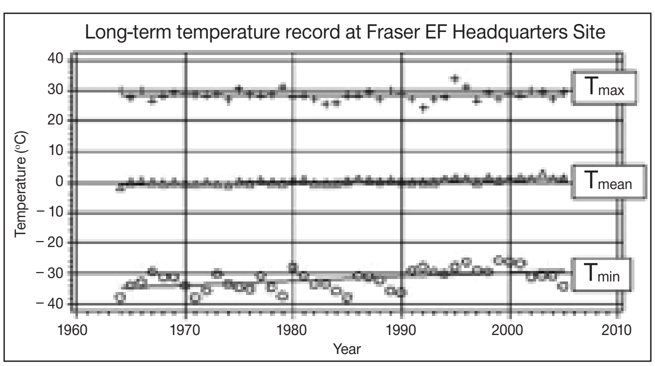


Figure 5.—*Year of occurrence versus mean peak water equivalent as measured on Fool Creek snow courses with fitted regression lines.*

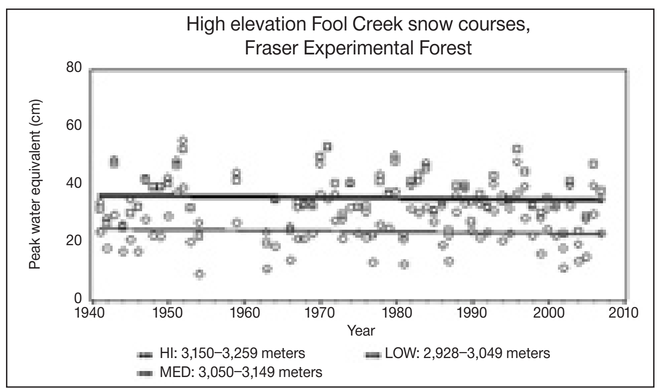
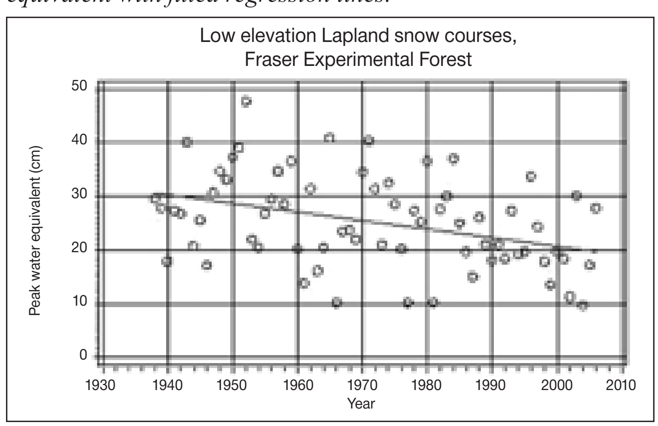


Figure 6.—*Year of occurrence versus mean peak water equivalent with fitted regression lines.*



by themselves, but the individual experimental forests and the EFR network provide the possibility of quantifying the effects while learning the causes. Learning the causes may mean quantifying processes, statistically relating independent and dependent relationships, developing useful empirical relationships, or even developing deterministic models capable of predicting observations or as-of-yet unobserved outcomes. Indeed, researchers are attracted to EFRs for model development, testing, and application as evidenced by the history of hydrological models partially developed at the Fraser Experimental Forest alone. These models include WATBAL (Leaf and Brink 1973), WRENS (Troendle and Leaf 1980), MicroMet (Liston and Elder 2006a), SnowModel (Liston and Elder 2006b), SnowAssim (Liston and Hiemstra 2008), and FASST and SNTHERM (Frankenstein et al. 2008).

Developing Latent Experiments by Using Long-Term Records

Because of the long history of experimental work at currently active EFRs and at those operated in the past, many opportunities exist to revisit the outcomes of previous research. At a minimum, such work can be valuable for extending the length of record to allow assessment of long-term recovery rates. As an example, the Alsea Experimental Watersheds of coastal Oregon were initially monitored between 1959 and 1973, with monitoring continuing long enough after the 1966 logging for researchers to conclude that hydrologic recovery from logging was nearly complete. The monitoring network was reestablished in 1990, and subsequent measurements demonstrated that the hydrologic regime had, in fact, *not* yet returned to pretreatment conditions (Stednick et al. 2006). Such sites also provide an opportunity to evaluate the effects of superimposing modern activities on the legacy conditions left by well-documented earlier experimental treatments.

Finally, EFRs sometimes produce surprises when functioning as observatories. Experiments and studies are designed to test hypotheses by measuring the variation of certain variables with enough time and precision to observe the effects of imposed changes or natural variability. Unexpected payoffs may accrue, however, especially if basic variables describing system functions are measured over long periods, when unusual events occur, new functional relations are discovered, or new questions arise. For example, interactions between woody debris and riparian forests were observed during a large flood at the H.J. Andrews Experimental Forest (Johnson et al. 2000). Sediment monitoring at Caspar Creek Experimental Forest has revealed a pulse of sediment caused by disturbances from logging that occurred three decades ago.

Expanding Applications of EFR Information

Although EFRs are themselves limited in area, they are usually embedded in much larger tracts of public lands. Even though the larger land base cannot be managed as a controlled experiment, the combination of the process-based understanding gained from EFR experiments with the records of treatments applied to the surrounding areas can be used to develop retrospective predictions of outcomes at the larger scale (Lisle et al. 2007). These predictions can then be tested through observation of current conditions at the larger scale. As references where system functions are relatively well understood, EFRs can be used to understand variations in ecosystem processes and conditions in managed watersheds that are subject to a wide range of disturbances. A reference framework can evolve as “client” watersheds accumulate information and contribute to the understanding initially anchored by reference watersheds or EFRs.

The infrastructure (meteorological stations, stream gauges, vegetation data, spatial data, etc.) existing at EFRs is unparalleled in potential to ask and answer timely, critical scientific and management-oriented questions through the development of process models and similar predictive tools. Hydrologic models, like atmospheric models, are very often used to forecast a particular outcome; e.g., timing and volume of runoff, peak flows, ground water levels, etc. Modelers and scientists often begin development using a single location or system. If a model is successful for that single system, then the modeler begins looking for ways to improve its performance, searching for other applications for the model, or attempts to make it more universal. The latter approach involves making the model more deterministic, or further parameterizing independent variables to fit more potential cases. EFRs offer the potential to help modelers and scientists in all these efforts. Many EFRs have long-term data, which allows modelers to look at variability over time—an important component of any model in terms of efficacy and model stability. EFRs also offer a broad variety of records of independent variables that may be useful for many different applications. Climate data is a good example: climate data from the Fraser Experimental Forest have recently been used for hydrological, biogeochemical, ecological, geomorphological, entomological, silvicultural, remote sensing, atmospheric dynamics, and climatological modeling.

Some examples provide evidence for the argument described previously. The Simultaneous Heat And Water (SHAW) model (Flerchinger and Saxton 1989a, 1989b) was largely developed at the Reynolds Creek Experimental Watershed, near Boise, ID (operated by the USDA Agricultural Research Service), which is characterized by arid rangelands with limited forest cover, typical of many midelevation watersheds in the West. The model proved valuable under these conditions and the developers began looking for ways to expand its applicability. In a radical departure from an arid midelevation basin, SHAW was modified and successfully applied to a low-elevation coastal forest at the H.J. Andrews Experimental Forest (Link et al. 2004). Flerchinger also was able to adapt the model to subalpine hillslopes at Fraser Experimental Forest, with some modifications for slope and canopy (Goodbody 2004). In all, there have been more than 40 papers written on the SHAW model and its utility to a wide variety of hydrologic environments and physiographies.

In its earliest incantations, SnowModel (Liston and Elder 2006b) was developed to model snow transport in an arctic environment. Again, the needs of Liston and other users drove an effort to expand the model's applicability over a wider range of the Earth's surface. Fraser Experimental Forest offered an opportunity to work in a forested environment where the effects of trees on radiation, wind, and interception and sublimation on snow processes could be intensively quantified. Existing infrastructure and long-term data (runoff, climate, silviculture), and contemporary data at high spatial and temporal resolutions (four-component radiation, interception, snowmelt, etc.) were available to drive the model under the most likely demanding uses. SnowModel has now been applied from Greenland to Antarctica and across a wide range of environments in between.

Snow Model Intercomparison Project 2 (SnowMIP2) was a research effort designed to compare existing snow process models and evaluate the effect of forests on their performance. In all, 33 models were tested by a large group of researchers using data sets from five sites. Models were submitted from scientists worldwide. Study sites and data sets were chosen from a worldwide pool of sites. Fraser Experimental Forest was one of the sites selected, due to the qualities mentioned previously. The results are published in Rutter et al. (2009), and the model evaluation work will prove valuable to scientists and those seeking to apply the best available model for their particular situation.

Conclusions

Interactions between vegetation and hydrology are fundamental ecosystem processes that govern the health of the Nation's forests and water supplies. These interactions have been studied intensively in the past, yet they deserve even more attention now as scientists grapple with the crucial problems presented by global change. Solutions will require integrating knowledge across a range of scale from the plant to the continent. In this range, process-based information is rich, deep, and widespread at the scale of stands or small watersheds, thanks to the operation of a network of experimental forests, ranges, and watersheds over many decades.

The pace of change and our limited ability to deflect trajectories influenced by management, including silviculture, means that we can ill afford to rely on adaptive management at a large scale to avoid problems compounded by global change. Instead, we must also use available information and models to predict the consequences of management as best we can. In this regard, EFRs provide an important role as observatories of vegetative and hydrologic phenomena, sites for controlled experiments imposing disturbance even wider in range than those imposed under present conditions, and interdisciplinary studies that inform models of ecosystem functions. Although small in area, EFRs represent a wide range of ecosystems and are strategically located to enable syntheses across continental-scale gradients. Examples of syntheses sketched out in this paper illustrate a potential to greatly enhance the latent value of data from EFRs that has accumulated over decades without an appreciation for its role in problems of the magnitude of global change.

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