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ORIGINAL ARTICLE

Nutrient Export from Watersheds on Mt. Desert Island, Maine, as a Function of Land Use and Fire History

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Abstract A study of 13 small (less than 7.5 km^2) watersheds on Mt. Desert Island, Maine, was conducted from January 1999 to September 2000 to determine nutrient export delivery to coastal waters around the island, and to determine whether a series of wildfires in 1947 have affected nutrient export in burned watersheds. Nutrient export (nitrate–nitrogen, total nitrogen, total phosphorus) was determined for each watershed during the study period, and was normalized by watershed area. The yield of nitrate–nitrogen (N) ranged from 10 to 140 kg/km^2/year. Total N yield ranged from 42 to 250 kg/km^2/year. Total phosphorus (P) yield ranged from 1.4 to 7.9 kg/km^2/year. Watersheds entirely within Acadia National Park (lacking human land-based nutrient sources) exported significantly less total N and total P than watersheds that were partly or entirely outside the park boundary. Nitrate–N export was not significantly different in these two groups of watersheds, perhaps because atmospheric deposition is a dominant source of nitrate in the study area. No relation was observed between burn history and nutrient export. Any effect of burn history may be masked by other landscape-level factors related to nutrient export.

Keywords Acadia National Park
Coastal watersheds · Fire effects · Land-use · Nitrogen export · Small watersheds

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1 Introduction

1.1 Background

Nutrient loading to coastal ecosystems in the northeastern U.S. has become an important issue. Recent evidence suggests that many estuaries in the Gulf of Maine region, including some estuaries on Mt. Desert Island, are becoming increasingly eutrophic in response to nitrogen (N) loading from nonpoint sources (Kinney and Roman 1998; Dow and Braasch 1996; Howes et al. 1996; Nixon 1996; Doering et al. 1995; and Nixon 1995); however, few studies of nutrient export in coastal New England streams with relatively low human influence are available to serve as a benchmark for assessing export from watersheds with higher population densities. With urbanization continuing rapidly in coastal watersheds of the U.S., fewer

and fewer areas are available to conduct research on background levels of nutrient export. Acadia National Park and Mt. Desert Island provide a suitable location to study nutrient export rates in unimpacted and low-impact watersheds in coastal northern New England; however even these areas are not immune to human effects, because deposition of atmospheric inorganic N is significant (Nelson et al. in press).

Acadia National Park in coastal Maine would appear to provide an ideal rural setting in terms of pristine waters, clean air, and low pollutant input. However, years of fog chemistry data (Kimball et al. 1988), abundant ozone advisories (Acadia National Park and Maine DEP records), and nearly 20 years of precipitation chemistry data (National Atmospheric Deposition Program, data retrieved from http://nadp.sws.uiuc.edu/nadpdata/, Feb. 2, 2001) show that Acadia National Park and Mt. Desert Island are actually subject to intense atmospheric pollutant loading. Episodic acidification by nitrate (nitric acid) has been documented (Kahl et al. 1992). How this nonpoint source loading to watersheds on the island translates to nutrient loading to coastal waterbodies, such as ecologically sensitive estuaries, has been poorly documented. This issue was identified by Acadia National Park as one of their high-priority resource-management issues (Kahl et al. 2000). This research was initiated, in part, to address this issue.

A large portion of Mt. Desert Island was intensely burned by a series of wildfires in 1947, including nearly one third of the Park. Because fire history may be a major control on N cycling (Riggan et al. 1994; Tiedemann et al. 1979), researchers began analyzing data collected in the early 1980s (Kahl et al. 1985) to see whether the burned and unburned watersheds on the island were exporting inorganic N at different rates. These rates, if different, would have important implications for the spatial distribution of nonpoint-source N loads to sensitive waterbodies. Early evidence suggested that N export was much higher in unburned watersheds than in burned watersheds, so researchers at the University of Maine and the U. S. Geological Survey (USGS) began a study in 1998 to fully investigate the hydrologic and ecologic effects of the 1947 fires, using a paired watershed design (Kahl et al. in press). One burned and one unburned watershed at high altitudes were selected for study. The unburned watershed exported 10 to 20 times more inorganic N than the burned watershed (Nelson et al. in press). Retention of incoming inorganic N was 96% in the burned watershed and 72% in the unburned watershed (Campbell et al. 2004; Nelson et al. in press).

Because only two watersheds on Mt. Desert Island were intensively studied since the early work by Kahl et al. (1985) and Heath et al. (1993), a broader investigation into nutrient export from other burned and unburned watersheds was begun in 1999 by the USGS. Funding for this study was provided by a USGS program earmarked for work in National Parks. Thirteen watersheds on the island were selected for study, half of which had more than 50% of their area burned by the 1947 wildfires. Nutrient export rates were calculated for each watershed, and rates for burned and unburned watersheds were compared.

This paper describes the part of the study investigating differences in nutrient export to coastal waters of Mount Desert Island, Maine. Methods and results of analyses of the loading of nutrients to coastal waters are presented, along with an analysis of the relation of nutrient loads to the 1947 wildfires and to the protected areas on the island.

1.2 Description of study area

Mt. Desert Island (Fig. 1) (280 km^2) is the largest island on the Atlantic Coast of the United States north of Cape Cod. The northern third of the island is characterized by gently sloping topography and a coastline with many inlets and mudflats. The southern two thirds of the island is dominated by a series of 200- to 500-m high mountains trending SW–NE, rocky coastlines, steeper topography (except for the far southwest part), and a deep fjord (Somes Sound) that nearly bisects the island (Fig. 1). Most of the island is underlain by a series of Devonian intrusive igneous rocks (primarily granites). Other bedrock units include Siluro–Devonian metamorphosed volcanic rocks and sediments, and a Cambro–Ordovician schist (Gilman et al. 1988).

The island's topography, and that of the stream watersheds included in this report, ranges from gently rolling hills with slopes of around 5% to mountains with slopes greater than 60%. Rainfall based on National Atmospheric Deposition Program data (19 years of record, data from http://nadp.sws.uiuc.edu/nadpdata/, Feb. 2, 2001) is 140 cm/year, which is

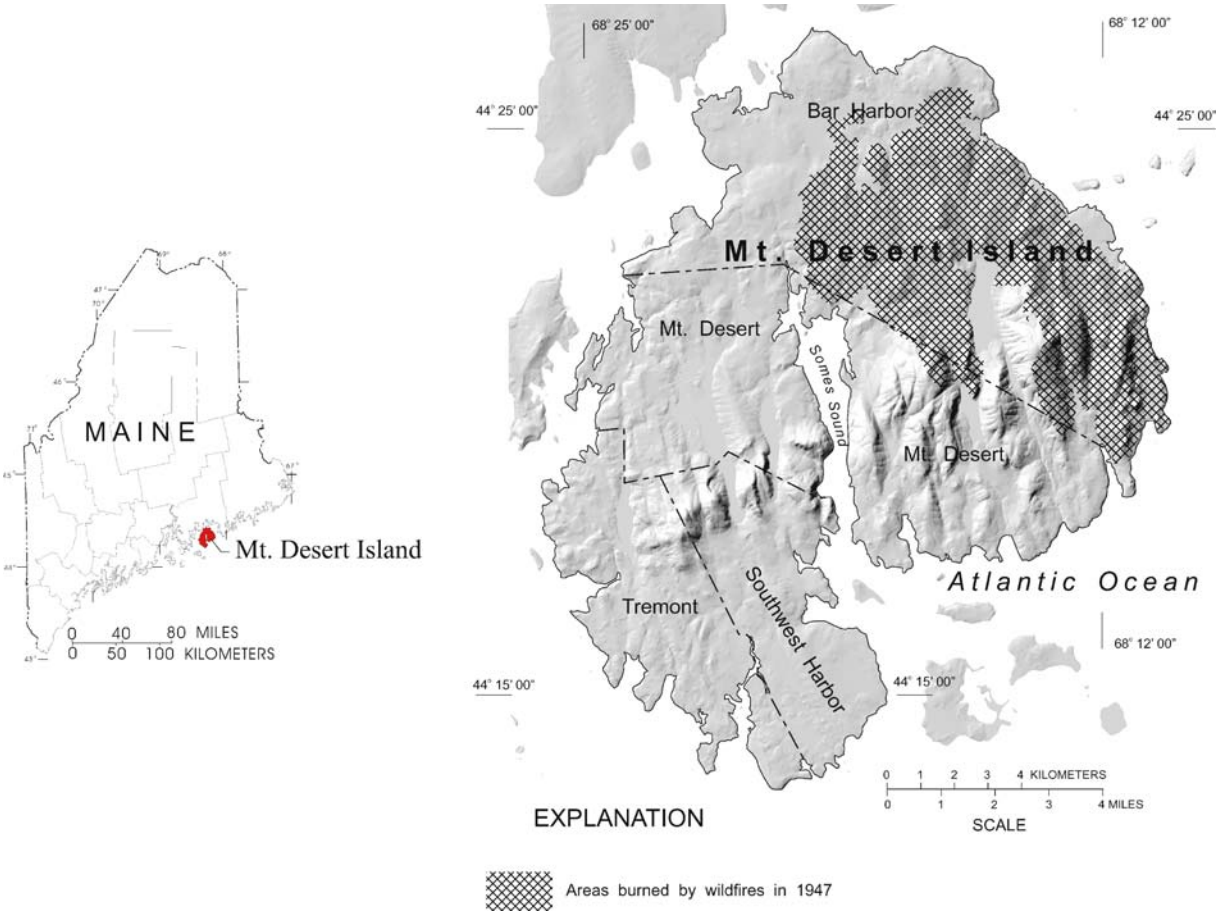

Fig. 1 Location of the study area, Mount Desert Island, Maine

approximately 20 cm greater than the rest of Maine (Nielsen 2002).

The island is divided into four townships: Bar Harbor, Mt. Desert, Southwest Harbor, and Tremont (Fig. 1), which have a combined year-round population of 8,770 (U.S. Bureau of the Census 2001). Much of the population lives in rural areas, which are served by domestic wells and on-site sewage-disposal systems. Acadia National Park receives 2.5 million visitors a year (David Manski, Acadia National Park Natural Resources Manager, personal communication, 2000), and comprises more than 50% of the land area of the island (Fig. 2). Other than areas directly adjacent to visitor centers, the Park is protected from human impacts other than those involved in foot and car traffic.

Land-use patterns for the island were determined by Acadia National Park in a survey of low-altitude infrared aerial photos taken in May, 1997 (Karen Anderson, National Park Service, personal communication, 2001). Most of the land is forested (76%). The forest is a mix of coniferous stands (primarily at higher altitudes), deciduous stands, and mixed forest. The area that burned in 1947 has regenerated primarily as a deciduous and mixed deciduous–coniferous forest. Wetlands cover 6 to 10% of the island (depending on which database is used). Agricultural land (2% of the island) is dominated by hay fields; livestock areas are uncommon. Urban land uses account for 10% of the total landscape (as of 1997), including the more densely developed residential areas. Rural residential developments have been increasing dramatically since the early 1990s (Dana Reed, Bar Harbor Town Manager, personal communication, 2002). These new developments are generally characterized by wooded lots of 0.4 – 0.8 ha

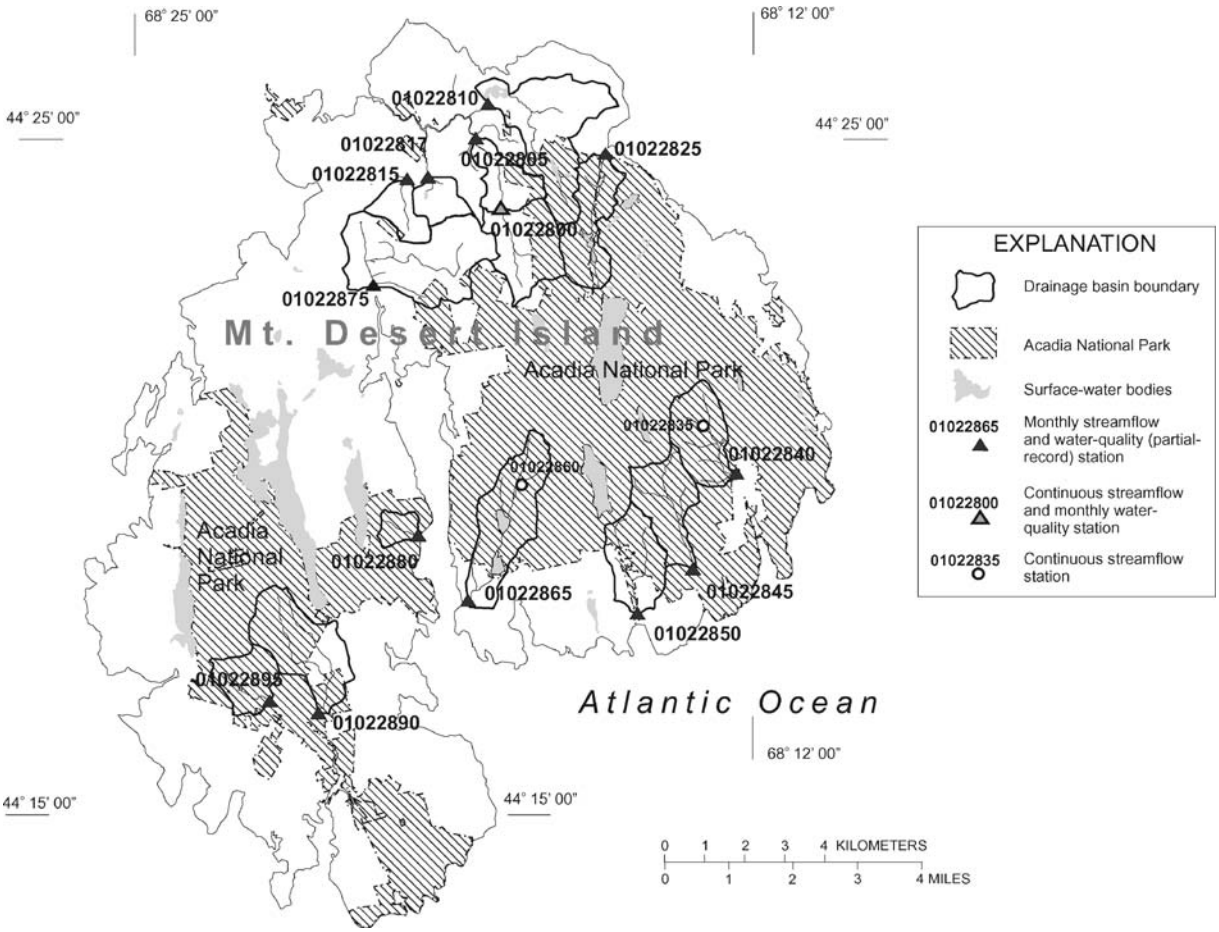

Fig. 2 Locations of watersheds and U.S. Geological Survey data-collection sites on Mt. Desert Island, Maine, 1999–2000

(1–2 acres) in size or larger. Few of these newer households have large yards with fertilized lawns (Dana Reed, personal communication, 2002).

2 Data Collection

2.1 Surface-water flow

Fourteen surface-water monitoring stations (Fig. 2) were established in the 13 watersheds on Mt. Desert Island to determine the mass of N and P entering estuaries and other coastal waters of the island (Table 1). The watersheds of these stations range from 0.84 to 7.48 km^2. Thirteen of the stations are partial-record stations, established at the lower ends of the 13 perennial streams. These stations measured on a monthly basis for streamflow and sampled for water quality. The 14th station (Old Mill Brook at Old Norway Drive) was established to continuously record streamflow data, and to also provide monthly water-quality samples. All streamflow data were collected using USGS methods described in Carter and Davidian (1968) and in Rantz (1982).

Watershed areas (Table 1) were originally delineated using topographic contours on USGS 1:24,000-scale quadrangle maps. In lower-relief areas, many of the watersheds were re-drawn using stereoscopically viewed 1:15,840-scale color infrared aerial photos Table 1).

2.2 Surface-water quality

Water-quality samples were collected monthly from either January or February 1999 through September 2000 at each of the 14 surface-water monitoring stations in Table 1. The hydrologic conditions during the sampling period varied. The first year (1999) was

Table 1 U.S. Geological Survey surface-water monitoring stations on Mt. Desert Island, Maine, 1999–2000, with watershed areas calculated using topographic maps and aerial photography

Station name	Station number	Latitude	Longitude	Drainage areas, km^2	
				Computed from topographic maps	Computed from aerial photography
Old Mill Brook at Old Norway Drive[1]	01022800	44 23 55	68 17 14	3.91	–
Old Mill Brook below Crooked Rd nr Bar Harbor	01022805	44 24 52	68 17 44	6.13	**6.85**
Stony Brook below Hamilton Pond nr Bar Harbor	01022810	44 25 28	68 17 29	6.73	**7.41**
Aunt Betseys Brook near Bar Harbor	01022815	44 24 22	68 19 10	1.62	**2.02**
French Hill Brook near Bar Harbor	01022817	44 24 23	68 18 44	1.40	**1.30**
Breakneck Brook near Bar Harbor	01022825	44 24 40	68 15 05	3.78	**3.71**
Otter Creek, near Bar Harbor	01022840	44 19 58	68 12 26	**3.50**	–
Hunters Brook near Seal Harbor	01022845	44 18 34	68 13 21	**3.55**	–
Stanley Brook near Seal Harbor	01022850	44 18 20	68 14 35	**3.51**	–
Hadlock Brook at Sargent Dr at Northeast Harbor	01022865	44 18 08	68 17 59	**5.54**	
Kitteredge Brook near Bar Harbor	01022875	44 22 46	68 19 52	7.36	**7.48**
Man of War Brook near Southwest Harbor	01022880	44 19 06	68 19 00	**0.84**	–
Marshall Brook near Southwest Harbor	01022890	44 16 29	68 21 05	5.11	**5.42**
Heath Brook near Tremont	01022895	44 16 40	68 22 05	2.36	**2.77**

[1] Continous streamflow station. The rest are all partial-record stations.

–, Not computed; km^2, square kilometers; nr, near; drainage area values in bold were used for calculating nutrient export rates; datum for latitude and longitude is NAD83.

marked by a relatively dry period from April to August, followed by greater than average precipitation in the fall (Nielsen 2002). During 2000, precipitation was much closer to the measured 19-year average at the Acadia National Park weather station, except for a very wet April (Nielsen 2002). Long-term streamflow data were not available to compare against measured streamflows during the study period.

Samples were analyzed for total N, nitrate (NO_3) (as N), ammonia (NH_3), and total P. Unfiltered grab samples were taken by rinsing the sample bottles three times in the stream water, then filling each directly from the stream. Samples were kept on ice until they were delivered to the laboratory within 12 to 48 h of collection. One 500-ml Nalgene bottle was used for nitrate and ammonia analysis. Nitrate and ammonia samples were filtered through a 0.4-μm polycarbonate filter in the laboratory within 48 h of collection. One 125-ml amber glass bottle was used for the total N and total P analyses. Samples were analyzed at the University of Maine-Orono Mitchell Center for Environmental and Watershed Research. Additional details of field and laboratory methods and the water-quality analyses are given in Nielsen et al. (2002).

3 Estimation of Daily Surface-Water Flows at Partial-Record Sites

Daily streamflows at the continuous-record site (station number 01022800) were computed as described in Rantz (1982). Streamflows at the 13 partial-record sites were calculated using the monthly streamflow measurements and applying a record-extension technique to estimate daily flows. The record-extension technique used is known by several names, including MOVE.1 (Maintenance of Variance-Extension, type 1) or the line of organic correlation (Helsel and Hirsch 1992). Another name is the 'geometric mean functional regression' (Halfon 1985). This technique produces streamflow estimates at a partial-record station with a statistical distribution

similar to that expected if the streamflow had actually been measured (Helsel and Hirsch 1992). Because streamflow data are highly skewed, a $\log_{10}$ transformation commonly is done to linearize the data.

The record extension was used to estimate mean daily flows from April 1, 1999 to Sept. 30, 2000 at each tributary stream. The April starting date was chosen because data collection at the Old Mill Brook streamflow gage began in April 1999. The record-extension technique uses log-transformed streamflow data from the 13 partial-record sites, where individual monthly measurements were made (Fig. 2), and data from one or more continuous-record index stations (Fig. 3). The individual streamflow measurements made at the partial-record sites were compared to the daily mean flows at five index stations–the continuous-record gages on upper Old Mill Brook (station 01022800), Cadillac Brook (01022835), and Upper Hadlock Brook (01022860) (all on Mt. Desert Island); and East Branch Bear Brook (01022294) and West Branch Bear Brook (01022295) (on the mainland). A correlation coefficient (r) was calculated for each index station/partial-record station pair. Correlation coefficients (Table 2) were used to help select which index station(s) to use to estimate daily mean flows for each partial-record station. Plots of the pairs of data also were examined for nonlinearity. Generally, the pairs of data having the best correlations were linear at all but the lowest flows, when flow in the Old Mill Brook gage (01022800) was zero or near zero. Although this was not ideal, it is not expected to affect the loading results significantly because the loads are much more dependent on periods of higher flow rather than periods of low flows. Some of the flow record at the Old Mill Brook gage is estimated because of ice cover. This, also, is not ideal but the errors associated with ice cover are not expected to significantly alter the results. The best-correlated index station was used for each partial-record station. Once the record extension was completed on the log-transformed data, the daily mean streamflows for each stream were retransformed back by taking the inverse log of the initial calculations.

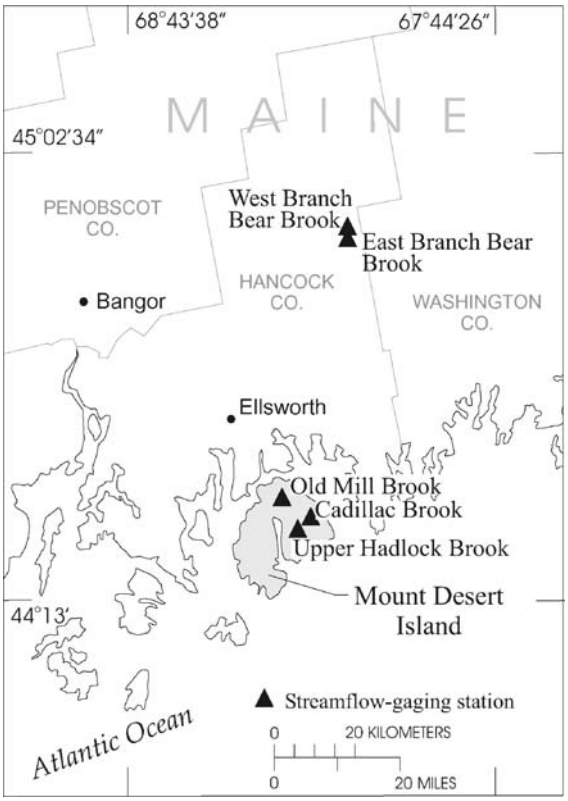

Fig. 3 Location of continuous-record streamflow index stations for MOVE.1 analysis

In some of the streams, this method generally will underpredict the flows, because the continuous streams go to zero flows during dry periods, when the partial-record streams don't. This is because station 01022800, Upper Old Mill Brook, which was used to estimate flows in several streams, has somewhat different storage and ground-water discharge characteristics than the partial-record streams.

4 Computation of Nutrient Export

Nutrient export for the 13 watersheds in the study were calculated using commonly used regression techniques to convert periodic measurements of flow and concentration into estimates of daily flux.

4.1 Water-quality sample data

The monthly water-quality sampling program for the streams resulted in 264 samples, ranging between 13 to 21 samples per site (Table 3). A summary of the concentration data is provided here; for the complete sampling dataset see Nielsen et al. (2002). Station numbers are given in parentheses within the text for reference.

Table 2 Correlation coefficients (r^2) between log-transformed streamflow data at the partial-record stations and the index stations

	Partial-record stations	Index stations (shown on Fig. 3)				
		Cadillac Brook	Upper Hadlock Brook	East Branch Bear Brook	West Branch Bear Brook	Upper Old Mill Brook
01022805	Old Mill Brook below Crooked Rd.	0.66	0.92	0.89	0.85	0.92
01022810	Stony Brook	0.54	0.68	0.88	0.81	0.88
01022815	Aunt Betsey's Brook	0.39	0.68	0.87	0.79	0.95
01022817	French Hill Brook	0.61	0.91	0.96	0.88	0.97
01022825	Breakneck Brook	0.74	0.80	0.86	0.82	0.94
01022840	Otter Creek	0.78	0.86	0.86	0.82	0.90
01022845	Hunters	0.69	0.74	0.77	0.77	0.88
01022850	Stanley Brook	0.61	0.68	0.81	0.78	0.87
01022865	Hadlock Brookat Sargent Drive	0.58	0.68	0.77	0.75	0.85
01022875	Kitteredge Brook	0.78	0.89	0.93	0.90	0.96
01022880	Man of War Brook	0.70	0.86	0.85	0.79	0.86
01022890	Marshall Brook	0.77	0.91	0.88	0.88	0.93
01022895	Heath	0.78	0.89	0.85	0.80	0.94

Nitrate (as N) concentrations ranged from below detection (<0.01 mg/l) to 1.5 mg/l. The lowest overall nitrate concentrations were measured at the Lower Old Mill Brook station (01022805), in which the median concentration was 0.011 mg/l. The highest concentrations of NO_3 were in Marshall (01022890) and Stanley (01022850) Brooks (median concentrations of 0.21 and 0.28 mg/l, respectively). Ammonia (NH_3) concentrations ranged from below detection (<0.05 mg/l) to 0.34 mg/l. Concentrations of NH_3 were below the detection limit in most streams. Marshall Brook (01022890) had the highest median concentration (0.05 mg/l). Total N concentrations ranged from 0.02 to 1.10 mg/l. Otter Creek (01022840) had the lowest total-N concentrations, with a median concentration of 0.09 mg/l. The highest median concentration of total N was 0.61 mg/l in samples from Stony Brook (01022810). Total P concentrations ranged from 1.0 to 56 μg/l. Median concentrations ranged from 3.0 μg/l (Otter Creek, 01022840) to 18 μg/l (Stony Brook, 01022810). The ratio of total N: Total P ranged from 1.8 to 170, with median ratios at the various stations ranging from 25 to 80.

These concentrations are similar to concentrations found in five other Mt. Desert Island streams by Doering et al. (1995). In that study, nitrate–N concentrations ranged from <0.003 to 0.29 mg/l, with mean concentrations from 0.003 to 0.175 mg/l. Ammonia–N concentrations ranged from 0.007 to 0.13 mg/l, with mean concentrations of 0.014 to 0.029 mg/l. Total N concentrations ranged from 0.058 to 0.723 mg/l, with mean concentrations of 0.420 to 0.59 mg/l.

4.2 Estimation of loads

Several methods exist for the computation of surface-water loads to a given waterbody when only discrete samples are available. A regression method known as the rating-curve method (Crawford 1991; Cohn et al. 1989) was used to estimate average loads in this study.

To determine the regression equations for each tributary, loads were computed for each set of measured concentration and streamflow data and then transformed to the natural log of the daily load to normalize the dataset. Natural log of load was the dependent variable. Various combinations of the natural log of streamflow, the square of the natural log of streamflow, time (or julian date), sine (time), and cosine (time) (representing seasonality in the sample data) were tested using an

Table 3 Summary of nutrient concentration data for samples from Mt. Desert Island streams, January 1999 through September 2000

Station number	Stream	Number of samples	Nitrate-N (mg/l)		Total N (mg/l)		Total P (μg/l)		Ammonia (mg/l)		Total N: Total P ratio	
			Range	Median	Range	Median	Range	Median	Range	Median	Range	Median
01022800	Upper Old Mill Brook	20	<0.01–0.31	0.025	0.02–0.33	0.20	2.0–15	4.5	<00.01–0.05	<0.05	2–85	39
01022805	Lower Old Mill Brook	17	<0.01–0.06	0.011	0.19–0.98	0.28	3.0–56	12	<0.05–0.05	<0.05	16–67	31
01022810	Stony Brook	16	<0.01–0.20	0.08	0.31–0.93	0.61	10–22	18	<0.05–0.24	<0.05	23–46	33
01022815	Aunt Betsey's Brook	16	<0.01–0.12	0.05	0.24–0.70	0.41	7.0–40	14	<0.05–0.29	<0.05	12–48	31
01022817	French Hill Brook	13	<0.01–0.09	0.023	0.20–0.50	0.40	6.0–25	11	<0.05–0.11	<0.05	19–44	25
01022825	Breakneck Brook	20	<0.01–0.27	0.10	0.12–0.43	0.18	2.0–14	5.0	<0.01–<0.05	<0.05	14–160	37
01022840	Otter Creek	20	<0.01–0.24	0.02	0.03–0.16	0.09	1.0–11	3.0	<0.01–<0.05	<0.05	15–80	33
01022845	Hunters Brook	20	<0.01–0.24	0.025	0.03–0.20	0.11	2.0–10	4.0	<0.01–0.08	<0.05	7.5–60	28
01022850	Stanley Brook	21	0.09–1.4	0.28	0.27–0.48	0.36	3.0–18	5.0	<0.01–0.11	<0.05	27–150	80
01022865	Lower Hadlock Brook	20	<0.01–.053	0.04	0.03–0.76	0.23	3.0–35	11	<0.01–0.13	<0.05	1.8–77	26
01022875	Kitteredge Brook	21	<0.01–0.23	0.05	0.25–0.98	0.53	6.0–34	11	<0.01–0.09	<0.05	20–71	34
01022880	Man of War Brook	20	<0.01–0.47	0.045	0.11–0.93	0.17	2.0–10	5.0	<0.01–<0.05	<0.05	25–100	37
01022890	Marshall Brook	20	<0.01–1.5	0.21	0.16–0.84	0.50	3.0–19	7.0	<0.01–0.34	0.05	23–170	55
01022895	Heath Brook	20	<0.01–0.23	0.02	0.19–1.1	0.47	3.0–46	7.5	<0.01–0.08	<0.05	24–100	47

N, nitrogen; P, phosphorus; mg/l, milligrams per liter; μg/l, micrograms per liter.

ordinary least-squares regression technique (Helsel and Hirsch 1992) with a log-linear retransformation bias correction to determine the best regression equation at each site (Crawford 1996). Equations were fit individually for each stream using the Aikaike Information Criteria to select the best combination of variables (Helsel and Hirsch 1992). An estimate of the standard deviation in the estimated average load was obtained using the method described by Likes (1980) and Gilroy et al. (1990) and was used to give rough 95% confidence intervals for the estimates at each stream.

A range of regression diagnostics was performed to test the regression assumptions for each constituent in each tributary. Residual plots of concentration against streamflow were analyzed, and nonnormality of the residuals was examined for each constituent with the Turnbull–Weiss Likelihood Ratio Normality Test statistic (Turnbull and Weiss 1978). Residual plots did not exhibit any curvature or other characteristics that would violate the assumptions of the regression method.

The regression equations and the daily flow estimates described earlier were used to estimate average annual and average summertime loads for total N, nitrate–N, ammonia (where possible) and total P for the 13 watersheds. Concentrations of ammonia were below the detection limit in enough samples to violate the conditions of the regression method for most of the sites;

thus the analysis for ammonia could not be applied to all the sites. The standard deviation and number of observations used to estimate each average load were used to calculate the 95% confidence intervals of the prediction as described in Helsel and Hirsch (1992).

5 Results and Discussion

5.1 Nutrient export from watersheds on Mt. Desert Island

The estimated average annual nutrient loads from each stream for 1999–2000 were converted to yield in kilograms per square kilometer per year (kg/km^2/year) by dividing the estimated annual average load by the watershed area. The estimated average summer loads (June–August) for 1999–2000, which represent the growing season, were converted to yields in kilograms per square kilometer per day. Because of the short period of data collection, other seasonal loads were not determined separately. Annual yields (1999–2000) from the 13 watersheds of nitrate–N, total N, and total P from the 13 watersheds are shown in Fig. 4 and Table 4. The 95% confidence intervals for the annual yield estimates also are shown on Fig. 4.

The reliability of the estimates (as expressed by the 95% confidence intervals of the estimated loads) varied widely. The 95% confidence intervals below are presented as a percentage of the estimated value. That is, if the 95% confidence interval for an estimate of 10 was plus or minus 4, it would be expressed as 40%. The estimates of nitrate–N yields were least reliable, because the 95% confidence intervals for nitrate–N ranged from 18% (in station 01022850, Stanley Brook) to more than 1,000% (in station 01022845, Hunters Brook) (Fig. 4). The median of the 95% confidence intervals for nitrate–N was 74% of the yield estimates. The estimates of the total N yields were more reliable. The 95% confidence intervals for total N ranged from 6% (station 01022805, Lower Old Mill Brook) to 45% (station 01022880, Man of War Brook), with a median of 19% (Fig. 4). For total P, the 95% confidence intervals ranged from 10% to 66% of the yield estimates (Fig. 4), with a mean of 35%.

Because of their upland locations, higher altitudes, and lack of human occupation, the streams entirely within Acadia National Park drain watersheds that are considered to be relatively unaffected by nutrient sources associated with human activity, other than atmospheric input. We tested whether this sub-population of the watersheds was different from the others with respect to nutrient export using the exact form of the Wilcoxon rank-sum test. This non-parametric test was used because of the small sample sizes, and the fact that the dataset cannot be assumed to follow a normal distribution. Differences were considered significant if the test showed an attained significance level (p value) of 0.05 or less. If the dominant nutrient sources in the watersheds are related to factors that do not vary inside and outside the Park (for example, atmospheric deposition), there should be no significant differences in the export rate from watersheds inside vs. outside the Park. If, however, the sources of a particular nutrient were from other sources, such as land-based human activity, there should be a significant difference in export from the two groups of watersheds.

5.1.1 Nitrate–N

Nitrate export from watersheds entirely within Acadia National Park [Breakneck Brook (01022825), Otter Creek (01022840), Hunters Brook (01022845), Man of War Brook (01022880), and Heath Brook (01022895)] ranged from 10 to 24 kg/km^2/year (annual) and 0.001 to 0.008 kg/km^2/day (summertime) (Fig. 5, Table 4). Differences in export from these watersheds are attributable to natural variations in landscape features such as soils, amount of wetlands, vegetative cover, interactions with ground water, or modeling errors.

There is much more variability in NO_3 export from watersheds that are partially to completely outside the park boundary. The annual rates range from 11 kg/km^2/year in Aunt Betsey's Brook to 140 kg/km^2/year in Marshall Brook, although most export rates are less than 30 kg/km^2/year. Summertime daily export ranged from 0.003 to 0.1 kg/km^2/day. The watersheds with the highest annual and summer NO_3 export (Marshall, Stony, and Stanley Brooks) have relatively high populations, and there is an unused, capped landfill in the upper reaches of the Marshall Brook watershed. Even with these three high-export watersheds, there was no significant difference in export of NO_3 from the watersheds inside the Park compared to watersheds outside the park for both annual export (p = 0.17) and summer-

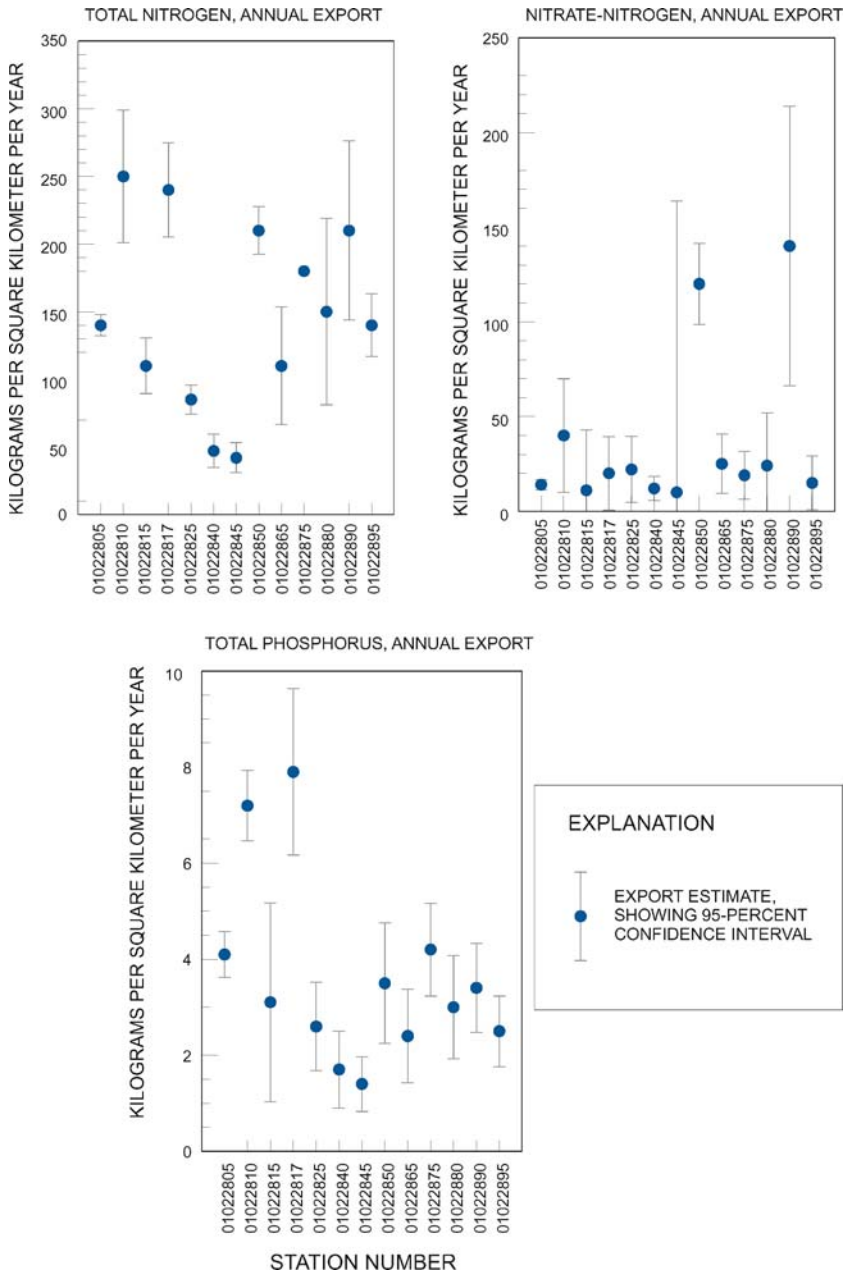

Fig. 4 Estimates of annual nutrient yield for 13 watersheds on Mt. Desert Island, 1999–2000, showing 95% confidence intervals

time export ($p = 0.53$) (Fig. 5). Possible explanations for this may be that the dominant source of NO_3 may be more related to atmospheric deposition than human sources, that the noise in the dataset is greater than a signal from anthropogenic sources, or that some other factor (perhaps related to soils, ground water, or wetlands) is responsible for the differences in NO_3 export among the watersheds.

5.1.2 Ammonia

Data for NH_3 were not sufficiently precise to determine yields of NH_3 from most of the watersheds, so these data are not presented in Table 4. Only three watersheds [Heath Brook (01022895), Marshall Brook (01022890), and Stanley Brook (01022850)] had sufficiently high NH_3 concentrations to determine

Table 4 Annual and summer (June–August) average nutrient export, and additional watershed characteristics from Mt. Desert Island watersheds, 1999–2000

Station number	Watershed	Area (km^2)	1999–2000 Annual average export ($kg/km^2/year$)			1999–2000 Summer average export (June–August) ($kg/km^2/day$)			Percent of water-shed burned	Burn category: burned (B) or unburned (U)
			NO_3–N	Total N	Total P	NO_3–N	Total N	Total P		
Watersheds partially or entirely outside Acadia National Park										
01022810	Stony Brook	7.41	40	250	7.1	0.01	0.1	0.004	61	B
01022815	Aunt Betsey's Brook	2.02	11	110	3.1	0.02	0.03	0.001	52	B
01022817	French Hill Brook	1.30	20	240	7.9	0.004	0.07	0.003	90	B
01022850	Stanley Brook	2.85	120	210	3.5	0.1	0.2	0.002	0	U
01022865	Lower Hadlock Brook	5.54	25	110	2.4	0.005	0.03	0.001	0	U
01022875	Kitteredge Brook	7.48	19	180	4.2	0.003	0.06	0.002	66	B
01022890	Marshall Brook	5.42	140	210	3.4	0.03	0.08	0.003	0	U
01022805	Old Mill Brook	6.85	14	140	4.1	0.003	0.06	0.002	87	B
Watersheds entirely inside Acadia National Park										
01022880	Man of War Brook	0.84	24	150	3.0	0.006	0.02	0.0005	0	U
01022825	Breakneck Brook	3.71	22	85	2.6	0.008	0.02	0.0006	100	B
01022840	Otter Creek	3.50	12	47	1.7	0.005	0.03	0.001	91	B
01022845	Hunters Brook	3.55	10	42	1.4	0.008	0.03	0.001	7	U
01022895	Heath Brook	2.77	15	140	2.5	0.001	0.06	0.001	0	U

km^2, square kilometer; NO_3, nitrate; N, nitrogen; P, phosphorus; $kg/km^2/year$, kilograms per square kilometer per year; $kg/km^2/day$, kilograms per square kilometer per day.

the annual export. Heath Brook, which is entirely within the Park boundary, exported 14 $kg/km^2/year$ (±10 $kg/km^2/year$), roughly equal to the annual NO_3 export. Marshall Brook and Stanley Brook, both of which had relatively high NO_3 and total N export, yielded an estimated 30 (±34) and 17 (±10) $kg/km^2/year$, respectively. These represent a much smaller fraction of the NO_3 export than in Heath Brook. Ammonia was not detected in enough of the samples in the remainder of the streams to calculate export. It is presumed that they had much lower export of NH_3 than the three streams above.

5.1.3 Total nitrogen

Annual total N export ranged from a low of 42 $kg/km^2/year$ in Hunters Brook, to 250 $kg/km^2/year$ in Stony Brook, a smaller relative range than for NO_3. The highest total N export for streams entirely within the Park boundary was 150 $kg/km^2/year$ in Man of War Brook. Four of the watersheds partially or completely outside the Park boundary had yields of total N higher than 200 $kg/km^2/year$. Overall, there was a significant difference in the annual yield between watersheds in and out of the park (p = 0.04) (Fig. 5), although the factors related to these differences are unknown. Summer export from watersheds outside the park also were significantly different than those inside the park (p = 0.048). The relative range (an order of magnitude) of total N export in the summer, however, was greater than the annual range (half of an order of magnitude).

Annual total N export was 2 to 10 times greater than the annual NO_3 export. In watersheds with known land-based NO_3 sources (Stanley Brook, septic systems near streams; Marshall Brook, landfill upstream), half the total N consisted of NO_3. In watersheds with no obvious NO_3 sources and significant wetlands (Aunt Betsey's Brook, Kitteredge Brook, and Heath Brook) NO_3–N accounted for approximately 10% of the total N. Other streams had intermediate ratios of total N: NO_3–N.

5.1.4 Total phosphorus

The range of total P export, from 1.4 to 7.9 $kg/km^2/year$, varies by a factor of 6, similar to the total N values. The streams completely within Acadia National Park

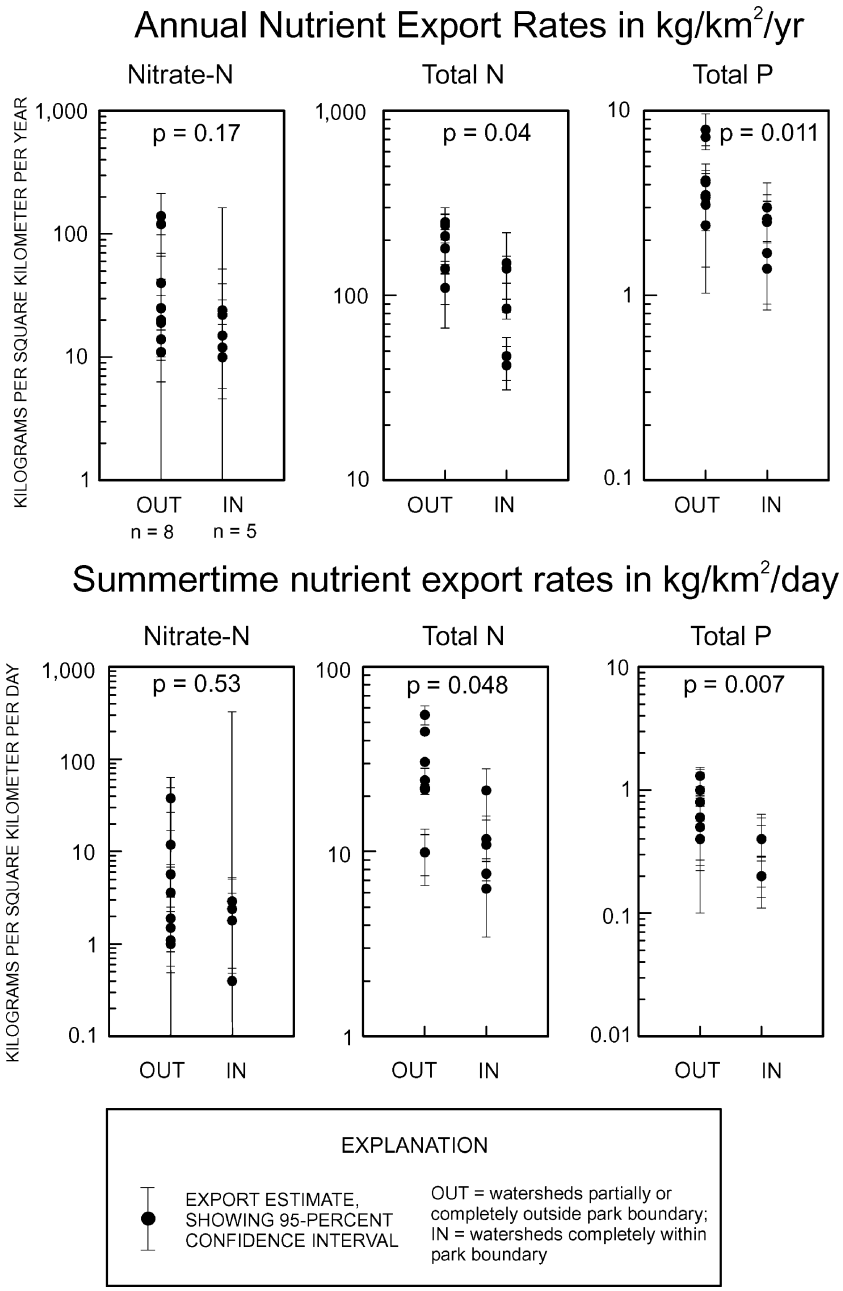

Fig. 5 Nutrient export rates (annual and summertime) for watersheds inside Acadia National Park and watersheds partially or completely outside the park

also had significantly different (lower) total P export than the other streams ($p = 0.011$). The two watersheds with the highest export rates (French Hill Brook and Stony Brook) have shallow ponds just upstream from the sampling points, although it is not known if these are contributing to the higher total P loads from these streams. Summertime total P export ranges from 0.0005 to 0.004 kg/km^2/day, and was significantly different between the two groups ($p = 0.007$). This suggests that total P export may be related to human activity, although the exact relations between different human influences and P export have not been investigated. Typically cited influences on P export (urbanization, industrial land use, agricultural runoff)

are not major factors in these watersheds, so the differences may be because of modest land disturbance and erosion.

5.2 Relation of nutrient loads to burn history

A large part of Mt. Desert Island was consumed by a wildfire during the fall of 1947 (Fig. 1). The fire was reported to have started in the northern part of the island, in the Northeast Creek watershed, and quickly spread south and east towards Bar Harbor. Eventually, approximately 25% of the island was severely burned. Previous data collected as far back as the early 1980s indicated that some of the burned and unburned watersheds at higher altitudes on the island were exporting inorganic N at very different rates (Kahl et al. 1985). Researchers at the University of Maine began a long-term study in 1998 to investigate the hydrologic and ecologic effects of the fires using a paired watershed design (Kahl et al. in press). One burned and one unburned watershed at high altitudes were selected for study (in the upper reaches of the Hadlock and Otter Creek watersheds), and those watersheds have been exporting N at very different rates since the study began. The unburned watershed exports 10 to 20 times more inorganic N than the burned watershed (Nelson et al. in press).

This variation in surface-water export may result from differences in the degree of N saturation (Aber et al. 1998; Stoddard 1994) in each watershed. Nitrogen saturation in forested watersheds occurs when the atmospheric supply outpaces the watershed's internal demand for N. A watershed can absorb atmospheric N only to the extent to which watershed plants and microbes can store or utilize it. Factors that can lead to N saturation in forested watersheds include high rates of N deposition, advanced stand age, and large pools of soil N (Stoddard 1994). The unburned watersheds all have older forests. In the burned watersheds, as the forest recovers from the burn, all the available atmospheric N may be consumed, thus decreasing the yield to streams.

The export rates from the 13 watersheds in this study were grouped according to the percentage of each watershed burned in the 1947 fires. The watersheds range from 0% to 100% burned (Table 4). Based on the amount burned, each watershed was assigned to a 'burned' or 'unburned' category. Plots of nutrient export (nitrate–N, total N, and total P) by burn category show that the unburned watersheds have similar concentrations to the burned watersheds. There does not appear to be any relation between export of total N and total P in these watersheds (Fig. 6), although in the summertime, the burned watersheds may be exporting slightly more total P than the unburned watersheds.

Statistical tests of the nutrient export from burned and unburned watersheds were computed to determine if the burned watersheds on Mt. Desert Island were exporting less N overall than the unburned watersheds, as was measured in the high-altitude paired watersheds. Wilcoxon rank-sum tests were performed for the annual and summer export of NO_3–N, total N, and total P (Fig. 6). Differences were considered significant if the test showed an attained significance level (p value) of 0.05 or less (p values for each test are shown on Fig. 6). There was no apparent relation between NO_3–N, total N, and total P export and the burn histories of the watersheds. This is in contrast to what was found in the smaller, high-altitude paired watersheds.

Additional landscape factors such as vegetation type, type and thickness of soils, riparian processing at the specific sampling sites, and presence or absence of wetlands also play a role in the export of nutrients from watersheds. Although the 13 watersheds in this study are all small (less than 7.5 km^2), are all situated in the same geographic area, and all but one are at least 80% forested (the median amount of forest cover is 88%), variations in these additional factors may be great enough to mask any potential differences in nutrient export that may be attributable to burn history. Although all of the unburned watersheds have older forests, any N saturation that might be occurring in these watersheds (which would increase N export, especially NO_3), is apparently not enough to uniformly increase export to a level that can be distinguished at this level of study. The previously observed differences in N export between high-altitude paired watersheds is not apparent across the wider spectrum of watersheds, because of the complexities of the overall landscape and N transport dynamics. Direct comparisons are complicated by the inability to find watersheds with matching characteristics for slope, soils, and wetland cover. In addition, the number of watersheds studied is relatively small and it may be necessary to study additional watersheds to detect differences related to burn history.

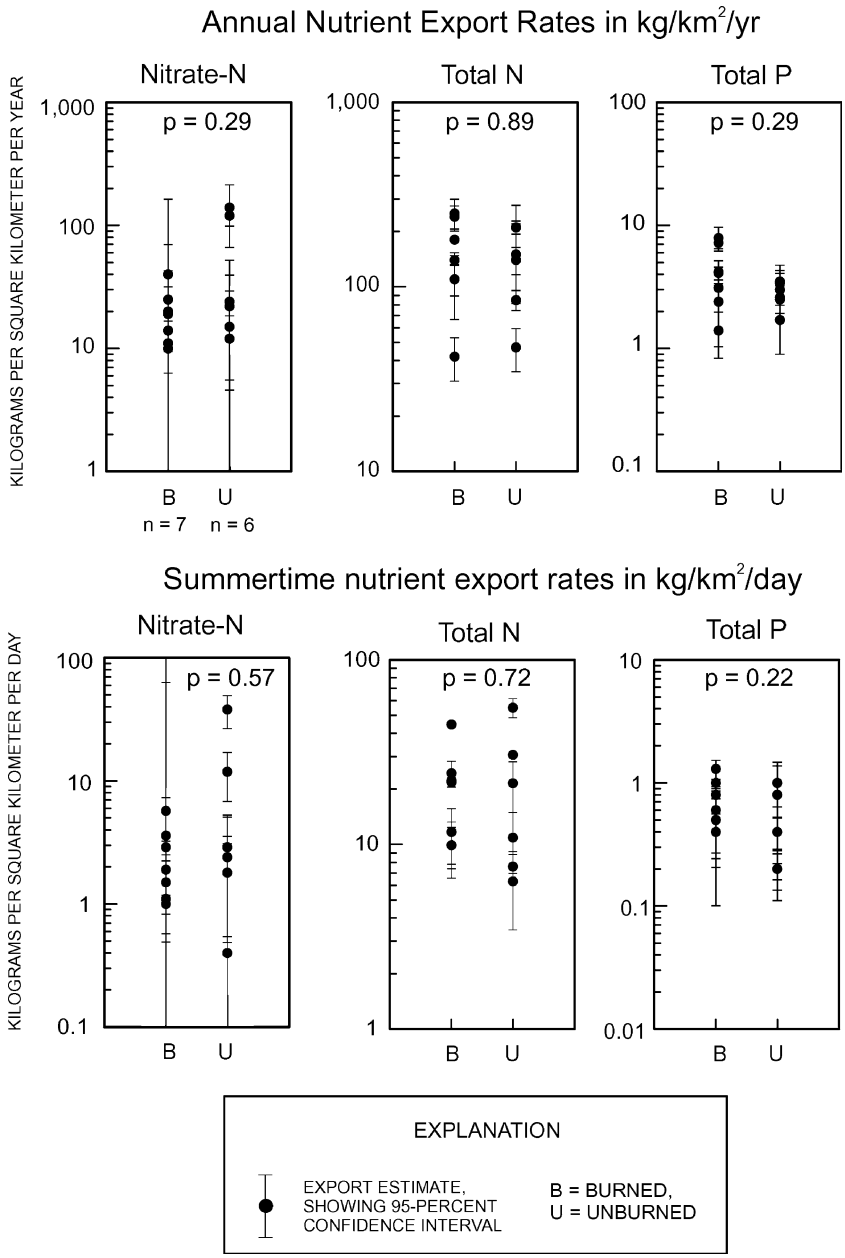

Fig. 6 Nutrient export from streams in burned and unburned parts of Mt. Desert Island, Maine

6 Summary

Nutrient export (expressed as a yield in kg/km^2/year) from 13 small watersheds on Mt. Desert Island, Maine, was estimated from data collected during January 1999 through September 2000. All the streams had relatively low yields of nitrate–N, total N, and total P. Yields from watersheds in the relatively undisturbed areas within Acadia National Park reflect the effects of atmospheric deposition of inorganic N and the lack of land-based sources of total N and total P. Nitrate export from Acadia National Park watersheds ranged from 10 to 24 kg/km^2/year; total N yield in these streams ranged from 42 to 150 kg/km^2/year; and total P yield ranged from 1.4 to 3.0 kg/km^2/year. Ranges in these values probably represent a combination of natural variation due to differences in landscape characteristics such as soils, bedrock and surficial geology, vegetation, amount of wetlands, precipitation patterns, and errors inherent in the calculation of loads.

Yields from the watersheds that are not entirely within the Park boundary were more variable than for the Park watersheds. The yield of nitrate–N in watersheds not entirely within the park ranged from 11 to 140 kg/km^2/year. Although nitrate export in some streams was an order of magnitude higher than in others (possibly because of human point- and nonpoint sources), there was no significant difference in nitrate export between these watersheds and watersheds entirely within the Park (p = 0.17, Wilcoxon rank-sum test). This is interpreted as being related to the predominance of atmospheric input, which does not respect Park boundaries, as the greatest single source of nitrate in the study area.

The export of total N from watersheds outside the park also was highly varied, from 110 to 250 kg/km^2/year. As a group, these export rates were significantly different than the export from the watersheds entirely within the park (p = 0.04). This may be related to land-based human sources of total N in the study area, or there may be another cause, such as the relative amounts of wetlands in the two subsets of watersheds.

Total P export from the watersheds outside the park boundary ranged from 2.4 to 7.9 kg/km^2/year. The export rates for this group also was significantly higher than for the watersheds entirely within the Park (p = 0.011). Although this is interpreted to be related to land-based human sources as the dominant input of total P to the study area, often-cited sources of P (urbanization, industrial land uses, and agricultural runoff) are not present in many of these watersheds.

Although nutrient export in small, high-altitude watersheds on the island was shown to be affected by the 1947 wildfire (Nelson et al. in press), this factor does not appear to be a strong influence on nutrient export for the island as a whole. Many other landscape factors relate to nutrient export, including agricultural land area, population density, road density, soils, wetland areas, geology, site-specific vegetation patterns, etc. These factors could be investigated to determine fully the suite of influences on nutrient export to coastal habitats from watersheds on the island, and to be able to predict which watersheds have the potential to contribute high levels of nutrients to coastal areas.

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