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Ecosystem Effects of a Tropical Cyclone on a Network of Lakes in Northeastern North America

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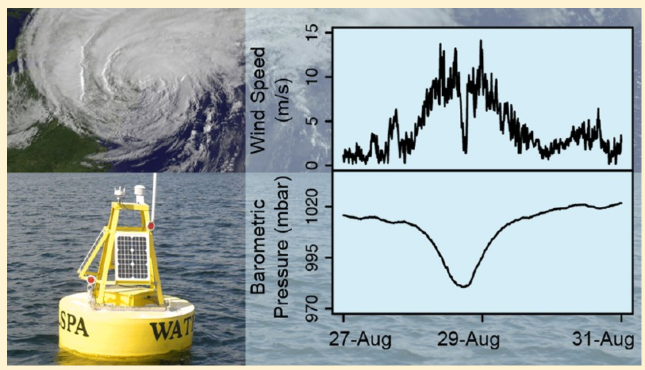
Supporting Information



ABSTRACT: Here we document the regional effects of Tropical Cyclone Irene on thermal structure and ecosystem metabolism in nine lakes and reservoirs in northeastern North America using a network of high-frequency, in situ, automated sensors. Thermal stability declined within hours in all systems following passage of Irene, and the magnitude of change was related to the volume of water falling on the lake and catchment relative to lake volume. Across systems, temperature change predicted the change in primary production, but changes in mixed-layer thickness did not affect metabolism. Instead, respiration became a driver of ecosystem metabolism that was decoupled from in-lake primary production, likely due to addition of terrestrially derived carbon. Regionally, energetic disturbance of thermal structure was shorter-lived than disturbance from inflows of terrestrial materials. Given predicted regional increases in intense rain events with climate change, the magnitude and longevity of ecological impacts of these storms will be greater in systems with large catchments relative to lake volume, particularly when significant material is available for transport from the catchment. This case illustrates the power of automated sensor networks and associated human networks in assessing both system response and the characteristics that mediate physical and ecological responses to extreme events.

INTRODUCTION

Tropical cyclones are known to disrupt thermal structure[1] and biological production[2−4] in individual lakes and estuaries, but little is known about the immediate ecological impacts in lakes across the landscape. Networks of ground-based sensors collecting data on metrics such as wind and precipitation have allowed effective tracking of the physical effects of tropical cyclones and other large-scale events. However, assessment of the regional effects of such events on ecological processes has been largely limited to satellite imagery (for example, Milward et al. 2010[5]). Given the expected increase in extreme weather events across much of the globe as the climate warms,[6] measuring and evaluating the physical, chemical, and ecological impacts of extreme precipitation events over short as well as long time scales has taken on new importance.[1]

In late August 2011, Tropical Cyclone Irene (hereafter Irene), moved through the Caribbean and up the east coast of North America (Figure 1). This significant storm made its third landfall near New York City, New York; heavy rain and tropical storm force winds persisted as the storm moved northward (Figure 1, Supporting Information (SI) Figures S1 and S2). Most of the damage in North America was due to wind, heavy rainfall, and flooding,[7] and the effects were visible across terrestrial landscapes and in stream and river flooding. Trees downed by wind contributed to the loss of electrical power to

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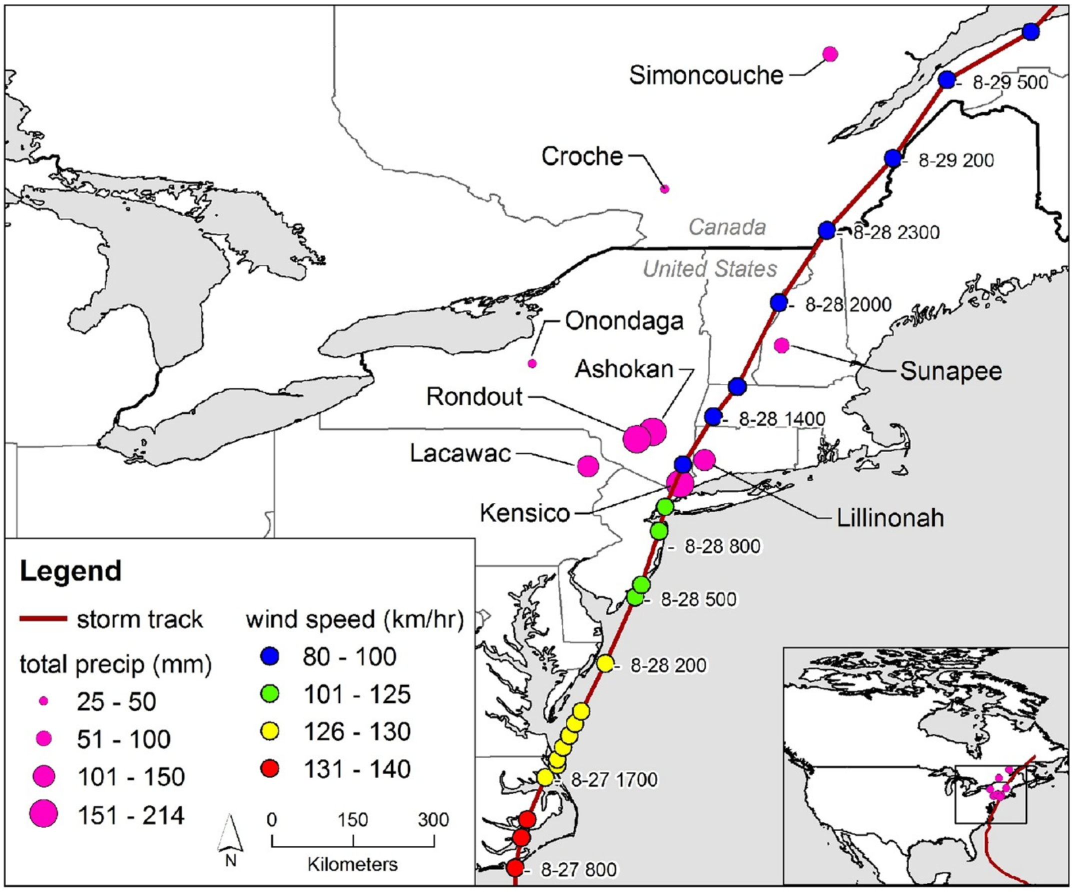

Figure 1. Map of study region and Irene storm track. Map of northeastern United States and southeastern Canada with study sites shown as pink circles. Size of the circle indicates the total precipitation from Tropical Cyclone Irene recorded at or near each lake (see SI for details). Wind speed and storm track data are from the U.S. National Weather Service; times are in Eastern Daylight Time.

more than 3 million people in northeastern North America, and some areas of this region experienced the worst flooding since 1927.[7]

The wind and rain associated with tropical cyclones can also lead to significant changes in the physical structure and biological functioning of aquatic ecosystems. Lake and estuarine studies from the southeastern U.S., where tropical cyclones are relatively common, show that the storms affect vertical thermal structure,[1] primary production,[2−4] and fish production.[3,8] In the northeastern U.S., major tropical cyclones are infrequent (hurricane landfall recurrence intervals ∼15−30 years[9]), and although tropical cyclone frequency may or may not increase with climate change, future storms are nonetheless likely to be more intense with higher rainfall rates.[10] Due to their size and potential longevity, these storms can affect large geographic areas. However, there has been no evaluation of the immediate regional impacts of tropical cyclones on aquatic systems in northeastern North America.

Here we assess the effects of Irene on thermal stability and ecosystem metabolism in nine diverse lakes and reservoirs (hereafter lakes) over a geographic area of 312 000 km^2, a region where lakes are an important feature of the landscape. We used a set of in situ, automated, monitoring systems associated with the Global Lake Ecological Observatory Network (GLEON) that record data at high frequency (10 min to 6 h) to document the timing, magnitude, and duration of changes in the condition of lakes with previously unavailable precision. We focused on the derivation and application of metrics that allowed for physical and biological comparison across systems that vary widely in their characteristics, including, catchment size and land cover, water residence time, bathymetry, and the initial state of systems at the time of the event. We then used these metrics to evaluate the temporal sequence of disturbance and recovery of biotic and abiotic characteristics that occurred as the storm passed through the region.

MATERIALS AND METHODS

Automated sensors located on floating buoys measured water temperature and dissolved oxygen and had been previously deployed in nine lakes and reservoirs across northeastern North America (Table 1; SI). Data were recorded at intervals ranging from 10 min to 6 h. Meteorological data were collected from the buoys or from other nearby sources, and barometric pressure measurements were normalized to sea level using the hypsometric equation (see SI). Short-term changes in lake residence time could be calculated at two of the sites using information from water budgets (see SI). Data from these sources were used in the calculation of the effects of Irene on the physical and ecological characteristics of the systems.

To assess the whole-lake energetic impact of this major physical disturbance, we quantified lake thermal stability as Schmidt stability (J m^{-2}), a measure of the amount of work required to overcome density stratification and completely mix a lake.[11,12] Daily Schmidt stability was calculated as in Idso[11]

Table 1. Lake and Catchment Characteristics, Storm Intensity Metrics, And Potential Volume Replacement for the Nine Study Lakes and Reservoirs, Northeastern North America[a]

name	latitude	longitude	elevation	area	catchment area	catchment area/lake area	mean depth	lake volume	residence time	Irene rainfall	max wind gust[d]	min barometric pressure	potential volume replacement
			m	ha	ha	ha/ha	m	m^3	days	mm	m/s	mbar	%
Ashokan	41.952	−74.208	180	1218	60 416	50.6	13.9	1.74×10^8	77	213[b]	18.01	974.5[b]	75.5[e]
Croche	45.992	−74.005	362	6	88	14.9	6.0	3.81×10^5	171	25[c]	15.96	997.4[c]	6.2
Kensico	41.089	−73.745	108	837	2593	4.1	12.9	1.61×10^8	58	168[b]	21.10	971.1[b]	5.6[e]
Lacawac	41.375	−75.288	446	20	48	3.3	6.5	1.32×10^6	1132	146[c]	22.13	982.4[c]	7.5
Lillinonah	41.478	−73.346	60	626	359 283	574.9	13.4	9.07×10^7	24	119[c]	20.07	973.7[c]	470.9
Onondaga	43.089	−76.211	112	1200	64 200	54.5	10.9	1.31×10^8	91	28[b]	12.87	994.1[b]	13.9
Rondout	41.826	−74.472	256	825	23 877	30.0	22.5	2.05×10^8	51	213[b]	18.01	974.5[b]	25.7[e]
Simoncouche	48.230	−71.250	340	87	2633	31.3	3.0	2.32×10^6	53	66[c]	14.00	994.7[b]	77.3
Sunapee	43.381	−72.054	333	1667	10 428	7.3	11.6	2.02×10^8	1132	90[c]	17.48	980.7[c]	5.4

[a]Potential volume replacement (PVR) is the ratio of the volume of water that fell on the catchment plus the lake during Irene relative to lake volume. [b]Data from airport or other nearby weather station. [c]Data from buoy or onsite weather station. [d]Data from best-fit airport for Irene storm (see Materials and Methods). [e]Includes water from outside catchment delivered via aqueducts. Aqueduct water increases PVR values by up to 2%.

using the software program Lake Analyzer.[12] Schmidt stability is calculated using the equation

$$\text{stability} = \frac{g}{A_s} \int_0^{Z_d} (z - z_v)\rho_z A_z \partial z$$

where g is acceleration due to gravity, A_s is the surface area of the lake, z_d is the maximum depth of the lake, z is the depth of the lake at any given interval, z_v is the depth to the center volume of the lake, ρ_z is density of water at depth z, and A_z is the area of the lake at depth z. Density was calculated using average daily water temperature at each depth. The calculation did not take into account the effect of changing lake depth; such changes would have negligible effects on our results because Schmidt stability is calculated using temperature and bathymetry profiles at 1 m resolution and storm inputs resulted in <1 m change in depth in lakes for which we have information. We have complete lake depth information for Ashokan. For that system, including lake depth in the calculations decreased daily Schmidt stability by 0−4% and overall change in stability by only 0.03% (see below).

Stability is influenced by lake morphometry, so for each lake we quantified daily Schmidt stability and used it to calculate two metrics of relative change: overall change in stability and the poststorm derivative of stability. The overall change in stability was calculated as the percent change from prestorm stability (the value on 26 August 2011) to minimum Schmidt stability in the three-day period (29 August-31 August 2011) following Irene. We chose 26 August as our prestorm value because it was the last full day before storm influence. We used a time window to identify the minimum poststorm stability due to differences in the timing of the storm and catchment hydrologic responses across systems. To calculate the post-storm derivative of stability, we first scaled Schmidt stability as a percentage of the initial seven day average (1−7 August 2011) for each lake. This facilitated comparisons of storm effect among lakes of different prestorm stability since the mean prestorm stability was found to be dependent on lake depth (SI Figure S5). The first derivative (rate of change) of the scaled stability (% day^{-1}) was taken for each lake using a simple differencing method (Δstability/Δtime) to examine the magnitude of daily change resulting from the storm. The poststorm derivative of stability is the minimum derivative (maximum absolute rate of change) observed during the three days following the storm. These metrics, which are essential for making comparisons across systems with different characteristics, can only be calculated using high frequency data. Both are responsive to factors such as the rate of hydrologic inflow and wind that may contribute to mixing over daily time intervals.

We examined catchment characteristics, lake morphometry, lake thermal structure, and local storm intensity as potential drivers of change in stability. Because the overall change in lake stability appeared to indicate a threshold change as a function of the potential volume replacement (PVR; the ratio of the volume of water falling on the catchment and lake relative to lake volume, expressed as a percentage; Figure 3a), we separated lakes into those above and below the PVR threshold for further analysis. We then analyzed the natural-log-transformed minimum derivative of the scaled stability using ANCOVA analysis with minimum barometric pressure (representing the magnitude of storm effect) as a covariate and PVR (greater or less than 50%) as a categorical explanatory variable. We used the full ANCOVA model including the

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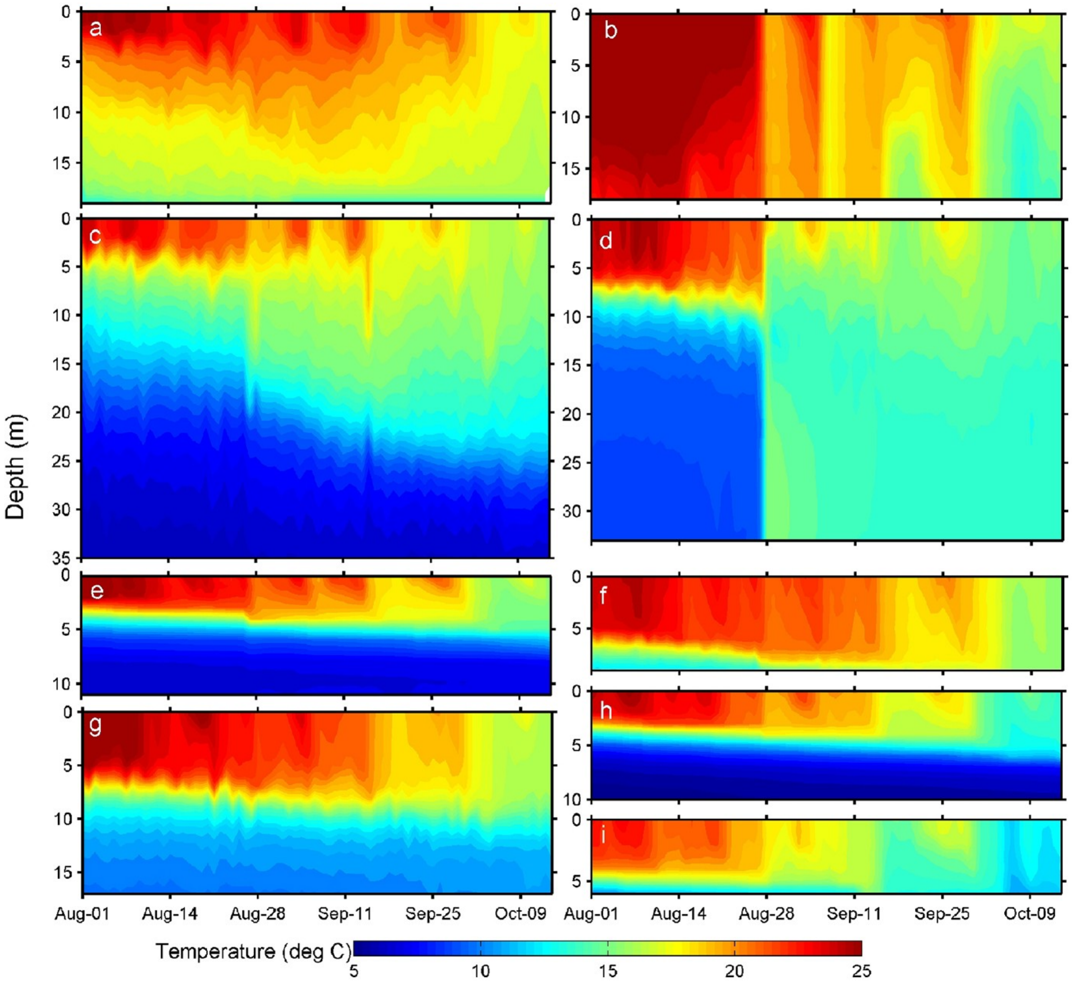

Figure 2. Temporal variation in water temperature across study lakes. Water temperature variation with depth from 1 August 2011 to 15 October 2011 in (a) Kensico Reservoir, (b) Lake Lillinonah, (c) Rondout Reservoir, (d) Ashokan Reservoir, (e) Lake Lacawac, (f) Lake Sunapee, (g) Lake Onondaga, (h) Lac Croche, and (i) Lac Simoncouche. Lillinonah (b), Ashokan (d), and Simoncouche (i) are lakes with high (>50%) potential volume replacement (see Materials and Methods). Sites are arranged by latitude with lower latitude lakes at the top of the figure. Minimum barometric pressure (indicating maximum storm intensity) during Tropical Cyclone Irene was 28 August in all lakes except Simoncouche (29 August).

interaction term to test the assumption of homogeneity of regression slopes. There was a significant interaction effect ($F_{1,5} = 80.11$, $p < 0.001$) indicating heterogeneity of slopes. Therefore, we used the Johnson-Neyman procedure[13] on back-transformed data to identify regions of storm intensity where there was a difference between PVR groups.

To assess storm effects on biological processes, we used high-frequency dissolved oxygen, water temperature, and meteorological measurements to calculate net ecosystem production (NEP), respiration (R), and gross primary production (GPP).[14] Seven lakes were included in the metabolism calculations. Kensico and Lacawac were not included due to lack of appropriate oxygen data. Sensors at each lake measured dissolved oxygen at one depth in the epilimnion (0.5−2 m for all lakes), water temperature throughout the water column, and photosynthetically active radiation (PAR) and wind speed above the lake. If there were fewer than four data points for dissolved oxygen concentration or water temperature per day, that day was discarded from further analysis; otherwise, gaps in data were linearly interpolated to 15 min time steps. If gaps in wind and PAR values were <60 min, those data were linearly interpolated to the 15 min time scale, but if the gaps were >60 min, that day was discarded from analysis. We modeled dissolved oxygen dynamics for each 24 h period using a simple model[14]

$$\frac{dO_2}{dt} = \text{GPP} - R + D \tag{1}$$

where dO_2/dt is the rate of change in dissolved oxygen concentration, GPP is the average daily rate of photosynthesis (mg O_2 L^{-1} d^{-1}), R is the average rate of respiration (mg O_2 L^{-1} d^{-1}), and D is the flux of oxygen between the lake water and the atmosphere. GPP and R are fit as constant daily rates with GPP only occurring during daylight. The atmospheric flux (D) was modeled using an empirical model from Cole and Caraco[15] where the movement of oxygen between the lake and atmosphere is dependent on the wind speed and the difference between the concentration of dissolved oxygen in the water and the concentration at saturation for that water temperature. We chose the Cole and Caraco 1998 wind formulation because the wind was lower than 10 m s^{-1} and in the range for which this model is most appropriate for all of the prestorm period and >87% of wind measurements for all lakes (>98% for all but

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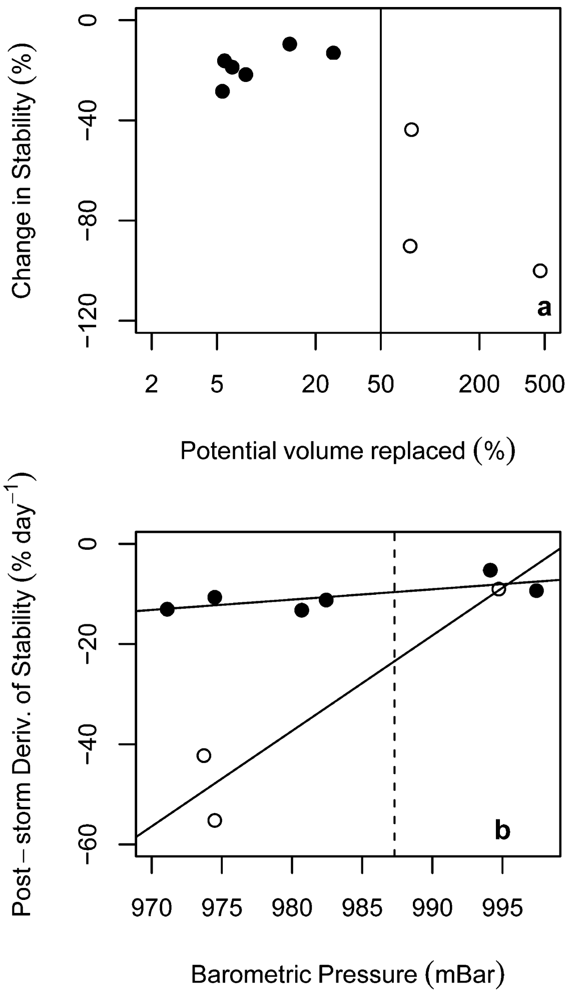

Figure 3. Lake stability response to storm and catchment drivers. (a) Relationship between percent change in stability (% change from 26 August 2011 to minimum value in the three days following the storm) compared to potential volume replacement (PVR; the ratio of the water that fell on the catchment plus the lake relative to the volume of the lake, expressed as a percentage) for each lake. Solid line indicates 50% PVR, the midpoint between lakes in our study with low PVR (closed circles, all ≤26%) and high PVR (open circles, all ≥75%). (b) The relationship between minimum barometric pressure during Irene and the poststorm derivative of stability (minimum derivative in the three days following the storm). Open circles represent systems with >50% PVR and closed circles represent systems with <50% PVR. The dotted line identifies the pressure (987.3 mmHg) below which the high PVR lakes (poststorm deriv. of stability = 1.9 × BP − 1904) are significantly different from the low PVR lakes (poststorm deriv. of stability = 0.21 × BP − 213) identified using the Johnson-Neyman procedure. Each point represents one lake.

three lakes) during the three days including and immediately following the storm.

In each lake, the metabolism model is based on a single spatial measurement of dissolved oxygen and our estimates of *R* and GPP are for the mixed layer only. We fit each 24 h lake-day with parameters GPP and *R* that minimized the negative log-likelihood fit for the lake[14] using R statistical packages.[16] NEP is calculated as GPP-*R*. To look at the effect of temperature on the decoupling of GPP and *R*, we standardized GPP (GPP_{20}) and *R* (R_{20}) to a constant temperature of 20 °C[17] to account for variable changes in temperature (measured at 1 m) across lakes from pre- to post- storm. In addition, we examined catchment characteristics, lake morphometry, lake thermal structure, and local storm intensity as potential drivers of change in metabolic rates.

■ RESULTS AND DISCUSSION

Irene's effect was dramatic across the focal region of our study. Thermal stratification, which characterizes most north-temperate lakes during the summer and early autumn and controls fundamental aspects of biogeochemistry and the distribution of organisms, was disrupted in all nine lakes (Figure 2).

Schmidt stability declined abruptly in all lakes following Irene (SI Figure S3). Deeper lakes were more stable before the storm (SI Figure S4), but prestorm stability did not predict the magnitude of change following the storm. Instead, a combination of storm intensity and catchment and lake characteristics was the best predictor of overall change in stability. Lakes that had the potential to receive the largest amounts of water relative to their volumes—"potential volume replacement" (PVR), a ratio of the water that fell on the catchment plus the lake relative to lake volume (expressed as a percentage)—had the largest overall percentage change in stability (Figure 3a). We used barometric pressure as a surrogate for storm intensity, as barometric pressure was negatively correlated with both maximum wind gust ($r = -0.78$, $p = 0.013$) and precipitation ($r = -0.86$, $p = 0.003$). PVR clearly mediated the poststorm derivative responses to storm intensity; at low barometric pressure (i.e., higher storm intensity) lakes with >50% PVR had greater rates of changes in stability than those with PVR <50% (Figure 3b; Johnson-Neyman procedure,[13] $p < 0.05$). Thus, while water loading was clearly important to changes in stability, neither storm intensity nor catchment and lake characteristics alone predicted the energetic disturbance of stability. Furthermore, although the greatest disruption of stability occurred in lakes with high PVR, even

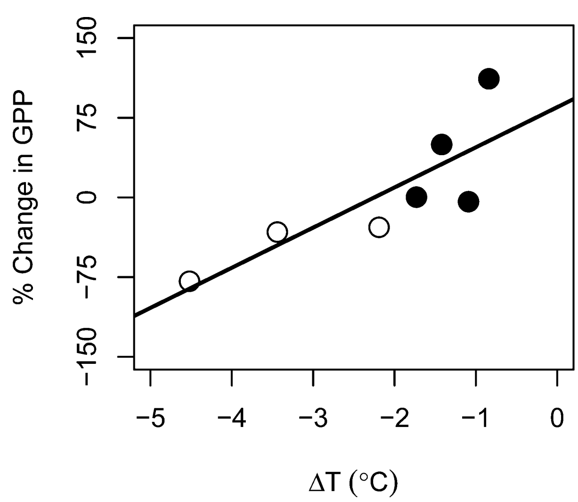

Figure 4. Relationship between storm responses of water temperature and gross primary production. The relationship between change in water temperature at 1 m (T) and change in Gross Primary Production (GPP) following Irene (% change in GPP = 37.8 × change in *T* + 84.9, $p = 0.02$, $r^2 = 0.67$). Change in GPP is the percent difference and change in T is the absolute difference between the 10 day mean after Irene and the 10 day mean before Irene. Each point represents one lake, where open circles denote lakes with high potential volume replacement and closed circles are those with low potential volume replacement (see Figure 3). Metabolism estimates are available for seven of the nine lakes.

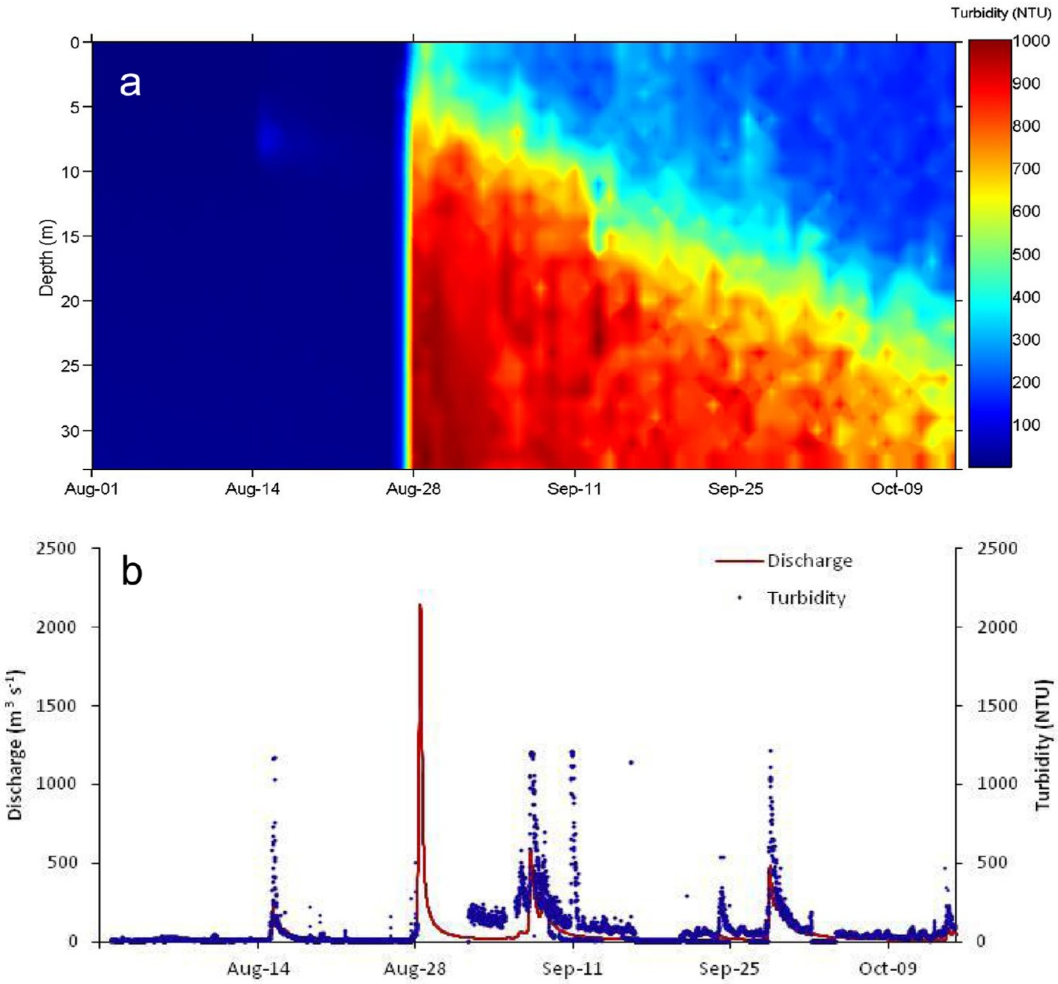

Figure 5. Turbidity in a stream and reservoir associated with Tropical Storm Irene. (a) Turbidity isopleths calculated from automated profile measurements made in Ashokan Reservoir, New York, from 01 August 2011 to 15 October 2011. Profiles were measured at 3−6 h intervals at 1 m vertical resolution. (b) Stream discharge and streamwater turbidity measured in the main inflow to the reservoir. Storm damage during peak discharge on 28 August prevented stream turbidity measurements, but turbidity in the stream likely exceeded 1000−1500 NTU.

lakes with low PVR had rapid and dramatic changes in stability related to storm intensity, as well as large inputs of water, leading to pronounced effects on water retention time. For example, short-term retention time was reduced by 50% in Lacawac and by 33% in Croche.

The loading of water that drove, in part, changes in physical structure also can affect ecosystem-wide biological processes such as gross primary production (GPP), respiration (R), and net ecosystem production (NEP = GPP − R) via changes in temperature or delivery of terrestrially derived organic matter, nutrients, or inorganic sediment.[3,18,19] NEP changed following Irene but the degree of change was not related to storm magnitude, changes in stability, the depth of the mixed layer, or characteristics of catchments or lakes. Across lakes, the change in GPP was predicted well by the change in temperature (p = 0.02, r^2 = 0.67), and the temperature changes were greatest in high PVR lakes (Figure 4). Reductions in water temperature could have impacted GPP via a direct physiological pathway or could be indirectly related to the increased terrestrial inputs in the high PVR lakes; in these highly affected systems, increased light limitation was likely due to absorption of light by inputs of particulate and dissolved organic matter (Figure 5).[18] In addition, existing primary producers may have been flushed as a result of lowered residence times due to water influxes.[19]

In contrast, changes in R and NEP were not predicted by changes in temperature. In some lakes, R increased following the storm (e.g., Ashokan, Rondout, and Sunapee), whereas R decreased in others (e.g., Lillinonah). However, across the region, the change in NEP in lakes was strongly negatively correlated with change in R (p = 0.002, r^2 = 0.87) (Figure 6) and was not correlated with change in GPP (p > 0.05). The same analysis on three randomly chosen 20-day periods (centered on 6 August, 15 September, and 1 October) produced no significant relationships (all p > 0.40) between NEP and R, suggesting that changes in respiration do not typically drive changes in NEP during late summer and early fall in these systems.

In many of our study lakes, increases in carbon loading from flooding and erosion were likely the cause of increased R which created or magnified net heterotrophic conditions. Across lakes, GPP and R were tightly coupled before Irene (p < 0.001, r^2 = 0.98) (Figure 7a), indicating a balance between internal production and respiration. After the storm, autochthonous production appeared to decrease in importance as a carbon source for respiration as GPP and R were decoupled (p = 0.21) (Figure 7b). Despite the importance of temperature change to the change in GPP, it does not appear to be responsible for the decoupling of GPP and R as GPP_{20} was strongly coupled to R_{20}

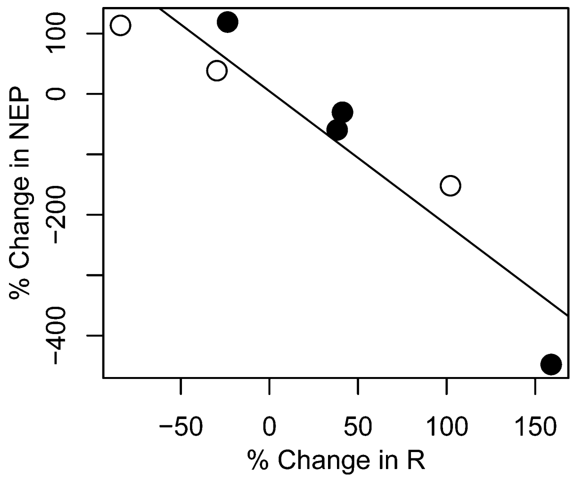

Figure 6. Relationship between storm responses of respiration and net ecosystem production. The relationship between changes in respiration (R) and changes in net ecosystem production (NEP) following Irene (% change in NEP = −2.2 × % change in R + 4.6, p = 0.002, r^2 = 0.87). Change in metabolism parameters are the percent difference between the 10 day mean after Irene and the 10 day mean before Irene. Each point represents one lake, where open circles denote lakes with high potential volume replacement and closed circles are those with low potential volume replacement (see Figure 3). Metabolism estimates are available for seven of the nine lakes.

prior to Irene (p = 0.001, r^2 = 0.97) and decoupled following Irene (p > 0.05).

The changes in R and NEP observed in our study (Figure 6) are likely a consequence of event-based loading of dissolved (DOC) and particulate (POC) organic carbon. Terrestrial carbon transported to lakes can support heterotrophic respiration[20,21] and play an important role in aquatic food webs.[22] The terrestrial export of carbon typically increases during storm events and with snowmelt[23,24] and annual organic carbon exports from catchments are controlled by moderate-to-large storm events.[25] In fact, up to 86% of annual DOC export from forested catchments, including sites from the Rondout and Ashokan catchments, has been shown to occur during these events.[24] Hyrdologic flows following Irene were the largest on record for some of our catchments, and terrestrial carbon transported to lakes during this period was likely a substantial portion of the annual carbon input.

As observed here across a large region, the effects of disturbance of lake stability generally may be shorter-lived than those of material inputs. Post-Irene recovery of Schmidt stability was rapid in most lakes and was related to the magnitude of initial effect (r^2 = 0.5, p = 0.033, SI Figure S5). All but one system (Ashokan) recovered to within 80% of prestorm stability within one week, supporting the observation that event-driven changes in stability tend to recover quickly[1,26] given favorable poststorm conditions. In contrast, recovery from effects associated with increased terrestrial organic matter and nutrient loading will depend on how long the material is retained within the system[4] and the degree to which its composition differs from background composition.[27,28] For example, DOC often leaves at a rate that depends on the residence time of the lake (~1 month to 3 years for the systems in this study) and the rate at which DOC is assimilated or degraded. In contrast, POC associated with high turbidity stormwater settles in lakes and, if not stored permanently, can increase respiration for years[20] (Figure 5).

Managing material flux from land to water is particularly important in systems where maintenance of trophic status or

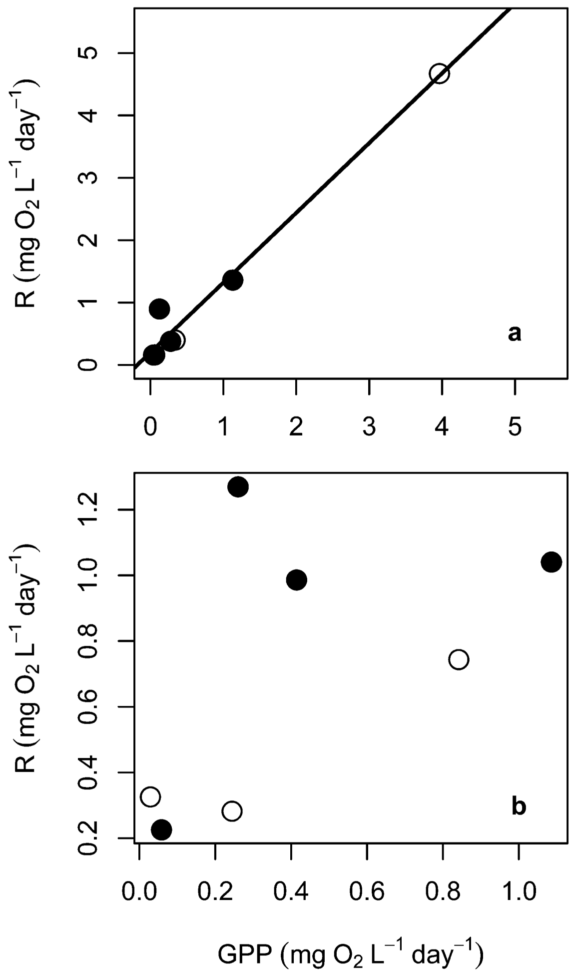

Figure 7. Decoupling of respiration and gross primary production following Irene. The relationship between average gross primary production (GPP) and average respiration (R) (a) pre-Irene (R = 1.1 × GPP + 0.2, p < 0.001, r^2 = 0.98, DF = 5; slope ± SE (1.1 ± 0.08) not statistically different from 1, t_4 = 1.48, p = 0.2) and (b) post-Irene (p = 0.22, DF = 5). Pre-Irene is defined as 10 days before and post-Irene as 10 days after the storm. Each point represents one lake, where open circles denote lakes with high potential volume replacement and closed circles are those with low potential volume replacement (see Figure 3). Metabolism estimates are available for seven of the nine lakes.

water clarity is critical to management of water quality. For example, nutrient loading is a concern for Lillinonah, a eutrophic system with severe summer algal blooms. Despite the fact that GPP in Lillinonah decreased following Irene, poststorm total phosphorus (TP) concentration (64 μg L^{-1}) was more than double prestorm TP concentration (26.8 μg L^{-1}) (t_6 = 15.9, p < 0.001). We predict increased algal growth in future years if Irene-liberated phosphorus is retained within the lake and is biologically available. Another of the heavily affected sites, Ashokan, is part of the New York City drinking water system which provides water to over 9 million people, and is frequently subject to turbid inputs as a result of stream channel erosion of catchment clay deposits.[29] Turbidity in the reservior following Irene was some of the highest recorded, and remained elevated for more than eight months following the storm (Figure 5). Loading models that used in-lake high-frequency sensor data directly influenced active management of the water delivery system; by understanding which systems had been impacted by turbidity and at what depths, reservoir operations were managed such that high quality drinking water continued to be delivered to consumers in New York City without interuption. This regional event illustrates the importance of anticipating and mitigating storm-related water quality impacts and the use of high-frequency data to underpin adaptive management scenarios during extreme events. Effective protection, management, and restoration of regional water resources, especially with climatic change, will require addressing long-term consequences of storm-driven loading of water and materials to lake ecosystems while accounting for system retention time and catchment characteristics that mediate and cause lags in the impacts of severe storms.

In the face of ongoing and future climate change, understanding the magnitude and extent of poststorm legacies, especially with respect to material inputs, is fundamental to understanding the linkages and feedbacks among air, land, water, and human systems. For example, regional carbon dynamics have been attributed in part to flushing of carbon from soils via precipitation and the evasion[30] from or processing[20] of that carbon in aquatic systems. Given predictions of increased frequency of intense storms in northeastern North America,[31] increases in the frequency and intensity of both physical and material disturbance in lakes should be anticipated. We suggest that large-scale (regional-to-global) automated sensor networks—and the associated human networks that allows contextualization and interpretation of the information—are essential to understanding short- and long-term impacts of extreme events and more gradual environmental changes. Such information can play a key role in mitigating the effects of environmental change on key ecological resources such as drinking water.

ASSOCIATED CONTENT

Supporting Information

Detailed information related to sensors and data collection, Figures S1−S5. This information is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest

Author Contributions

KW conceived of the idea for the paper and was the driving force behind the collaboration. JK led the overall synthesis and writing, along with HE, DR, and KW. SE, HE, BH, JK, DO, DP, DV, and KW provided data from study systems. DR conducted the metabolism analysis. HE, JK, DR, and KW led the stability analysis. HE, BH, DP, and DV did the potential volume replacement calculations. NS and DV led the Lake Analyzer analysis. AL compiled the airport data. BH compiled the precipitation data. AL, DR, and NS prepared the figures. HE, BH, JK, AL, DR, DP, NS, DV, and KW contributed to data interpretation and writing.

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