

# Effects of Harvesting Forest Biomass on Water and Climate Regulation Services: A Synthesis of Long-Term Ecosystem Experiments in Eastern North America

Jesse Caputo,<sup>1\*</sup> Colin M. Beier,<sup>1</sup> Peter M. Groffman,<sup>2</sup> Douglas A. Burns,<sup>3</sup> Frederick D. Beall,<sup>4</sup> Paul W. Hazlett,<sup>4</sup> and Thad E. Yorks<sup>5</sup>

<sup>1</sup>Department of Forest and Natural Resources Management, SUNY College of Environmental Science and Forestry, 1 Forestry Drive, Syracuse, New York 13210, USA; <sup>2</sup>Cary Institute of Ecosystem Studies, 2801 Sharon Turnpike, Millbrook, New York, USA; <sup>3</sup>U.S. Geological Survey, 425 Jordan Road, Troy, New York 12180, USA; <sup>4</sup>Natural Resources Canada, Canadian Forest Service, 1219 Queen Street East, Sault Ste. Marie, Ontario P6A 2E5, Canada; <sup>5</sup>Environmental Biology Program, Cazenovia College, 22 Sullivan Street, Cazenovia, New York 13035, USA

## ABSTRACT

Demand for woody biomass fuels is increasing amidst concerns about global energy security and climate change, but there may be negative implications of increased harvesting for forest ecosystem functions and their benefits to society (ecosystem services). Using new methods for assessing ecosystem services based on long-term experimental research, post-harvest changes in ten potential benefits were assessed for ten first-order northern hardwood forest watersheds at three long-term experimental research sites in northeastern North America. As expected, we observed near-term tradeoffs between biomass provision and greenhouse gas regulation, as well as tradeoffs between intensive harvest and the capacity of the forest to remediate nutrient pollution. In both cases, service provision began to recover along with the regeneration of forest vegetation; in the case of pollution

remediation, the service recovered to pre-harvest levels within 10 years. By contrast to these two services, biomass harvesting had relatively nominal and transient impacts on other ecosystem services. Our results are sensitive to empirical definitions of societal demand, including methods for scaling societal demand to ecosystem units, which are often poorly resolved. Reducing uncertainty around these parameters can improve confidence in our results and increase their relevance for decision-making. Our synthesis of long-term experimental studies provides insights on the social-ecological resilience of managed forest ecosystems to multiple drivers of change.

**Key words:** forest biomass; ecosystem services; water regulation; climate regulation; tradeoff analysis; forest recovery.

---

Received 22 April 2015; accepted 23 August 2015  
published online 27 October 2015

**Electronic supplementary material:** The online version of this article (doi:10.1007/s10021-015-9928-z) contains supplementary material, which is available to authorized users.

\*Corresponding author; e-mail: jcaputo@esf.edu

## INTRODUCTION

Escalating global concerns about long-term energy supply and climate change have brought about renewed interest in utilizing woody biomass from

forests as a source of energy. Biomass is widely seen as a renewable, low-carbon fuel with potential for lowering net emissions of greenhouse gases, improving energy security, facilitating desired land management activities, and providing rural economic opportunities (Manley and Richardson 1995; Munsell and Germain 2007; Perez-Verdin and others 2008; Richter and others 2009; Aguilar and Saunders 2010; Defries and Pandey 2010; Openshaw 2010). At the same time, it is widely acknowledged that biomass harvesting has the potential to result in undesirable environmental outcomes (Hacker 2005; Lattimore and others 2009; Williams and others 2009; Berger and others 2013; Lattimore and others 2013). Therefore, the discussion surrounding bioenergy has placed strong emphasis on understanding the extent to which the expanded use of bioenergy will be socially and environmentally sustainable (Robertson and others 2008; Janowiak and Webster 2010; Solomon 2010; Volk and others 2010; Zabel 2010; U.S. Department of Energy 2011).

To date, efforts to assess the sustainability of wood-based biofuels have focused on a relatively small number of tools and methods, with an emphasis on resource availability (U.S. Department of Energy 2011; Davis and others 2012; Schulze and others 2012; Goerndt and others 2012), life cycle assessment (LCA) modeling (Fantozzi and Buratti 2010; Buonocore and others 2011; Djomo and others 2011; Lippke and others 2011a, b; Caputo and others 2014), and criteria-and-indicators protocols (Lattimore and others 2009; Roundtable on Sustainable Biofuels 2010; Lattimore and others 2013). Collectively, these efforts provide estimates of maximum sustained yield, greenhouse gas emissions, and energy return on investment (EROI), but do not address the myriad other social and ecological factors (and interactions) that shape the long-term sustainability of woody biomass as a source of energy.

An ecosystem services framework can provide a richer understanding of how a broader variety of forest benefits may be impacted by forest harvesting, including clean water, wildlife habitat, wild foods, nutrient regulation, flood prevention and drought mitigation, recreational opportunities, and spiritual and aesthetic satisfaction, among others (MEA 2005). Efforts to quantify the services of forests and woodlands have focused on provisioning (for example, fiber and food) and climate regulation benefits (for example, carbon sequestration), as well as biodiversity (Beier and others 2008; Duncker and others 2012; García-Nieto and others 2013; Grêt-Regamey and others 2013; Schwenk and others 2012; Cademus and others 2014; Biber and others

2015). Although forests and woodlands have been found to provide greater levels of benefits as compared to other ecosystems (for example, Brown 2013), the relationship between forest structure and service provision is not uniform across time and space (Polasky and others 2014). Furthermore, individual services interact with each other in complex ways and this interaction can obscure the relationship between ecosystem structure and any one service (Bennett and others 2009; Robertson and others 2014). New methods and tools are needed to better resolve this complexity and support the scientific and decision-making basis for managing ecosystem services (Carpenter and others 2006; Daily and Matson 2008; Daily and others 2009).

In this study, we evaluated the effects of harvesting biomass on the capacity of the forest ecosystem to provide water and climate regulation benefits to local and global beneficiaries. We use a new approach for measuring regulating services based on coupling long-term experimental research with empirical proxies of human demand (Beier and others 2015). Unlike other studies which use modeling outputs to estimate changes in ecological capacity under multiple scenarios (Duncker and others 2012; Grêt-Regamey and others 2013; Schwenk and others 2012), our approach makes use of empirical observations and long-term data describing ecosystem function in experimental watersheds in response to harvest. Changes in ten potential benefit flows were estimated over time and compared across ten managed (experimental) and unmanaged (reference) mixed hardwood forest watersheds at three research sites in northeastern North America—a region with considerable interest in and potential for using forest biomass as an energy feedstock (Buchholz and others 2011; Levin and others 2011; Goerndt and others 2012). We assembled data from experimental watersheds harvested at different times and varying intensities using silvicultural practices commonly utilized in the region. Based on ecosystem responses to harvesting, we assessed tradeoffs between the provision of woody biomass and drought mitigation, flood prevention, remediation of nutrient pollution, provision of clean drinking water, carbon sequestration, and several other potential benefits. We also sought to characterize temporal patterns of tradeoffs and recovery after harvest to gain insight into the resilience of forest ecosystem services to multiple drivers of change. We expected to observe tradeoffs between biomass provision and greenhouse gas regulation, but hypothesized that harvest-induced tradeoffs related to water quality and quantity regulation would be less apparent. We also hypothesized that tradeoffs resulting from harvesting would

increase in magnitude with harvest intensity, although not necessarily in a linear fashion.

## METHODS

### Sites

We compiled and analyzed data from watersheds at three independent, long-term experimental research sites: the Hubbard Brook Experimental Forest (HB), Turkey Lakes Watershed (TL), and the Neversink River Research Watershed (NR). Each of these sites has one or more experimental watersheds which were subjected to a variety of harvest regimes, as well as an uncut reference catchment. For each watershed, we had access to long-term data on stream flow, stream chemistry, and vegetation growth (Online Appendix 1).

Although choice of harvest treatments was ultimately limited by the original experimental design at the three sites, the treatments included in our study represent the full range of silvicultural treatments common to the region (Table 1; Online Appendix 1). Several of these treatments—for example, shelterwood harvest, silvicultural clearcut, selection harvest, and timber stand improvement (TSI) cutting (that is, thinning)—are standard silvicultural practices often recommended for use in managing northern hardwoods (Nyland 1987). Also included was the practice of diameter-limit harvesting (or “high-grading”), which is very common in the region (Nyland 1992; Munsell and

others 2008) despite evidence that it results in long-term degradation of the growing stock (Nyland 2007). Study watersheds also represented a range of harvest intensity; for the purpose of this study, we renamed watersheds to reflect both the site and the harvest intensity (Table 1). High-intensity treatments such as clearcutting and diameter-limit harvesting were conducted on HB-H1 (HB watershed 4), HB-H2 (HB watershed 5), NR-H (NR watershed DC57), and TL-H (TL catchment 31). Low-intensity treatments, including selection harvests, shelterwood harvests, and TSI (or thinnings), were conducted on NR-L (NR watershed SC40), TL-L1 (TL catchment 33), and TL-L2 (TL catchment 34). Unharvested references included HB-R (HB watershed 6), NR-R (NR watershed CL25), and TL-R (TL catchment 31). Data span from 1964 to 2007 at HB, from 1981 to 2009 at TL, and from 1992 to 2000 at NR.

### Measures of Ecosystem Services

To quantify the effects of biomass harvesting on water and climate regulation services of northern hardwood forests, we analyzed data from long-term ecosystem experiments using a suite of measures pertaining to four categories of ecosystem services: water flow regulation (WFR), water quality regulation (WQR), greenhouse gas regulation (GHGR), and fiber provisioning (FP). Within each category, we quantified one or more metrics which represent a specific benefit (Table 2). For

**Table 1.** Study Watersheds at Three Sites in Northeastern North America, Hubbard Brook Experimental Forest (HB), Turkey Lakes Watershed (TL), and Neversink River Research Watershed (NR)

Watershed	Site	Original (local) name	Description
HB-R	HB	6	Reference
HB-H1	HB	4	Strip clearcut; harvested in sequential 25-m strips in 1970, 1972, and 1974; streamside buffers left unharvested
HB-H2	HB	5	Clearcut; whole-tree harvest in late 1983; all residues removed
NR-R	NR	CL25	Reference
NR-L	NR	SC40	Timber stand improvement cutting; 5.6% of the basal area on approximately 32% of the watershed area was removed in 1995–1996
NR-H	NR	DC57	Partial clearcut; 97% of the basal area was removed in 75% of the watershed area in 1996–1997
TL-R	TL	32	Reference
TL-L1	TL	33	Selection harvest; 29% basal area removed in 1997
TL-L2	TL	34	Shelterwood harvest; 42% basal area removed in 1997
TL-H	TL	31	Diameter-limit harvest; all trees >10 cm were removed in 1997, equivalent to 89% of the basal area

*Watersheds are labeled by site and by cutting intensity. H = high intensity; L = low intensity; R = reference.*

example, for water flow regulation (WFR), we measured three benefit types: flood prevention, drought mitigation, and flow stability. Each of the ten benefit metrics was normalized to a [0,1] scale in order to explore relative tradeoffs among services in the 5-year period following harvest. Tradeoffs among services were evaluated via a principal components analysis of the rescaled benefit metrics. In order to estimate the recovery time of certain services, we also calculated the differences in the rescaled service metrics between reference and treatment watersheds. Detailed methods for calculating and rescaling ecosystem service metrics from the raw data are in Online Appendix 1. All data analysis was conducted using R (R Core Team 2012).

## RESULTS AND DISCUSSION

### Fiber Provisioning

High-intensity treatments yielded more biomass for energy production (75–180 t ha<sup>-1</sup>) than did low-intensity treatments (6–50 t ha<sup>-1</sup>). HB-H2, where all residues were removed, produced the greatest amount of biomass (175.4 t ha<sup>-1</sup>), which was more than twice as much as the second most productive watershed, HB-H1 (83.5 t ha<sup>-1</sup>).

### Greenhouse Gas Regulation

We observed a direct tradeoff between biomass harvesting and aboveground carbon mitigation benefits over the 5-year post-harvest period

**Table 2.** Metrics Used to Quantify Ecosystem Capacity to Provide Benefits (Ecosystem Services) Based on Long-Term Experimental Research on Northern Hardwood Forests in Eastern North America

Service	Benefit type	Units	Metric	Threshold description
Water flow regulation (WFR)	Flood prevention (FLD)	None	% of days in which flood thresholds are not exceeded	Maximum dam outflow (HB); 95th percentile daily discharge (TL, NR)
	Drought mitigation (DRT)	None	% of days in which drought thresholds are not exceeded	County-level annual water withdrawals (HB, NR); 5th percentile daily discharge (TL)
	Flow stability (STB)	# days	# of days between subsequent threshold events	No threshold
Water quality regulation (WQR)	NO <sub>3</sub> <sup>-</sup> regulation (NTR)	None	% of days in which drinking water standards were met	Drinking water standards; New Hampshire (HB), New York (NR), Ontario (TL)
	Cl <sup>-</sup> regulation (CHL)	None		Drinking water standards; New Hampshire (HB), New York (NR), Canada National Standards (TL)
	SO <sub>4</sub> <sup>2-</sup> regulation (SLF)	None		Drinking water standards; U.S. federal secondary standards (HB, NR), Canada National Standards (TL)
	pH regulation (pH)	None		Drinking water standards; U.S. federal secondary standards (HB, NR), Canada National Standards (TL)
	Remediation of nutrient pollution (PRM)	None	Ratio of eutrophication potential of streamwater to eutrophication potential of precipitation	No threshold
Greenhouse gas regulation (GHGR)	Aboveground carbon mitigation (CRB)	t ha <sup>-1</sup>	Carbon content of standing trees plus carbon benefit of using harvested biomass minus process emissions	No threshold
Fiber provisioning (FP)	Biomass harvest (BMS)	t ha <sup>-1</sup>	Cumulative mass of biomass harvested from watershed, for use as energy feedstock	No threshold

(Figure 1). This tradeoff was expected, given that the largest component of this benefit comes from carbon sequestered and stored in living biomass, which is removed via harvest. Although the use of biomass in place of fossil fuels partially offsets that loss, the benefit associated with this substitution—0.38 unit of carbon gained for each unit of carbon in harvested biomass (Lippke and others 2012)—does little to reduce the overall tradeoff. Consequently, harvested watersheds incurred an immediate net loss of carbon benefits of up to 25 t C ha<sup>-1</sup>. We note this estimate does not include measures or estimates of belowground carbon. Belowground carbon—including soil carbon—is difficult to estimate, but evidence suggests that it is primarily driven by geophysical site considerations and does not differ significantly between harvested and unharvested stands (Lippke and others 2011b). Earlier research has yielded evidence that harvesting forests for biomass results in a short-term loss of

carbon to the atmosphere, a so-called “carbon debt” (Fargione and others 2008; Mika and Keeton 2013). As forest carbon recovers, however, it is thought that the cumulative carbon benefits associated with substituting fossil fuels with renewable biomass ultimately result in net negative carbon emissions (Lippke and others 2011a; Walker and others 2013; Miner and others 2014).

### Water Flow Regulation

Tradeoffs between harvesting and water flow regulation benefits were nominal. Changes in WFR metrics (flood prevention, drought mitigation, and flow stability) immediately following harvest were smaller than expected for the intensively harvested watersheds (Figure 1). Previous research has established that vegetation harvest reduces total transpiration, as well as the interception of rainfall, which in turn tends to increase average streamflow

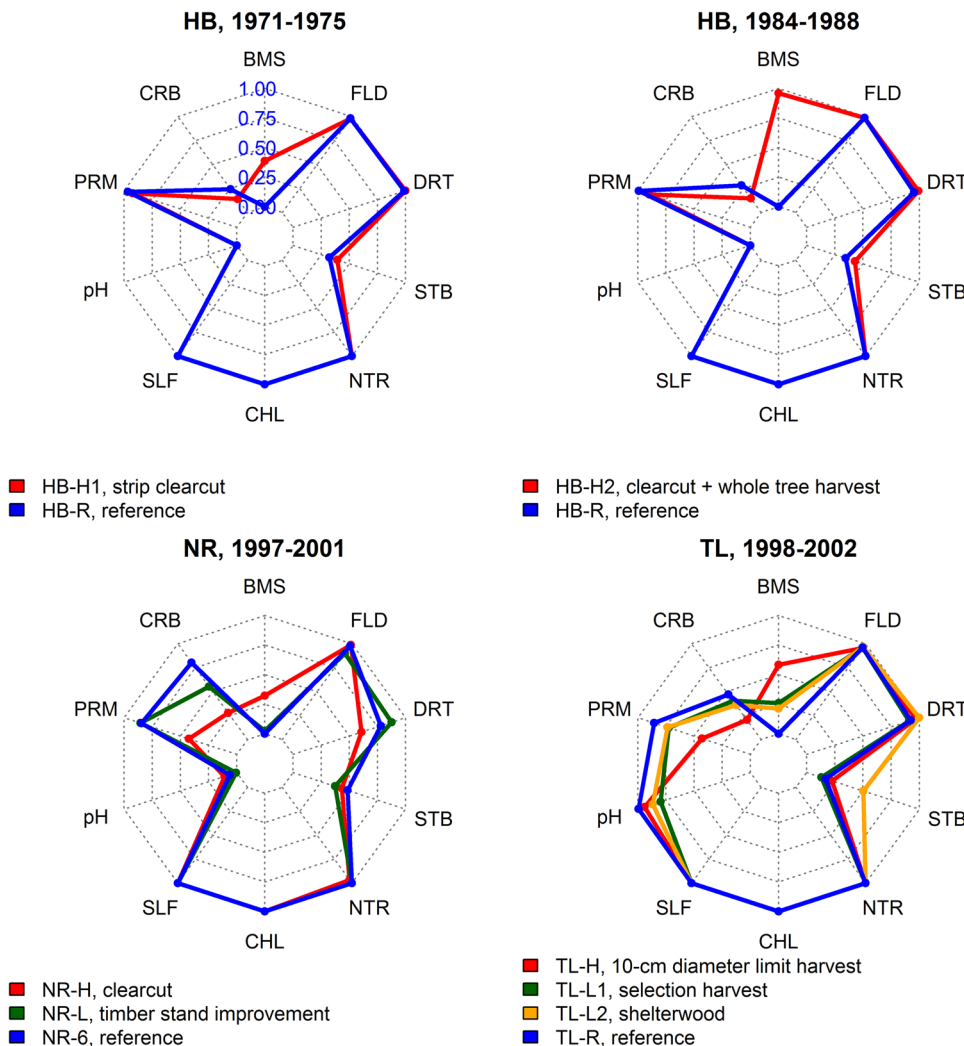


Figure 1. Comparison of rescaled ecosystem service metrics at ten watersheds at Hubbard Brook Experimental Forest (HB), Turkey Lakes Watershed (TL), and Neversink River Research Watershed (NR) over a 5-year period after harvesting. Labels: *BMS* biomass harvest, *FLD* flood prevention, *DRT* drought mitigation, *STB* flow stability, *NTR* NO<sub>3</sub><sup>-</sup> regulation, *CHL* Cl<sup>-</sup> regulation, *SLF* SO<sub>4</sub><sup>2-</sup> regulation, *pH* pH regulation, *PRM* remediation of nutrient pollution, *CRB* aboveground carbon mitigation.

(Douglas and Swank 1972; Hornbeck and others 1993; Stednick 1996). In the case of less intensive harvests, such as the selection and shelterwood at Turkey Lakes (TL-L1 and TL-L2, respectively), effects on flow were difficult to detect. Wang and others (2006) observed no change in streamflow after a shelterwood harvest removed 33% of basal area from a watershed nearby the Neversink River study site. Significant changes in streamflow have occurred primarily where harvesting has been extensive across an entire catchment and/or conducted using intensive techniques such as whole-tree removal (Hornbeck and others 1993; Stednick 1996). Such changes were documented in watersheds HB-H1 and HB-H2 at Hubbard Brook, where harvesting increased mean discharge for 5–10 years (Bailey and others 2003; Campbell and others 2007). Therefore, we expected to observe an increase in drought mitigation and a decrease in flood prevention in the intensively harvested watersheds (HB-H1, HB-H2, NR-H, and TL-H).

Contrary to expectations, the harvest-mediated tradeoff between flood prevention and drought mitigation was not evident in the 5-year period following harvest treatments (Figure 1). Neither was variation in flow stability—the mean duration (days) between observed high or low flow events—consistently related to the occurrence or intensity of a biomass harvest. The absence of a harvest-mediated tradeoff in flow regulation benefits suggests that, although absolute changes in streamflow did occur after harvesting, these changes did not cause stream flow to exceed the ranges that defined the flood prevention and drought mitigation services. We note that our results are consistent with the model simulations of Duncker and others (2012) that found only nominal differences in flow regulation among different harvest scenarios.

The limited effect of harvesting on flow regulation may be due in part to the low functional loads placed on the system during the post-harvest period. If conditions of high precipitation or acute moisture stress are rare, then on average, the capacity of harvested watersheds to provide benefits may be similar to the reference watersheds. This does not mean that there is necessarily no impact of harvesting on ecosystem capacity under more extreme (although less common) conditions. For example, Beier and others (2015) found that the probability that a harvested watershed could provide flood regulation benefits decreased relative to the reference as precipitation intensity increased, while a harvested watershed was increasingly more likely than an unharvested reference to provide

drought mitigation benefits as available moisture declined.

Using the same methods for a larger group of study watersheds, we observed similar dynamics in the current analysis (Figure 2). At both HB and TL, the vast majority of measurement days experienced low levels of precipitation (<25 mm) in the preceding 48-hr period. Given these typically low functional loads, the mean probability that watersheds had capacity to regulate floods was close to 100%. On the occasional days on which precipitation loads were more extreme, however, the capacity to provide this service declined. At HB, the difference between the harvested and reference watersheds was negligible regardless of precipitation intensity. However, at TL, the probability of flood prevention in the most intensively harvested watershed (TL-H) decreased relative to the other watersheds as antecedent precipitation increased. On the other hand, watersheds that had been intensively harvested were more likely than reference watersheds to provide drought mitigation benefits under conditions of moisture deficit (<0 mm available moisture) and less likely as available moisture increased. Whereas conditions of intense short-term precipitation were rare, watersheds more commonly experienced conditions of moisture deficit (based on our calculations). Approximately, half of measurement days followed months in which available moisture was less than 0 mm. Consequently, the impacts of harvesting on drought mitigation, while still nominal, were overall greater than the impacts on flood prevention during the study period.

## Water Quality Regulation

A tradeoff between harvesting and pollution remediation benefits—the net reduction of the eutrophication potential of rainfall—was observed depending on the intensity of the harvest (Figure 1). Watersheds that were harvested using high-intensity treatments exhibited the largest relative declines in the pollution removal benefit. At the reference watersheds, as well as the less intensive partial harvests, the ratio of eutrophication potential of stream water (output) versus that of rainwater (input) remained between 0.1:1 and 0.3:1 throughout the study period. These ratios indicate a net removal of the nutrient pollution in precipitation by the forested watersheds. In the watersheds with more intensive harvests, these output:input ratios sharply increased to exceed 1:1 shortly after harvest. Values greater than 1:1 indicated a net source of nutrient pollution from the watershed to stream water. The

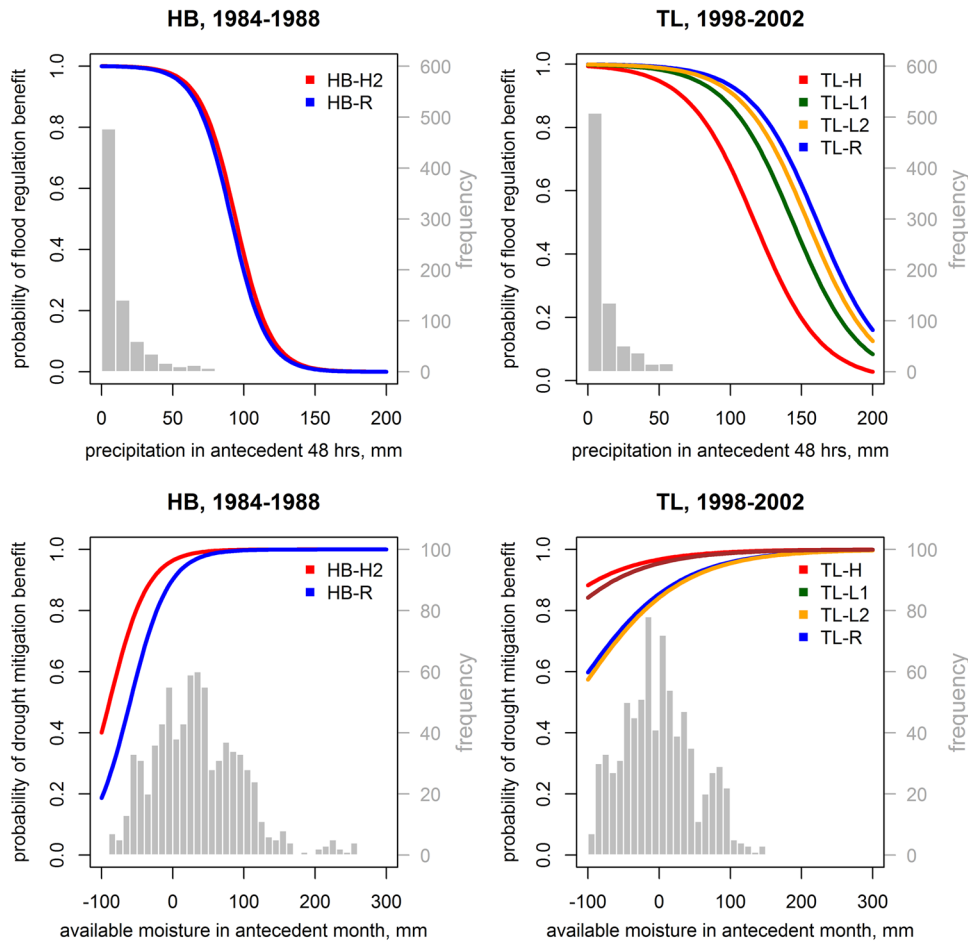


Figure 2. Probability of flood prevention and drought mitigation benefits at selected watersheds at Hubbard Brook Experimental Forest (HB) and Turkey Lakes Watershed (TL) over the 5-year period after harvest, modeled as a function of antecedent precipitation (48 h) and available moisture (1 month). Histograms illustrate the distribution of the relevant functional load at the reference watershed. HB-H2 (clearcut with whole-tree harvest) was harvested in 1983. Watersheds TL-H (diameter-limit harvest), TL-L1 (selection harvest), and TL-L2 (shelterwood harvest) were harvested in 1997. Watersheds HB-R and TL-R are unharvested references.

maximum value of this metric (4.6:1) was recorded for HB-H2 (clearcut with whole-tree harvest) in the first year after treatment.

Nitrate regulation benefits were provided consistently by all watersheds, with one exception: in NR-H, nitrate concentrations exceeded drinking water standards on 13.2% of measurement days during the first year after harvest (1997). Prior research at NR attributed these increases in stream nitrate in this watershed to the lack of vegetation to take up soil nitrate (McHale and others 2008). Other studies in the area suggest that changes in stream nitrate are not detectable following harvests of less than 40 % basal area reduction (Wang and others 2006; Siemion and others 2011). Siemion and others (2011) found that maximum nitrate concentration never exceeded drinking water standards after a series of harvests that reduced basal area by 22–68 %. Given that the clearcut with whole-tree harvest in HB-H2 removed 100 % of the aboveground biomass in the catchment, we expected to observe a deficit in nitrate regulation benefits after harvest, but the nitrate flux that occurred (Campbell and others 2007) did not result in

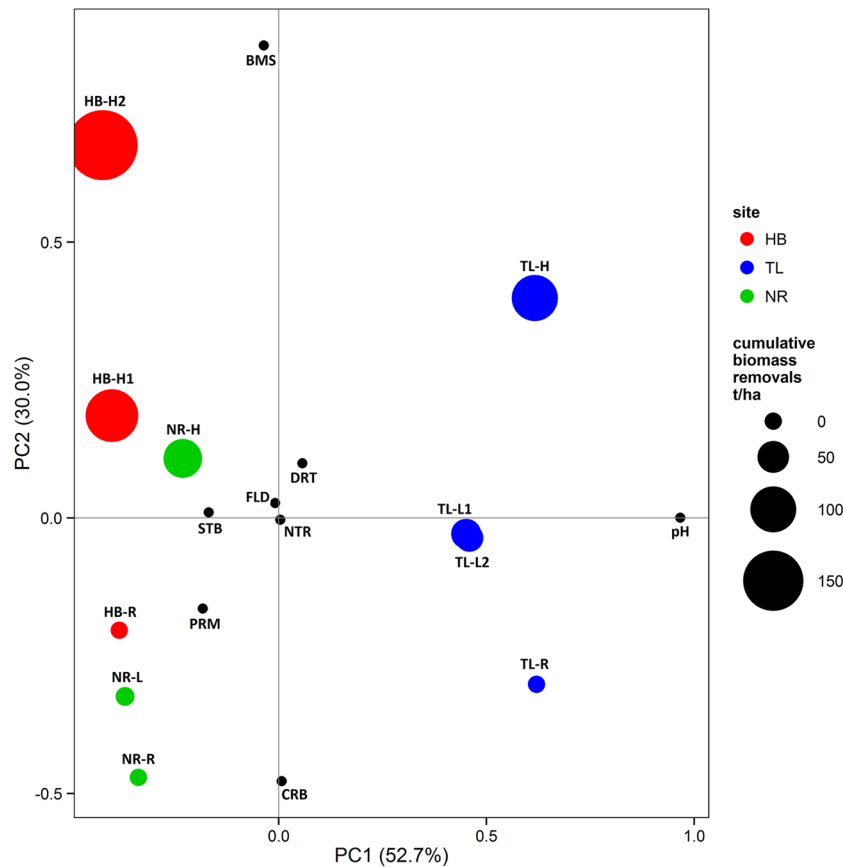
exceedance of New Hampshire drinking water standards. Again, using model simulations, Duncker and others (2012) found that nitrate always remained within standards in both harvested and reference stands.

Chloride and sulfate never exceeded standards at any of the sites throughout the entire time period (that is, service provision = 100%).

Regulation of pH differed by site due to local geology and hydrologic pathways (Hazlett and others 2001). Drinking water standards for pH were never satisfied at any of the watersheds at HB, and standards were met no more than 40.7 % of the time at NR (less than 15.6 % of the time at NR-L and NR-R). Comparatively, at TL, pH usually remained within the legal drinking water standards (more than 68.9 % of the time in TL-H, TL-L2, and TL-R). Drinking water standards for pH were the same in the US and Canada.

## Multiple Site Synthesis

We synthesized tradeoffs and synergies among the potential benefits of biomass harvesting, water



**Figure 3.** Results of principal component analysis based on provision of ecosystem services at watersheds in northeastern North America during a 5-year post-harvest period. Watersheds include those at Hubbard Brook Experimental Forest (HB), Turkey Lakes Watershed (TL), and Neversink River Research Watershed (NR). *Colored bubbles* show individual watershed scores on the first two components, with size of point corresponding to intensity of harvest and color corresponding to site. *Black points* show loading of individual service metrics on the first two components. Service metrics: *BMS* biomass harvest, *FLD* flood prevention, *DRT* drought mitigation, *STB* flow stability, *NTR*  $\text{NO}_3^-$  regulation, *pH* pH regulation, *PRM* remediation of nutrient pollution, *CRB* aboveground carbon mitigation (Color figure online).

regulation, and climate regulation—and across multiple sites and time periods—using principal components analysis of the rescaled service metrics (Figure 3). Sulfate and chloride regulation, which never deviated from 100% provision in any watershed, were excluded from analysis. The first two principal components explained 82.7% of total variance in all potential benefits (excluding  $\text{SO}_4^{2-}$  and  $\text{Cl}^-$ ) in the 5-year period after harvest. The first component (PC1) corresponds to variation in pH regulation, which was lower at HB and NR and higher at TL, and can be attributed to differences in ecosystem state factors related to parent material lithology and hydrologic flow pathways (Hazlett and others 2001). Variable loadings on PC1 suggest that other benefits are mostly unrelated to pH regulation, but that flow stability and pollution remediation may have weak negative associations with pH regulation.

The second principal component (PC2) corresponds with the tradeoff between biomass removal and aboveground carbon sequestration, which provides a climate regulation benefit. Intensively harvested watersheds have positive loadings on PC2, whereas the unharvested reference watersheds have negative loadings. Water flow and water quality regulation benefits are clustered around the zero point, except for pollution remediation, which is negatively loaded on PC2 and, to a lesser extent, PC1. We interpreted these results to suggest that the magnitude of the tradeoff between pollution remediation and biomass provisioning correlates with the intensity of harvest. In addition, there may also be a negative relationship between nutrient remediation and the same state factors that control ecosystem capacity to regulate stream pH. Other water regulation benefits were much less



sensitive to forest harvest, regardless of the intensity of biomass removal.

### Temporal Dynamics of Harvest Impacts and Recovery

To gauge the resilience of ecosystem services to biomass harvesting, we assessed the temporal dynamics of the two benefit metrics that had the largest tradeoffs with biomass harvest (pollution remediation and greenhouse gas regulation) over a longer time period. We examined the magnitude of the harvest impact and the recovery trajectories of these benefits in the most intensively harvested watersheds at HB (HB-H2) and TL (TL-H). NR-H was not included because observations did not extend more than 5 years post-harvest. Although the post-harvest loss of the pollution remediation benefit was much greater in HB-H2, both harvested watersheds recovered within about 7 years to provide an equal or greater benefit than the unharvested watersheds (Figure 4). Regeneration of forest vegetation following disturbance is essential to the recovery of ecosystem controls on water and nutrient cycles (Campbell and others 2007) and, in turn, their potential benefits to local beneficiaries. Although this pollution remediation benefit may be resilient to forest management practices that result in timely forest regeneration (including all those evaluated here), prior research suggests that for each year that forest vegetation recovery is delayed, approximately 2–3 decades of net pollution removal is needed to offset the eutrophication ‘cost’ incurred by harvesting (Beier and others 2015). Such ‘costs’ resulting from deficits in service provision may cause structural or behavioral changes in beneficiary populations, which in turn could affect future demand for benefits; for example, the creation of water treatment facilities to substitute for drinkable (or potable) ground water sources.

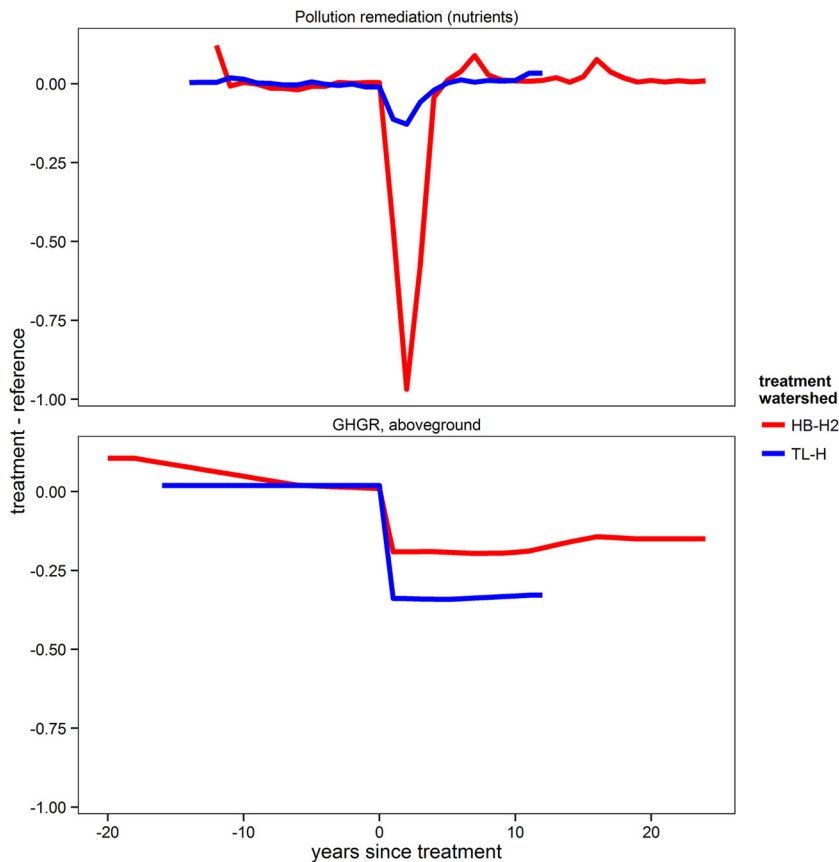
By contrast, greenhouse gas regulation benefits were much slower to recover after harvest because these benefits are linked directly to aboveground biomass, which may aggrade continuously for 80 or more years before approaching its maximum (Bormann and Likens 1979; Keeton and others 2011). Our results are consistent with studies suggesting that, although use of biomass fuels as fossil substitutes can reduce total carbon emissions, their use creates an initial “carbon debt” that can persist for decades (Fargione and others 2008; Mika and Keeton 2013; Walker and others 2013; Miner and others 2014).

### Estimating Societal Demand

Ecosystem services are rarely—if ever—directly observable phenomena. Instead, services are human constructs that are highly sensitive to how they are defined and measured. For example, in this study, we defined the flood prevention service as maintaining streamflow below particular thresholds, and we measured the service based on the frequency of threshold exceedance. Another measure of flood regulation could be related to differences in total magnitude of discharge during flood events (that exceeded the high flow thresholds). Although such a metric might have yielded different insights than our current results, prior work at HB found that the recovery of flow magnitude in harvested watersheds occurred within a timeframe similar to what we observed, that is, approximately 5–10 years (Bailey and others 2003; Campbell and others 2007).

Because ecosystem services are not directly observable, they are generally estimated from measures of ecosystem functional capacity, human demand for benefits, or both. Efforts to combine multiple datasets are often complicated by mismatches in spatial or temporal scale. For example, the forest harvest and streamflow data that we used as measures of functional capacity were collected at the level of first-order catchments; measures of human demand for flow regulation benefits (for example, surface water use, flood control infrastructure) were made at the scale of counties and larger watersheds. To resolve this scale mismatch, we downscaled measures of social demand to the level of individual catchments. If we were to scale up our analyses, measures of service demand would (necessarily) scale up linearly, whereas measures of supply would not, limiting our ability to interpret our results in terms of the entire landscape. Similarly, we addressed a temporal scale mismatch between streamflow data (annual) and vegetation data (collected once or twice a decade), by interpolating vegetation data to an annualized scale. Although this is a reasonable approach with a slowly changing variable such as forest biomass, it is possible that we may have missed possible short-term fluctuations in aboveground carbon.

Several of our measures of ecosystem services require the identification of critical thresholds beyond which it is assumed that benefits are not provided. Whenever possible, thresholds are estimated from empirical measures of societal demand for specific ranges of ecosystem conditions. How-



**Figure 4.** Long-term changes in pollution remediation and greenhouse gas regulation services at two harvested watersheds in northeastern North America. Watershed HB-H2 is part of the Hubbard Brook Experimental Forest (HB) and was harvested using clearcutting with whole-tree harvest in 1983. Watershed TL-H is part of the Turkey Lakes Watershed (TL) and was treated with a 10-cm diameter-limit harvest in 1997. Values are calculated as the difference between the treated watershed and a reference watershed on a [0,1] scale.

ever, data representing societal demand are often lacking or ambiguous and different interpretations of the data that do exist commonly lead to different estimates of demand. Because different threshold values can result in very different estimates of potential benefits, as well as different conclusions regarding tradeoffs among them, we have designed our approach to incorporate a range of alternative threshold values. For example, in the absence of data regarding water use or flood infrastructure at TL in rural Ontario, the high and low flow thresholds were defined based on percentiles (<5% for low flows and >95% for high flows) of the pooled distribution of daily discharge observations. To test the sensitivity of our metrics to these values, we used alternative sets of thresholds based on different percentile ranges, recalculated estimates of drought mitigation, flood prevention, and flow stability benefits, and incorporated the results into an interactive chart (see [http://forestecoservices.net/TL\\_thresholds.php](http://forestecoservices.net/TL_thresholds.php)). When thresholds were more strictly defined (for example, the 95th instead of the 90th percentile), we found a reduced likelihood that stream discharge would exceed those thresholds, resulting in smaller differences in

service provision between managed and unmanaged forest watersheds.

Another example can be drawn from the NR site located in the New York City watershed. In another interactive chart (see <http://forestecoservices.net/fvMap.php>), we estimated changes in drought mitigation benefits depending on whether we defined the low flow threshold using local (county-level) water demand or the much higher water demand from the New York metropolitan area. Higher water demand results in lower capacity for drought mitigation under the same moisture conditions. Similarly, we defined the service of water quality regulation based on the exceedance probabilities associated with legal drinking water standards. People certainly benefit from clean drinking water, but clean water also supports stream communities that may provide indirect benefits in the form of recreational fishing and aesthetics. If we had defined water quality metrics based on (presumably) stricter ecological thresholds, it is possible that we would have found a greater tradeoff between harvesting and water quality regulation.

Identifying the “right” thresholds requires a stronger understanding of the benefits that people

derive from ecosystems and societal demand for those benefits. Further research is needed to carefully elucidate and quantify the specific benefits that people receive from ecosystems, as well as the thresholds and benchmark values that determine when, where, and to whom those benefits are being provided. Methods and tools are also needed to identify and measure the cultural services provided by forests and woodlands. The high value placed on these services makes them of prime importance in the areas such as the US Northeast (Butler and Leatherberry 2004) and may underlie the reluctance of some landowners in the region to engage in active forest management practices such as biomass harvesting (Butler and others 2010).

## CONCLUSIONS

Demand for woody biomass from forests as renewable energy feedstock is increasing in northeastern North America. Drawing on several long-term ecosystem experiments, we estimated the impacts of biomass harvesting on the water and climate regulation benefits that hardwood forests in this region provide to local and global beneficiaries. Tradeoffs between biomass provision and the benefits of greenhouse gas regulation and pollution removal were observed, but overall the impacts of biomass harvest on the regulation of water quality and quantity were nominal and short-lived. Although absolute changes in service provision were smaller using low-intensity silvicultural practices (that is, selection harvest, shelterwood system)—water regulation services were largely resilient to more intensive biomass removals, including the diameter-limit harvesting that largely characterizes forest management in this region. Although these conclusions are consistent with previous work (Biber and others 2015; Grêt-Regamey and others 2013; Duncker and others 2012; Schwenk and others 2012), we emphasize that recovery of forest vegetation after harvest is critical to the resilience of the ecosystem's capacity to provide water regulation benefits (Beier and others 2015). If forest regeneration fails or is inhibited, then deficits in water regulation benefits may persist and potentially become worse. Future efforts must focus on resolving uncertainties around scale and the societal demand for benefits, to more accurately assess the resilience of forest ecosystem services to multiple drivers of change.

## ACKNOWLEDGMENTS

This research was supported by funding from the U.S. Forest Service Northeastern States Research

Cooperative ([www.nsrc.org](http://www.nsrc.org)). We extend thanks to our collaborators for their expertise and logistical support, including the Hubbard Brook Research Foundation, Natural Resources Canada, the U.S. Geological Survey, the Cary Institute of Ecosystem Studies, and the Gund Institute for Ecological Economics. Any use of trade, firm, or product names is for descriptive purposes and does not imply endorsement by the U.S. Government.

## REFERENCES

- Aguilar FX, Saunders A. 2010. Policy instruments promoting wood-to-energy uses in the continental United States. *J For* 108(3):132–40.
- Bailey AS, Hornbeck JW, Campbell JL, Eagar C. 2003. Hydrometeorological database for Hubbard Brook Experimental Forest: 1955–2000. General Technical Report NE-305. Newtown Square, PA: Department of Agriculture, Forest Service, Northeastern Research Station.
- Beier CM, Patterson TM, Chapin FSIII. 2008. Ecosystem services and emergent vulnerability in managed ecosystems: a geospatial decision-support tool. *Ecosystems* 11(6):923–38.
- Beier CM, Caputo J, Groffman PM. 2015. Measuring ecosystem capacity to provide regulating services: forest removal and recovery at Hubbard Brook (USA). *Ecol Appl* 25(7):2011–21.
- Bennett EM, Peterson GD, Gordon LJ. 2009. Understanding relationships among multiple ecosystem services. *Ecol Lett* 12(12):1394–404.
- Berger AL, Palik B, D'Amato AW, Fraver S, Bradford JB, Nislow K, King D, Brooks RT. 2013. Ecological impacts of energy-wood harvests: lessons from whole-tree harvesting and natural disturbance. *J For* 111(2):139–53.
- Biber P, Borges JG, Moshhammer R, Barreiro S, Botequim B, Brodrechtová Y, Brukas V, Chirici G, Cordero-Debets R, Corrigan E, Eriksson LO, Favero M, Galev E, Garcia-Gonzalo J, Hengeveld G, Kavaliauskas M, Marchetti M, Marques S, Mozgeris G, Navrátil R, Nieuwenhuis M, Orazio C, Paligorov I, Pettenella D, Sedmák R, Smreček R, Stanislovaite A, Tomé M, Trubins R, Tuček J, Vizzarri M, Wallin I, Pretzsch H, Sallnäs O. 2015. How sensitive are ecosystem services in European forest landscapes to silvicultural treatment? *Forests*. 6(5):1666–95.
- Bormann FH, Likens GE. 1979. Pattern and process in a forested ecosystem. New York: Springer. p 253.
- Brown G. 2013. The relationship between social values for ecosystem services and global land cover: an empirical analysis. *Ecosyst Serv* 5:58–68.
- Buchholz T, Canham CD, Hamburg SP. 2011. Forest biomass and bioenergy: opportunities and constraints in the northeastern United States. Millbrook: Cary Institute of Ecosystem Studies. p 75.
- Buonocore E, Franzese PP, Ulgiati S. 2011. Assessing the environmental performance and sustainability of bioenergy production in Sweden: a life cycle assessment perspective. *Energy*. doi:10.1016/j.energy.2011.07.032.
- Butler BJ, Leatherberry EC. 2004. America's family forest owners. *J For* 102(7):4–14.
- Butler BJ, Ma Z, Kittredge DB, Catanzaro P. 2010. Social versus biophysical availability of wood in the Northern United States. *North J Appl For* 27(4):151–9.

- Cadmus R, Escobedo FJ, McLaughlin D, Abd-Elrahman A. 2014. Analyzing trade-offs, synergies, and drivers among timber production, carbon sequestration, and water yield in *Pinus elliotii* forests in Southeastern USA. *Forests* 5:1409–31.
- Campbell JL, Driscoll CT, Eagar C, Likens GE, Siccama TG, Johnson CE, Fahey TJ, Hamburg SP, Holmes RT, Bailey AS, Buso DC. 2007. Long-term trends from ecosystem research at the Hubbard Brook Experimental Forest. General Technical Report NRS-17. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station.
- Caputo J, Balogh SB, Volk TA, Johnson L, Puettmann M, Lippke B, Oneil E. 2014. Incorporating uncertainty into a life cycle assessment (LCA) model of short-rotation willow biomass (*Salix* spp.) crops. *Bioenergy Res* 7(1):48–59.
- Carpenter SR, DeFries R, Dietz T, Mooney HA, Polasky S, Reid WV, Scholes RJ. 2006. Millennium ecosystem assessment: research needs. *Science* 314(5797):257–8.
- Daily GC, Matson PA. 2008. Ecosystem services: from theory to implementation. *Proc Natl Acad Sci USA* 105(28):9455–6.
- Daily GC, Polasky S, Goldstein J, Kareiva PM, Mooney HA, Pejchar L, Ricketts TH, Salzman J, Shallenberger R. 2009. Ecosystem services in decision making: time to deliver. *Front Ecol Environ* 7(1):21–8.
- Davis SC, Dietze M, DeLucia E, Field C, Hamburg SP, Loarie S, Parton W, Potts M, Ramage B, Wang D, Youngs H, Long SP. 2012. Harvesting carbon from eastern U.S. forests: opportunities and impacts of an expanding bioenergy industry. *Forests* 3:370–97.
- DeFries R, Pandey D. 2010. Urbanization, the energy ladder and forest transitions in India's emerging economy. *Land Use Policy* 27(2):130–8.
- Djomo NS, El Kasmioui O, Ceulemans R. 2011. Energy and greenhouse gas balance of bioenergy production from poplar and willow: a review. *Glob Change Biol Bioenergy* 3:181–97.
- Douglas JE, Swank WT. 1972. Streamflow modification through management of eastern forests. USDA Forest Service Research Paper SE-94. Triangle Park: USDA Forest Service, Southeastern Forest Experiment Station.
- Duncker PS, Raulund-Rasmussen K, Gundersen P, Katzensteiner K, De Jong J, Ravn HP, Smith M, Eckmüllner O, Spiecker H. 2012. How forest management affects ecosystem services, including timber production and economic return: synergies and trade-offs. *Ecol Soc* 17(4):50.
- Fantozzi F, Buratti C. 2010. Life cycle assessment of biomass chains: wood pellet from short rotation coppice using data measured on a real plant. *Biomass Bioenergy* 34(12):1796–804.
- Fargione J, Hill J, Tilman D, Polasky S, Hawthorne P. 2008. Land clearing and the biofuel carbon debt. *Science* 319(5867):1235–8.
- García-Nieto AP, García-Llorente M, Iniesta-Arandia I, Martín-López B. 2013. Mapping forest ecosystem services: from providing units to beneficiaries. *Ecosyst Serv* 4:126–38.
- Goerndt ME, Aguilar FX, Miles P, Shifley S, Song N, Stelzer H. 2012. Regional assessment of woody biomass physical availability as an energy feedstock for combined combustion in the US northern region. *J For* 110(3):138–48.
- Grêt-Regamey A, Brunner SH, Altwegg J, Christen M, Bebi P. 2013. Integrating expert knowledge into mapping ecosystem services tradeoffs for sustainable forest management. *Ecol Soc* 18(3):34.
- Hacker JJ. 2005. Effects of logging residue removal on forest sites: a literature review. Eau Claire: West Central Wisconsin Regional Planning Commission.
- Hazlett PW, Semkin RG, Beall FD. 2001. Hydrologic pathways during snowmelt in first-order stream basins at the Turkey Lakes Watershed. *Ecosystems* 4:527–35.
- Hornbeck JW, Adams MB, Corbett ES, Verry ES, Lynch JA. 1993. Long-term impacts of forest treatments on water yield: a summary for northeastern USA. *J Hydrol* 150(2–4):323–44.
- Janowiak MK, Webster CR. 2010. Promoting ecological sustainability in woody biomass harvesting. *J For* 108(1):16–23.
- Keeton WS, Whitman AA, McGee GC, Goodale CL. 2011. Late-successional biomass development in northern hardwood-conifer forests of the northeastern United States. *For Sci* 57(6):489–505.
- Lattimore B, Smith CT, Titus BD, Stupak I, Egnell G. 2009. Environmental factors in woodfuel production: opportunities, risks, and criteria and indicators for sustainable practices. *Biomass Bioenergy* 33(10):1321–42.
- Lattimore B, Smith CT, Titus B, Stupak I, Egnell G. 2013. Woodfuel harvesting: a review of environmental risks, criteria and indicators, and certification standards for environmental sustainability. *J Sustain For* 32(1–2):58–88.
- Levin R, Krigstin S, Wetzel S. 2011. Biomass availability in eastern Ontario for bioenergy and wood pellet initiatives. *For Chron* 87(1):33–41.
- Lippke B, Gustafson R, Venditti R, Volk T, Oneil E, Johnson L, Puettmann M, Steele P. 2011a. Sustainable biofuel contributions to carbon mitigation and energy independence. *Forests* 2:861–74.
- Lippke B, Oneil E, Harrison R, Skog K, Gustavsson L, Sathre R. 2011b. Life cycle impacts of forest management and wood utilization on carbon mitigation: knowns and unknowns. *Carbon Manag* 2(3):303–33.
- Lippke B, Puettmann ME, Johnson L, Gustafson R, Venditti R, Steele P, Katers JF, Taylor A, Volk TA, Oneil E, Skog K, Budsberg E, Daystar J, Caputo J. 2012. Carbon emission reduction impacts from alternative biofuels. *For Prod J* 62(4):296–304.
- Manley A, Richardson J. 1995. Silviculture and economic benefits of producing wood energy from conventional forestry systems and measures to mitigate negative impacts. *Biomass Bioenergy* 9(1–5):89–105.
- McHale MR, Murdoch PS, Burns DA, Baldigo BP. 2008. Effects of forest harvesting on ecosystem health in the headwaters of the New York City water supply. U.S. Geological Survey Scientific Investigations Report 2008–5057. Catskill Mountains: U.S. Geological Survey Scientific Investigations. pp 2008–5057.
- Mika AM, Keeton WS. 2013. Factors contributing to carbon fluxes from bioenergy harvests in the US Northeast: an analysis using field data. *GCB Bioenergy* 5(3):290–305.
- Millennium Ecosystem Assessment. 2005. Ecosystems and human well-being: synthesis. Washington, DC: Island Press.
- Miner RA, Abt RC, Bowyer JL, Buford MA, Malmshiemer RW, O'Laughlin J, Oneil EE, Sedjo RA, Skog KE. 2014. Forest carbon accounting considerations in US bioenergy policy. *J For* 112(6):591–606.
- Munsell JF, Germain RH. 2007. Woody biomass energy: an opportunity for silviculture on nonindustrial private forestlands in New York. *J For* 105(8):398–402.

- Munsell JF, Germain RH, Munn IA. 2008. A tale of two forests: case study comparisons of sustained yield management on Mississippi and New York nonindustrial private forestland. *J For* 106(8):431–9.
- Nyland RD (Ed.). 1987. *Managing northern hardwoods: proceedings of a silvicultural symposium: 1986 June 23–25*. Syracuse (NY): SUNY College of Environmental Science and Forestry.
- Nyland RD. 1992. Exploitation and greed in eastern hardwood forests. *J For* 90(1):33–7.
- Nyland RD. 2007. *Silviculture: concepts and applications*. Prospect Heights. Long Grove: Waveland Press. p 682.
- Openshaw K. 2010. Biomass energy: employment generation and its contribution to poverty alleviation. *Biomass Bioenergy* 34(3):365–78.
- Perez-Verdin G, Grebner DL, Munn IA, Sun C, Grado SC. 2008. Economic impacts of woody biomass utilization for bioenergy in Mississippi. *For Prod J* 58(11):75–83.
- Polasky S, Lewis DJ, Plantinga AJ, Nelson E. 2014. Implementing the optimal provision of ecosystem services. *Proc Natl Acad Sci* 111(17):6248–53.
- R Core Team. 2012. *R: a language and environment for statistical computing, version 2.15.1—'Roasted Marshmallows'*. Vienna: R Foundation for Statistical Computing. ISBN 3-900051-07-0. <http://www.R-project.org/>.
- Richter DDB Jr, Jenkins DH, Karakash JT, Knight J, McCreery LR, Nemestothy KP. 2009. Wood energy in America. *Science* 323(5920):1432–3.
- Robertson GP, Dale VH, Doering OC, Hamburg SP, Melillo JM, Wander MM, Parton WJ, Adler PR, Barney JN, Cruse RM, Duke CS, Fearnside PM, Follett RF, Gibbs HK, Goldemberg J, Mladenoff DJ, Ojima D, Palmer MW, Sharpley A, Wallace L, Weathers KC, Wiens JA, Wilhelm WW. 2008. Agriculture: sustainable biofuels redux. *Science* 322(5898):49–50.
- Robertson M, BenDor TK, Lave R, Riggsbee A, Rubl JB, Doyle M. 2014. Stacking ecosystem services. *Front Ecol Environ* 12(3):186–93.
- Roundtable on Sustainable Biofuels. 2010. *RSB principles and criteria for sustainable biofuel production*. RSB-STD-01-001 (version 2.0). Roundtable on Sustainable Biofuels.
- Schulze ED, Körner C, Law BE, Haberl H, Luysaert S. 2012. Large-scale bioenergy from additional harvest of forest biomass is neither sustainable nor greenhouse gas neutral. *GCB Bioenergy* 4(6):611–16.
- Schwenk WS, Donovan TM, Keeton WS, Nunery JS. 2012. Carbon storage, timber production, and biodiversity: comparing ecosystem services with multi-criteria decision analysis. *Ecol Appl* 22(5):1612–27.
- Siemion J, Burns DA, Murdoch PS, Germain RH. 2011. The relation of harvesting intensity to changes in soil, soil water, and stream chemistry in a northern hardwood forest, Catskill Mountains, USA. *For Ecol Manag* 261(9):1510–19.
- Solomon BD. 2010. Biofuels and sustainability. *Ann N Y Acad Sci* 1185:119–34.
- Stednick JD. 1996. Monitoring the effects of timber harvest on annual water yield. *J Hydrol* 176(1–4):79–95.
- U.S. Department of Energy. 2011. *U.S. billion-ton update: supply for a bioenergy and bioproducts industry*. In: Perlack RD, Stokes BJ, Eds. ORNL/TM-2011/224. Oak Ridge, TN: Oak Ridge National Laboratory.
- Volk TA (Lead.). 2010. Appendix K: sustainability criteria. In: Jarnefeld, J, Ed. *Renewable fuels roadmap and sustainable biomass feedstock supply for New York*. Albany: New York State Energy Research and Development Authority (NSERDA).
- Walker T, Cardellicchio P, Gunn JS, Saah DS, Hagan JM. 2013. Carbon accounting for woody biomass from Massachusetts (USA) managed forests: a framework for determining the temporal impacts of wood biomass energy on atmospheric greenhouse gas levels. *J Sustain For* 32(1–2):130–58.
- Wang X, Burns DA, Yanai RD, Briggs RD, Germain RH. 2006. Changes in stream chemistry and nutrient export following a partial harvest in the Catskill Mountains, New York, USA. *For Ecol Manag* 223(1–3):103–12.
- Williams PRD, Inman D, Aden A, Heath GA. 2009. Environmental and sustainability factors associated with next-generation biofuels in the U.S.: what do we really know? *Environ Sci Technol* 43(13):4763–75.
- Zabel R. 2010. Guest editor's introduction: forest biomass utilization: the impact on forest resources. *West J Appl For* 25(1):4.