Vegetation treatments and hydrologic responses at the Hubbard Brook Experimental Forest, New Hampshire

John L. Campbell[1], Amey S. Bailey[1], Christopher Eagar[1], Mark B. Green[1,2], and John J. Battles[3]

Background

By the late 19th and early 20th century, extensive forest harvesting was occurring throughout the United States, often with little regard for natural resources. The effects of logging on the environment were relatively unknown, which contributed to rising environmental concerns. Relationships between forests and stream water yield were of particular interest, because of speculation that logging exacerbated flooding and caused streams to dry up. Despite extensive monitoring and research over the last century, many aspects of the relationship between logging and streamflow remain unresolved and highly contentious (Eisenbies et al. 2007). One of the first major scientific endeavors to address this issue was the Wagon Wheel Gap study in Colorado that began in 1910 and lasted 17 years. The study was initiated by Carlos Bates from the U.S. Forest Service (USFS) and Alfred Henry from the Weather Bureau, and was the first of its kind to quantitatively determine the impacts of harvesting on the volume and timing of streamflow, soil erosion, and sediment loading (Bates and Henry 1928). They used the paired watershed approach that was originally developed in Switzerland, whereby streamflow draining a manipulated watershed is compared to streamflow from a nearby unmanipulated reference watershed. In the years that followed, the paired-watershed method gained popularity in the U.S. and streamflow gauging stations were installed at a number of experimental forests operated by the USFS, including the Coweeta Hydrologic Laboratory, North Carolina in 1934, H.J. Andrews Experimental Forest, Oregon in 1949, and Fernow Experimental Forest, West Virginia in 1951.

The Hubbard Brook Experimental Forest (HBEF) was born out of this same USFS initiative to address relationships between forest management and flooding. The Hubbard Brook Valley was selected from among several candidate sites in the White Mountains of New Hampshire. It was considered the ideal place for a watershed study because it had many small tributaries with well defined topography, watertight bedrock, and uniform forest cover. In 1955, the HBEF was officially established as a center for hydrologic research in New England. Shortly thereafter, the USFS developed a network of precipitation and stream gauging stations, weather instrumentation, as well as vegetation monitoring sites. Early studies evaluated the impact of harvesting on stream water yield and quality, and flood flow. Beginning in 1960, researchers from the USFS and Dartmouth College began using the gauged watersheds at the HBEF as experimental ecosystems for studying the fluxes and cycling of elements, leading to the establishment of the Hubbard Brook Ecosystem Study.

In 1988, the HBEF was designated a Long Term Ecological Research (LTER) site by the National

[1]U.S. Forest Service, Northern Research Station, Durham, NH
[2]Plymouth State University, Plymouth, NH

Science Foundation. The USFS continues to operate and maintain the HBEF and has developed an extensive research program there. Ongoing efforts among a diverse group of cooperating institutions have resulted in one of the longest and most extensive continuous databases on the hydrology, biology, geology, and chemistry of natural ecosystems. Scientists can now use a record of more than 40 years of comparisons of treated and unmanaged forest conditions.

Site description

The Hubbard Brook Experimental Forest (43°56 N, 71°45 W) is a 3,160-ha bowl-shaped valley ranging in elevation from 222 m to 1,015 m. The climate is cool, humid and continental with an average monthly low air temperature of -9 ºC in January to a high of 18 ºC in July. Average annual precipitation is 1400 mm and is distributed fairly evenly throughout the year. A snowpack usually persists from late December until mid-April, with a peak depth in March. Vegetation is predominantly northern hardwood (American beech, sugar maple and yellow birch) with coniferous species (red spruce and balsam fir) occurring at higher elevations and on steeper slopes. Spodosols are the dominant soil type: Typic Haplorthods derived from glacial basal till. They have a sandy loamy texture and are well drained and shallow, with bedrock occurring at a depth of 1-2 m.

The boundary of the HBEF follows the watershed boundary of Hubbard Brook, a tributary to the Pemigewasset River. The Pemigewasset River merges with the Winnipesaukee River in Franklin, New Hampshire to form the Merrimack River, which ultimately flows into the Atlantic Ocean in Newburyport, Massachusetts. Within the HBEF Valley, there are ten intensively monitored subwatersheds that range in size from 12 to 77 ha (Table 1). Overall, these subwatersheds are representative of the central New England landscape in terms of vegetation, soils and stream chemistry, which is important to land managers in the region, as the HBEF is a primary source of information on forest research (Hornbeck et al. 1997a). Streamflow is gauged at nine of these watersheds with either a solitary V-notch weir or a V-notch weir in conjunction with a San Dimas Flume, which better captures high flow events. Six of the watersheds are clustered on a south-facing slope and three are 4 km away on a north-facing slope. Additionally, a tenth ungauged watershed (W101) is situated equidistant between the south- and north-facing watersheds. Five of the watersheds have not been subjected to experimental manipulations, including the hydrological and biogeochemical reference watersheds (W3 and W6, respectively). A total of four whole-watershed cutting experiments (described below) have occurred at the HBEF. A fifth watershed (W1) was subjected to a calcium addition with the intent of replacing calcium lost from soil exchange sites due to decades of exposure to acidic deposition. Calcium silicate (wollastonite) was applied to the entire watershed by helicopter in October 1999. While the calcium application affected vegetation (Juice et al. 2006) and perhaps hydrology through enhanced evapotranspiration, the results are still somewhat preliminary and are beyond the scope this paper. This paper focuses more specifically on streamflow responses to the whole-watershed cutting experiments described below.

Watershed 2 (Clear-felling and herbiciding,1965-1968)

The major objective of the W2 experiment, which involved clear-felling with followup herbicide applications, was to eliminate transpiring vegetation to evaluate its influence on streamflow and nutrient cycling. All woody vegetation in W2 was cut between 18 November and 31 December 1965, during which time the ground was covered by at least 30 cm of snow. Stems and branches were lopped to a maximum height of 1 m above the ground and the cut trees were left in place. No roads or trails were constructed, and no vehicles were permitted in the area to minimize site disturbance. Herbicides were applied during the following three growing seasons to suppress regrowth and kill herbaceous vegetation. During the first grow-

Figure 1. Aerial view of the experimental watersheds ca. 1970 showing the strip cut (WS4) and the devegetation experiment (WS2).

ing season after the cut (1966), bromicil was sprayed by helicopter at a rate of 27 kg per hectare in a mixture of 120 g of 80% bromacil per liter of water (Pierce 1969). During the subsequent two growing seasons (1967 and 1968), the herbicide 2,4,5-T was mixed with water (1:25) and applied by personnel carrying backpack mist blowers. The amount of vegetative regrowth before spraying was about the same during the three summers herbicides were applied, and the applications were equally effective in eliminating most of the vegetative regrowth.

Watershed 4 (Progressive strip cut, 1970-1974)

A progressive strip cut was applied to W4 to determine the effect of this more moderate cutting technique on forest regeneration, stream water yield, and nutrient export. In a progressive strip cut, all trees are removed by periodic cutting of adjoining strips over several years. Strip cutting is a less intensive method of harvesting compared to clear-cutting (described below), because the trees are removed over multiple years, thereby minimizing effects on stream water chemistry and flow. Prior to the cut, W4 was surveyed and divided into 49, 25-m wide strips that were roughly parallel to topographic contours. Every third strip was cut at two year intervals and all merchantable materials were removed by the contractor using rubber-tired cable skidders. The first series of strips was cut in October 1970 (see Figure 1) and the second series of strips, immediately downhill from the first series, was cut in fall 1972. After the third and final set of strips was cut in 1974, the entire watershed had been harvested except for an uncut buffer zone that was left along the stream channel.

Watershed 101 (Block clear-cut, 1970)

A block clear-cut was performed at W101 during fall 1970, immediately after the initial strip was cut in W4. Block clear-cutting is a complete harvest of all trees in a single operation. The purpose of the clear-cut in W101 was to contrast a more intensive management practice with the less intensive progressive strip cut. In this application, trees greater than 5 cm diameter at breast height (d.b.h.) were cut, and all merchantable products were removed by rubber-tired skidders. In contrast to W4, no buffer zone was left along the stream channels. Effects on stream chemistry and stand regeneration have been monitored at W101. However, for financial reasons, no stream gauge was installed, making it difficult to quantitatively compare effects on streamflow with measurements from the other gauged watersheds.

WS	Area (ha)	Year gauged	Weir type	Year of treatment	Treatment
1	11.8	1956	90° V-notch	1999	Calcium addition
2	15.6	1957	120° V-notch	1965-1968	Devegetation
3	42.4	1957	120° V-notch	-	Hydrologic reference
4	36.1	1960	120° V-notch	1970-1974	Progressive strip cut
5	21.9	1962	90° V-notch/Flume	1983-1984	Whole-tree harvest
6	13.2	1963	90° V-notch/Flume	-	Biogeochemical reference
7	77.4	1965	120° V-notch/Flume	-	None -- Reference
8	59.4	1968	120° V-notch/Flume	-	None -- Reference
9	68.4	1995	120° V-notch	-	None -- Reference
101	12.1	-	-	1970	Block clear-cut

Table 1. Description of experimental watersheds.

Watershed 5 (Whole-tree harvest,1983-1984)

A commercial whole-tree harvest was carried out on W5, a management practice that is regaining interest due to rising demand for biofuels. Compared to conventional stem-only harvests, whole-tree harvesting involves the removal of most of the aboveground biomass (boles and branches), raising concerns about nutrient removals and impacts on site productivity. In this application, all trees greater than 5 cm d.b.h. were cut with chain-saws and a track-mounted feller buncher equipped with hydraulic shears. Trees were harvested and removed from the watershed between October 1983 and January 1984, at which time there was a machine accident, leaving the upper one-third of the watershed uncut. Trees from most of the upper portion of the watershed were removed during the following summer. Felled trees in one small area (~12% of the watershed) were not removed until 1985, and about 3% of the watershed was inaccessible and remained uncut. In this treatment, no buffer of trees was left along the stream channel.

Vegetation regrowth

The HBEF is largely a second growth forest. Much of the Hubbard Brook Valley was logged intensively between 1909 and 1917, with some additional salvage logging in the wake of the 1938 hurricane that affected much of the northeastern U.S. Vegetation monitoring at the HBEF began in 1965 at the reference watershed, W6, approximately 48 years after the initial harvest (Figure 2). Aboveground live biomass increased at W6 from 1965 to 1982 and then leveled out. In recent years, total live biomass of larger trees (≥10 cm d.b.h.) has begun to decline unexpectedly. This decline reflects a combination of decreased growth rates and increased mortality rates of the dominant species (sugar maple, American beech, and yellow birch) (Siccama et al. 2007). Beech bark disease, which typically kills older American beech trees, has contributed to recent biomass declines in larger size classes. Among the three northern hardwood species, yellow birch has experienced the greatest increase in mortality and has also shown significant declines in radial growth (Siccama et al. 2007). Widespread birch dieback (yellow birch and white birch (Betula papyrifera)) has been reported previously in the region and has been attributed, at least in part, to climate (as reviewed by Millers et al. 1989; Bourque et al. 2005). It is not yet clear what is causing yellow birch decline at the HBEF; however, it could be the result of several major climatic events that have been observed at the site in recent years including the ice storm of 1998, and episodes of deep soil frost and drought. Sugar maple has also been declining at the HBEF (Juice et al. 2006; Siccama et al. 2007) and across the region (Long et al. 2009). Decreases in sugar maple growth and increased dieback at higher elevations at the HBEF have led to several major research initiatives at the site. Much of this interest stems from the long history of research on acidic deposition at the HBEF. The HBEF is where acid rain was first documented in North America

(Likens et al. 1972), and research at the HBEF indicates that decades of exposure to acidic precipitation has caused significant declines in the pool of available Ca in soil, perhaps as much as 50% (Likens et al. 1998). Inadequate base cation nutrition, most notably Ca and Mg, has been identified as a predisposing stressor for sugar maple decline.

Following each vegetation experiment at the HBEF, trees have been measured at plots on the watersheds (Figure 2). While forest inventory methodologies vary among watersheds (e.g., plot size, sampling interval), all use the same general approach, which involves measuring trees and calculating aboveground biomass with allometric equations. Results from these long-term vegetation measurements show that the pattern of regrowth on the cut watersheds at the HBEF is typical of northern hardwood forests. In the first year or two after cutting, the watersheds are dominated by herbs and shrubs, most notably asters and raspberries. Three to five years after cutting, early successional trees dominate, particularly pin cherry and to a lesser extent, aspen. Pin cherry is well adapted to large-scale disturbances such as clear-cuts, because it is a rapid growing, shade-intolerant species that germinates from seeds that lay dormant in the forest floor. Pin cherry is relatively short-lived and begins to die out 30-40 years after establishment, giving rise to the longer-lived American beech, sugar maple and yellow birch trees that comprise the northern hardwood forest. While these three tree species dominate in later successional stages, they often occur in varying mixtures with other species, including paper birch, red spruce, white ash, red maple, and balsam fir.

Each cutting experiment at the HBEF has resulted in somewhat different responses in species composition and growth (Figure 2). For example, strip cutting on W4 reduced the number of pin cherry and allowed sugar maple and yellow birch to become established and accumulate biomass in larger size classes more rapidly during the first 30 years of regeneration (Martin and Hornbeck 1990). Results suggest that less intensive cuts reduce pin cherry abundance and lower overall stem density, improving growth of species of more important commercial value. In contrast, the rate of biomass accumulation on W2 was less than the other watersheds likely because of repeated treatment with herbicides (Fahey et al. 2005). Reduction in vegetative sprouting and decline in site fertility due to high nutrient leaching probably also contributed to the difference in biomass accumulation between W2 and the other watersheds. The commercial whole-tree harvest on W5 and the block clear-cut on W101 were the most operationally similar among the four treatments and had similar amounts of biomass accumulation over time. Despite some initial differences in species composition and growth, among all four of the treated watersheds biomass is on a trajectory of accumulation that is similar to the older second growth forests at the HBEF. These results suggest that while the different cutting practices influence initial forest composition and growth, the overall impact on total aboveground biomass is minimal over the long-term at the HBEF.

Hydrologic responses

The small, gauged watersheds at the HBEF make it possible to quantify the effects of the various vegetation treatments on water yield (Hornbeck et al. 1997b). We used an approach whereby linear regression relationships between annual water yield in the treated watersheds and the reference watershed were established for the pre-treatment period. These calibrations are based on 7, 9, and 20 years of pre-treatment data for watersheds 2, 4, and 5, respectively. Regression equations were then used to predict what streamflow values would have been in the absence of treatment. Change in water yield due to the treatment is calculated as the difference between predicted and measured streamflow (Figure 3). Results from this analysis show that water yield increased in all watersheds immediately after vegetation was cut, and then decreased as the forest regenerated. Water yield increases were greatest at W2, where vegetation regrowth was suppressed by herbicide applications. The increase in water yield at W4, also lasted for multiple years,

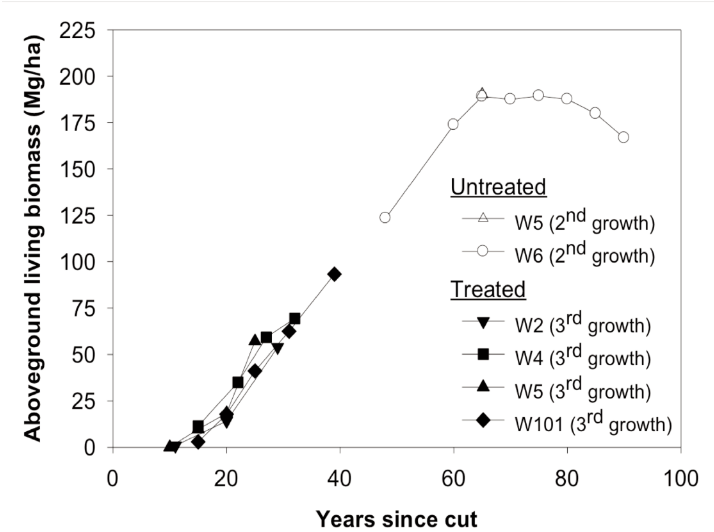

Figure 2. Aboveground live biomass (Mg/ha) for trees ≥10 cm dbh at W5 (whole tree harvest), W6 (reference), W2 (clear-fell/herbicide), W4 (strip cut), W101 (clearcut). Hollow symbols indicate second growth forests and solid symbols indicate third growth forest following experimental treatment.

since strips were cut in three phases (1970, 1972, 1974). In contrast, the increase in water yield at W5 (whole-tree harvest) only lasted one year before returning to baseline. After the initial increase, W2 (clear-felling/herbicide) and W4 (strip cut) had a decrease in water yield that lasted for about 20 years. This decrease is due to the high transpiration rates of early successional trees, especially pin cherry. Since these young, regenerating forests have the capacity to transpire more than mature forests, less water is available for streamflow. Interestingly, the hydrologic response to whole-tree harvest (W5) was unlike W2 and W4, yielding less water initially and having no prolonged period of decreased water yield. It remains uncertain why W5 behaved differently; however, it is likely due to factors that impact transpiration. A potential factor that could lead to lower transpiration on W5 is a lack of regeneration on skid roads. The road network at W5 occupied 12% of the watershed area, whereas it occupied only 2% in W4 and 0% in W2 since cut trees were left in place (Hornbeck et al. 1997b). Another factor that could reduce the amount of transpiring vegetation is heavy moose browse that appears more severe near the top of W5 compared to the other watersheds. W5 also has a greater proportion of American beech which has high stomatal resistance, potentially resulting in less transpiration in this watershed.

Forest Harvesting and Nutrient Removal

The energy crisis of the 1970s led to interest in decreasing U.S. dependence on foreign oil by increasing the use of domestic wood for energy. The greater demand for forest biomass resulted in a trend toward more intensive forest harvesting practices that sparked considerable debate about soil nutrient depletion and long-term declines in forest productivity. The two major pathways for nutrient loss associated with harvesting are through direct removal in the biomass, as well as shorter-term increases in leaching losses after the cut. The extent of these losses are largely influenced by factors such as type of harvest, rotation length, site characteristics, tree species, and stand age. Results from the

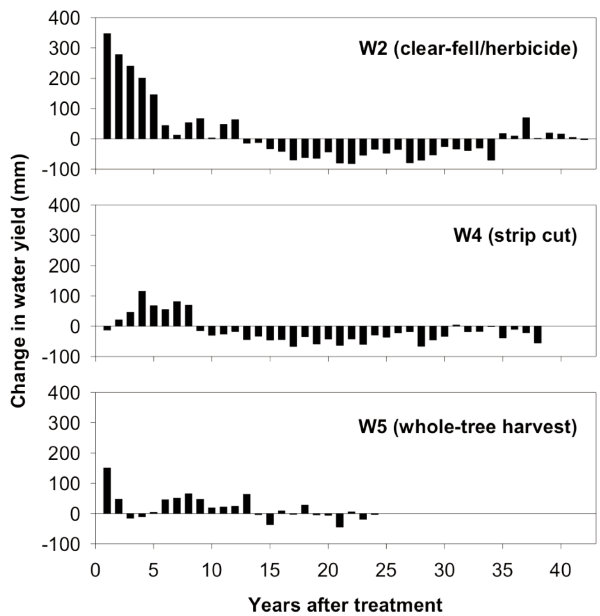

Figure 3. Changes in annual water yield for cut watersheds.

HBEF and elsewhere have generally shown that conventional forestry does not lead to nutrient depletion, particularly if the rotations are sufficiently long and slash is left on site. However, more intensive harvesting practices can increase the removal of nutrients (e.g., Hornbeck and Kropelin 1982). In recent years, concerns about nutrient depletion have resurfaced due to a rising demand for biofuels stemming from higher energy prices and incentives to produce renewable energy. The expansion of a wood-based bioenergy industry could be economically beneficial; however, it is also important to consider the long-term sustainability of forests. While much of the research that occurred decades ago is still relevant, more studies are required to fully understand the consequences of intensive harvesting, particularly as they relate to new markets (e.g., wood pellets). The advent of new spatial techniques such as GIS and remote sensing makes it possible to move beyond the individual site based studies of the past to more comprehensive regional analyses.

Conclusion

Long-term vegetation measurements at the HBEF have improved our understanding of how forests respond to disturbance. The intensity and type of vegetation treatment impacts the composition and accumulation rate of biomass in the regenerating forest. Other factors, such as climate, disease, and air pollution also influence vegetation trends, as demonstrated by surveys in more mature forests at the HBEF that have not been subjected to experimental manipulations. One of the great strengths of the vegetation experiments at the HBEF is that they were done in small gauged watersheds, making it possible to quantify effects on streamflow and nutrient losses. These vegetation studies at the HBEF have improved our understanding of the relationship between forest management and stream water resources in the northern hardwood forest. Past concerns about the effect of harvesting on streamflow and water quality in the Northeast may have been reasonable at the time, since logging in the late 19th and early 20th century was often conducted carelessly with little consideration for environmental impacts. We now know that harvesting effects on streams can be greatly reduced or eliminated if best management practices are followed. While a desirable forest management objective may be to increase stream flow for uses such as municipal water supply, recreation, and wildlife, research from the HBEF and elsewhere in the Northeast has shown that increases in water yield due to harvesting are relatively short-lived and are not sustained over the long-term. In fact, depending on the treatment, cutting may actually decrease water yield for several decades because young, regenerating forests can have higher transpiration rates, resulting in less streamflow. In the future, the rising demand for bioenergy may result in more intensive forest management practices. Management plans that include intensive harvesting should consider the potential for soil nutrient depletion and its effect on forest sustainability. Long-term data, such as those presented in this paper, are the keystone of the HBEF and will continue to provide valuable insight into how forests respond to different types and levels of disturbance. Future work should focus on ecological responses to harvesting within the context of other global change drivers. Factors such as climate change, atmospheric deposition, and rising atmospheric carbon dioxide affect forests in complex ways and will influence responses to harvesting. The long term data from Hubbard Brook are a critical resource for evaluating these responses and can be used to validate models used to make projections under different future scenarios.

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Ann E. Camp
Yale School of Forestry and Environmental Studies

Lloyd C. Irland
Yale School of Forestry and Environmental Studies

Charles J.W. Carroll
Yale School of Forestry and Environmental Studies

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Yale University
School of Forestry and Environmental Studies
Global Institute of Sustainable Forestry
360 Prospect Street, New Haven, Connecticut 06511 USA
www.yale.edu/gisf