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# Brook Trout Declines with Land Cover and Temperature Changes in Maryland

SCOTT A. STRANKO*
*Maryland Department of Natural Resources, 580 Taylor Avenue, Annapolis, Maryland 21401, USA*

ROBERT H. HILDERBRAND AND RAYMOND P. MORGAN II
*Appalachian Laboratory, Center for Environmental Science, University of Maryland,*
*301 Braddock Road, Frostburg, Maryland 21532, USA*

MARK W. STALEY, ANDREW J. BECKER, AND ANN ROSEBERRY-LINCOLN
*Maryland Department of Natural Resources, 580 Taylor Avenue, Annapolis, Maryland 21401, USA*

ELGIN S. PERRY
*2000 Kings Landing Road, Huntingtown, Maryland 20639, USA*

PAUL T. JACOBSON
*Langhei Ecology, LLC, 14820 View Way Court, Glenelg, Maryland 21737, USA*

*Abstract.*—We examined the influence of landscape alteration and in situ stream habitat variables on brook trout *Salvelinus fontinalis* by using a landscape-scale, space-for-time substitution analysis and a smaller data set that tracked long-term changes in land use over time. Forested land cover within a catchment was the overall best landscape-scale predictor of brook trout occurrence at a given site; measures of impervious land cover and urbanization were also important predictors. Brook trout were almost never found in watersheds where impervious land cover exceeded 4%, as assessed from the 2001 National Land Cover Dataset (2001 NLCD); the single exception was in a stream that displayed consistently low water temperatures. Landscape-scale analyses indicated that increases in water temperature and erosion were associated with increasing percentages of urbanization and imperviousness and decreasing percentage of forested land cover. Three of six brook trout populations that were followed over time were extirpated within the last 15 years (between 1990 and 2005), coinciding with increases in urbanization and impervious land cover. At these sites, water temperatures were substantially greater than at the three sites with extant brook trout. Land use amounts derived from high-resolution aerial photography showed substantially greater amounts of urbanization and particularly impervious land cover than did amounts derived from the 2001 NLCD. The differences in measured land cover between imagery types warrant caution when stating upper threshold limits of land cover, because use of imagery methods interchangeably may produce inconsistent results. Our findings suggest that brook trout are very sensitive to landscape alterations in Maryland and disappear at low levels of impervious land cover regardless of the specific mechanism involved.

Populations near the periphery of a species' geographic distribution may be particularly sensitive to relatively minor anthropogenic perturbations. Brook trout *Salvelinus fontinalis* in the Piedmont physiographic province of Maryland are near the southeastern edge of the species' native distribution. Water temperature is vitally important (Meisner 1990; Raleigh 1982), because brook trout appear to only occupy streams with summer temperatures that remain less than 24°C and they prefer much cooler streams (MacCrimmon and Campbell 1969). In addition, brook trout are found primarily in streams with high-quality physical habitat and limited amounts of silt deposition (Raleigh 1982; Argent and Flebbe 1999; Curry and MacNeill 2004), acidity (Baker and Christensen 1991; Carline et al. 1994), and other anthropogenic stressors.

Declines in brook trout distribution and abundance have frequently been attributed to the degradation of streams' physical and chemical habitat conditions resulting from landscape alterations, such as forest clearing and agriculture. MacCrimmon and Campbell (1969) attributed reductions in the original range of brook trout through the late 1960s to pollution, siltation, and stream warming associated with logging. Hudy et al. (2005) cited agriculture as the most widely

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* Corresponding author: sstranko@dnr.state.md.us

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distributed factor causing negative effects on brook trout across the eastern range of the species. Booth et al. (2002) found that forest cover loss was the most important factor degrading streams and that low levels of development and forest clearing are sufficient to substantially alter hydrological and biological stream conditions.

Recent brook trout declines and extirpations from many central Maryland streams appear to be correlated with relatively minor amounts (<2%) of total impervious land cover (Boward et al. 1999; Morgan et al. 2004) within a watershed. Impervious land cover is frequently used as an indicator of human disturbance (primarily as related to urbanization) and is correlated with increases in stream temperature (Klein 1979; Galli 1991; Schueler 1994), sediment (Wolman and Schick 1967; Fox 1974; Swarts et al. 1978), and habitat instability (May et al. 1997; Booth and Jackson 1997) relative to streams in undeveloped areas.

Threshold values at which impervious land cover negatively affects stream biota have been widely reported. Total impervious cover of 10–15% in a stream catchment has most often been reported as the threshold for maintaining biological integrity (Klein 1979; Luchetti and Furstenberg 1993; Wang et al. 2001). According to Schueler (1994), declines in spawning success of brown trout *Salmo trutta* were evident above 10% total impervious land cover in a catchment. However, certain sensitive biota may be eradicated from streams when total impervious land cover exceeds 5% (Yoder et al. 2000; Angermeier et al. 2004; Southerland et al. 2005) and possibly when impervious cover is as low as 3% (Booth and Jackson 1997). Populations living near the edges of a species' geographic distribution may be affected at even lower levels of human disturbance. Overall, correlations between stream ecological conditions and imperviousness are likely to be region, watershed, and species specific and may depend on other landscape factors, such as soil type and forested land cover (Booth et al. 2002).

Correlations between ecological conditions and landscape alterations typically employ spatial analyses rather than assessing changes over time. Although such space-for-time substitutions identify probable patterns, long-term monitoring of brook trout numbers and changes in landscape factors would build a strong case for the progressive effects of landscape disturbance.

The Maryland Department of Natural Resources (MDDNR) Fisheries Service has collected quantitative data on brook trout distribution and abundance for over 30 years (Stinefelt et al. 1985). During this time, brook trout numbers have declined precipitously in many streams and the species has disappeared completely from several streams in the rapidly developing Baltimore metropolitan area. Our goals were to (1) determine whether brook trout declines and disappearance over time in several Baltimore-area streams were correlated with landscape alterations and (2) compare results from space-for-time substitutions with temporal results as brook trout numbers declined.

## Methods

*Analysis of temporal trends.*—We analyzed temporal trends in brook trout density within six streams in the Baltimore metropolitan area by using data from the MDDNR Fisheries Service. The streams included Baisman, Goodwin, Timber, and Red runs; Sawmill Branch; and Stillwater Creek. All are situated in the eastern Piedmont and have the same general underlying geology (metamorphosed clastic sedimentary rocks; McCartan et al. 1998).

Brook trout sampling in the six streams occurred as early as 1972, and all streams were sampled during 2005. However, sampling years varied substantially among streams. All temporal trend sites were sampled for brook trout at least nine times over the last 35 years. Brook trout were collected by backpack electrofishing, but differences in the number of electrofishing passes over the 30 years of sampling prompted us to use only the first electrofishing pass to allow data comparability. Section length and average stream width were measured at each site to determine brook trout density.

Using ArcMap 9.1 software (ESRI 2005), we hand digitized the catchment upstream from each sampling site based on U.S. Geological Survey (USGS) quarter quad topographic lines. Aerial photographs for the six stream catchments were acquired to match as closely as possible to sampling periods. Sources for aerial photography included the MDDNR, Maryland Department of Planning, Baltimore County Office of Planning, Baltimore County Natural Resources Conservation Service, and purchases from private companies. All of the aerial photographs were of sufficient resolution to allow discrimination among landscape features, such as roads, parking lots, driveways, rooftops, farm fields, and forests.

After the georeferencing of each aerial photograph, the catchment boundary was overlaid and forest, agricultural areas, developed areas, and specific impervious features were hand digitized within the catchment boundaries and within a 100-m buffer surrounding all streams in the catchment. For all years with available aerial photographs, the percentages of land area consisting of agriculture, forest, development, and impervious features were calculated from the hand-digitized information for the stream buffer and for the entire catchment.

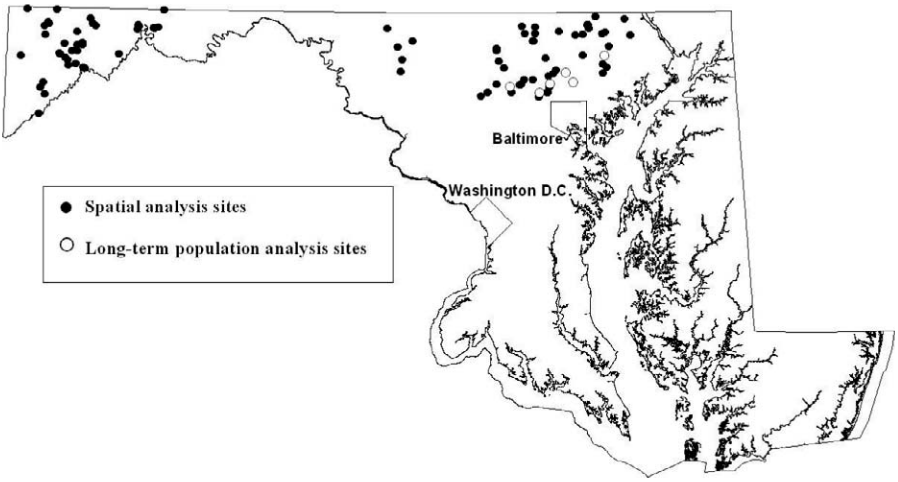

FIGURE 1.—Map of site locations used for long-term population analysis (open circles) and spatial analysis (shaded circles) of Maryland brook trout populations.

Satellite-derived land cover (based on 30-m pixel summaries) for all catchments was calculated from the 2001 National Land Cover Dataset (2001 NLCD; Homer et al. 2007). The 2001 NLCD provided an opportunity to compare land cover results estimated from high-resolution aerial photographs with estimates from the 30-m-resolution satellite data. Land cover percentage estimates for temporal trend sites reported in the Results are from aerial photos unless otherwise specified.

In situ habitat data were collected only during 2005 at five of the six streams for which temporal trend data existed; Sawmill Branch was excluded because continuous temperature data were not available. Habitat characteristics were evaluated using Maryland Biological Stream Survey (MBSS) protocols (Kazyak 2001) and included continuous temperature, site temperature coincident with brook trout sampling, riffle embeddedness, bank erosion, instream habitat structure, and pool and riffle quality. During July through August, continuous stream water temperatures were recorded every 20 min by use of Hobo temperature loggers. Temperature logger data were summarized by calculating the mean, maximum, mean average daily, and mean maximum daily temperatures and the proportion of readings exceeding 20, 22, and 24°C. The percentage of riffle habitat embedded with fine sediment (riffle embeddedness) was recorded based on a visual estimation of the percentage of gravel and larger substrates that were surrounded by fine sediment. Instream habitat structure (scale = 0–20), pool quality (0–20), riffle quality (0–20), and eroded bank area were rated by experienced MBSS personnel using a well-defined visual assessment protocol that included extensive quality controls (see Kazyak [2001] for a detailed description of the quality control procedures). Eroded bank area (hereafter, erosion) was estimated based on the linear extent and average height of both banks (left and right) that were eroded within a 75-m section of stream.

*Analysis of spatial trends*.—Data were examined for potential spatial trends and a space-for-time substitution using a total of 286 sites (Figure 1). These data represent one-time, unrepeated samples that were drawn from a subset of the 1995–2004 MBSS data. Sites were separated into two groups: 151 sites where brook trout were collected and where no known brook trout stocking event had occurred within the previous 35 years; and 135 sites where brook trout were expected to occur but nevertheless were absent. The sites where brook trout were expected to occur were identified using a hierarchical screening approach (Stranko et al. 2005) to determine suitable brook trout habitat conditions based on nine stream variables that are not typically affected by human influences: major river basin, physiography, catchment size, altitude, stream gradient, dissolved organic carbon, stream width, thalweg depth, and discharge. Catchment size was determined from the hand-digitized catchments for each site, whereas site altitude was taken from USGS topographic maps. Stream gradient, dissolved organic carbon, stream width, thalweg depth, and discharge were calculated based on measurements taken concurrently with brook trout sampling during summer base flow conditions. Stream gradient was measured over 75 m. Dissolved organic carbon was based on a grab

TABLE 1.—Land cover percentages determined by hand digitization of high-resolution aerial photographs (photo) or derived from 30-m-resolution satellite data (satellite; 2001 National Land Cover Dataset; Homer et al. 2007) for six Maryland streams. Aerial photographs from 2001 were not available; therefore, estimates from the years closest to 2001 were used.

| | Forest | | Agriculture | | Developed | | Impervious | |
|---|---|---|---|---|---|---|---|---|
| Stream | Photo | Satellite | Photo | Satellite | Photo | Satellite | Photo | Satellite |
| Goodwin Run[a] | 62 | 65 | 0 | 0 | 38 | 34 | 25 | 18 |
| Baisman Run[b] | 76 | 75 | 14 | 23 | 10 | 1 | 4 | <1 |
| Timber Run[c] | 73 | 75 | 17 | 25 | 10 | 1 | 3 | <1 |
| Sawmill Branch[d] | 55 | 56 | 9 | 14 | 36 | 30 | 6 | 1 |
| Red Run[d] | 48 | 53 | 8 | 10 | 44 | 37 | 10 | 5 |
| Stillwater Creek[d] | 23 | 19 | 7 | 16 | 69 | 64 | 41 | 14 |

[a] Aerial photographs were from 1999.
[b] Aerial photographs were from 2000.
[c] Aerial photographs were from 2002.
[d] Aerial photographs were from 1998.

sample of water that was sent to the laboratory for analysis. Stream width and thalweg depth were averages of four wetted-extent measurements taken at 25-m intervals throughout the 75-m-long site. Discharge was calculated using the USGS method (Rantz 1982).

For all 286 spatial trend sites, forested, agricultural, developed, and impervious land cover percentages were extracted from the 2001 NLCD. Land cover estimates were determined for a 100-m buffer along all streams within each catchment as well as for the entire catchment. Due to the large number of sites in the spatial trend data set, we could not hand digitize the aerial photographs but instead relied on the 2001 NLCD. In situ habitat variables were available for 116 of the 286 spatial trend sites: 81 sites where brook trout were present and 35 sites where brook trout were expected but absent. Habitat information was collected as described for temporal trends.

Statistical analyses were conducted using all sites for which data were available (286 sites for landscape data; 116 sites for in situ habitat data). We used nonmetric multidimensional scaling (NMS) to explore correlations between brook trout presence and landscape or in situ variables. Logistic regression was used to determine the best predictors of brook trout presence from land use data.

## Results

The percentages of forested, agricultural, developed, and impervious land cover estimated from the satellite-based 2001 NLCD were different from those estimated using high-resolution aerial photography (Table 1). Forested land cover estimates displayed the greatest similarity between the two methods. Agriculture estimates were consistently higher and developed estimates were consistently lower for aerial photography than for the 2001 NLCD; estimates differed by as much as 9%. The most dramatic disparity between estimates from the two methods was observed for impervious land cover. Satellite-derived estimates were consistently lower than the aerial photograph-derived estimates; at four of six sites, impervious land cover estimates based on the 2001 NLCD were not more than one-third of the hand-drawn estimates from aerial photographs. Within Timber Run, Baisman Run, and Sawmill Branch, catchment features such as houses, driveways, and roads were obvious on aerial photographs and accounted for as much as 6% impervious land cover, but little to no developed or impervious land cover (1% or less) was estimated from the 2001 NLCD. Developed and impervious land cover percentages were highly correlated ($r = 0.96$ from the 2001 NLCD), but results for both land use measures are included here because impervious features were often present in areas where land cover was predominately agriculture or forest; thus, both developed and impervious land cover percentages were important in analyses.

### *Space-for-Time Substitution Analysis*

Our landscape-scale analyses showed that brook trout occurred in areas of low stream temperature, low erosion, high forestation, low agriculture, and low impervious land cover (Figure 2). Axis 1 of the NMS ordination of habitat variables represented a disturbance gradient running from forest ($r = -0.41$) to human-altered attributes, such as the proportion of stream temperature readings exceeding 20°C ($r = 0.90$), mean stream temperature ($r = 0.85$), and maximum stream temperature ($r = 0.83$). Other variables that were significantly associated with axis 1 included stream temperatures exceeding 22°C ($r = 0.69$) and impervious land cover ($r = 0.50$). Axis 2 formed a land use gradient running from agricultural ($r = -0.83$) to forested ($r = 0.84$) sites. Correlations with NMS axes

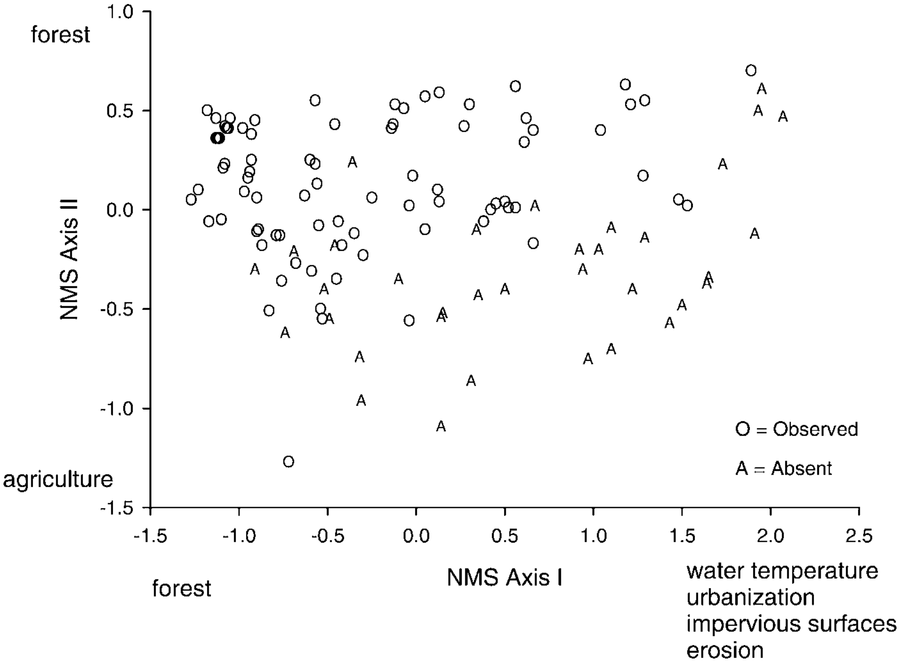

FIGURE 2.—Nonmetric multidimensional scaling (NMS) ordination of habitat variables at sites in Maryland where brook trout were either observed (O) or absent but predicted to be present (A). Habitat variables that were significantly associated with axis scores are listed by each axis.

were slightly weaker for land use within the stream buffer than for land use in the entire catchment.

Lack of disturbed land cover substantially influenced the likelihood of brook trout presence. Brook trout were never observed in streams with catchments exceeding 4% impervious land cover in the 2001 NLCD (Figure 3). For every 1% increase in impervious land cover within a catchment, the odds of brook trout presence decreased by 0.599; brook trout were predicted to be absent from watersheds where impervious cover exceeded 3.3% (logistic regression: intercept = 1.689, estimate = –0.513, $P = 0.002$, odds ratio confidence interval = 0.43–0.83). The best-competing logistic regression models for predicting brook trout presence from land use data always included forested cover in the catchment and either developed land cover in the stream buffer or impervious land cover in the catchment.

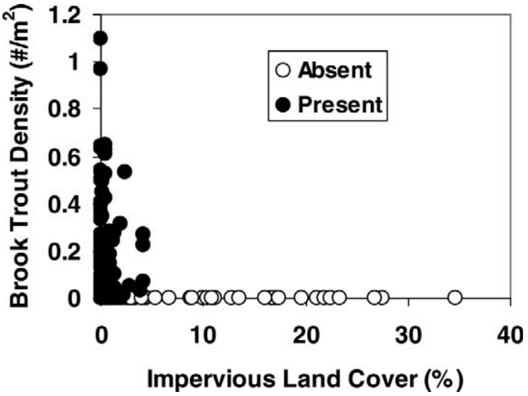

FIGURE 3.—Relationship between brook trout density (fish/m²) and percentage of impervious land cover in Maryland stream catchments where the species was present and sites where the species was expected but absent.

### *Temporal Data*

Although we observed substantial variability in brook trout density among the six temporal sites (Figure 4), the trend at each site was a decrease in brook trout density as forested land cover decreased and impervious land cover increased. Correlations between agricultural land cover and brook trout density over time could not be examined because agriculture was less than 30% at all sites and all years and either decreased or stayed the same at all sites over time.

Based on estimates taken from aerial photographs, forested land cover coincident with brook trout disappearances ranged from 50% in Red Run to 73% in Timber Run; brook trout were present in three of the streams where forested land cover was less than 60% (Sawmill Branch, Red Run, and Stillwater Creek). The

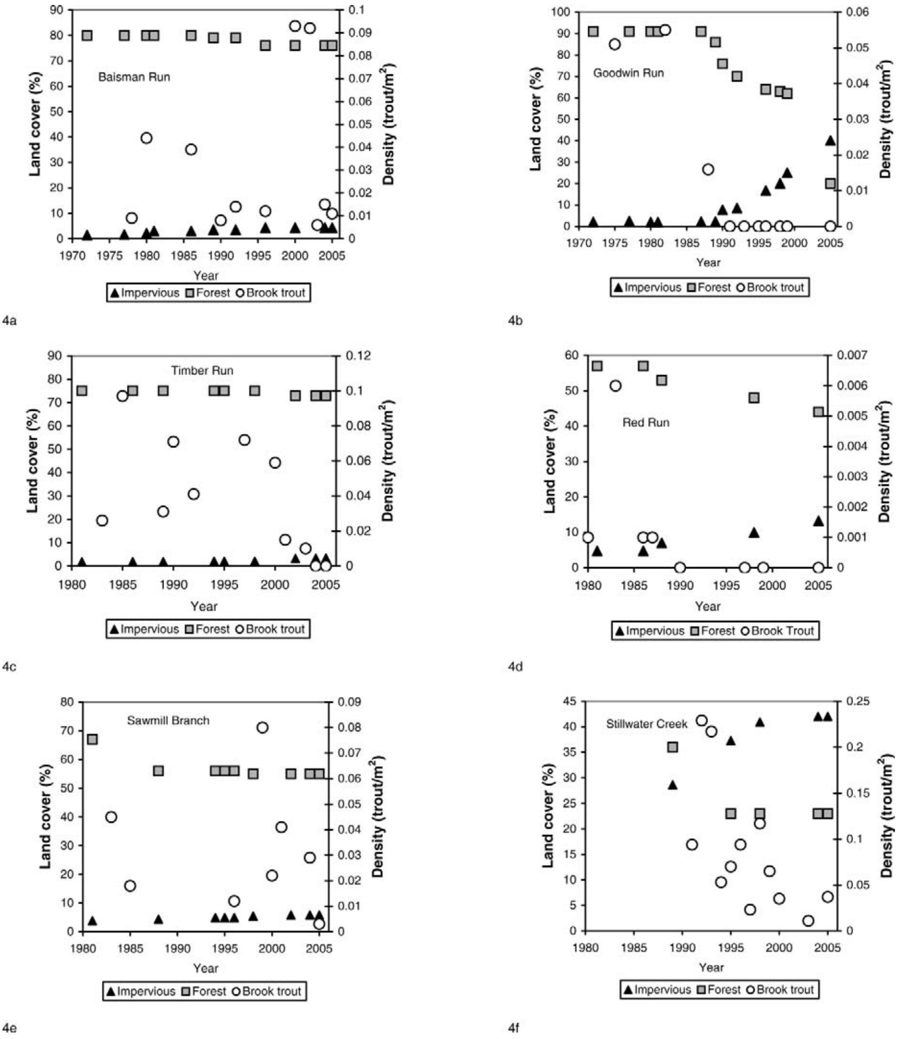

FIGURE 4.—Brook trout density (fish/$m^2$; open circles) in relation to forested (gray squares) and impervious (black triangles) land cover percentages over time in six Maryland streams: (**a**) Baisman Run, (**b**) Goodwin Run, (**c**) Red Run, (**d**) Timber Run, (**e**) Sawmill Branch, and (**f**) Stillwater Creek.

disappearance of brook trout from three of the streams analyzed for temporal trends was coincident with relatively low levels of impervious land cover (as little as 3% in Timber Run during 2004 and as much as 8% in Goodwin Run during 1990). Brook trout remained at relatively low densities in Sawmill Branch (0.003 fish/$m^2$), where impervious land cover was 6%, and in Baisman Run (0.005 fish/$m^2$), where impervious land cover was 4%.

The disappearance of brook trout at low percentages of impervious land cover did not occur in Stillwater Creek (Carroll County). Although density declined over time in Stillwater Creek, brook trout persisted despite impervious land cover percentage estimates in excess of 40% (as estimated from aerial photography). Moreover, forested land cover has been less than 25% since 1995. Based on the extensive spatial and temporal data examined by MDDNR in the Piedmont and Highlands regions (over 1,500 streams sampled), no other Maryland stream has higher amounts of urbanization while still retaining a native population of brook trout. Additionally, very few other streams retained brook trout when forested land cover was less than 25%.

Temperature was the only habitat variable that differed between temporal trend sites with extant brook trout and those where brook trout were extirpated (Table 2). All temperature measures taken at sites with

TABLE 2.—Land cover percentages determined by hand digitization of high-resolution aerial photographs and values of in situ habitat variables measured in 2005 for six Maryland streams (asterisks indicate streams with extant brook trout populations; brook trout were extirpated from the remaining streams). Continuous temperature data were not available for Sawmill Branch.

| Variable | Goodwin Run | Baisman Run* | Red Run | Timber Run | Sawmill Branch* | Stillwater Creek* |
|---|---|---|---|---|---|---|
| Forested land cover (%) | 20 | 76 | 44 | 73 | 55 | 23 |
| Agricultural land cover (%) | 0 | 14 | 4 | 17 | 9 | 5 |
| Developed land cover (%) | 80 | 10 | 52 | 10 | 36 | 72 |
| Impervious land cover (%) | 40.0 | 4.0 | 13.0 | 3.0 | 6.0 | 42.0 |
| Instream habitat (scale of 0–20) | 14 | 18 | 15 | 16 | 15 | 16 |
| Erosion ($m^2$) | 38 | 0 | 28 | 72 | 17 | 70 |
| Pool quality (0–20) | 11 | 16 | 15 | 14 | 8 | 10 |
| Riffle quality (0–20) | 13 | 12 | 13 | 14 | 11 | 12 |
| Riffle embeddedness (%) | 35 | 15 | 30 | 25 | 30 | 20 |
| Proportion of temperatures > 20°C | 0.424 | <0.001 | 0.758 | 0.573 | - | 0.011 |
| Proportion of temperatures > 22°C | 0.088 | 0.000 | 0.292 | 0.206 | - | 0.002 |
| Proportion of temperatures > 24°C | 0.003 | 0.000 | 0.043 | 0.052 | - | <0.001 |
| Mean temperature (°C) | 20.0 | 15.7 | 21.0 | 20.2 | - | 16.2 |
| Maximum temperature (°C) | 26.0 | 20.1 | 25.4 | 26.8 | - | 24.9 |
| Mean average daily temperature (°C) | 20.0 | 15.7 | 21.0 | 20.2 | - | 16.2 |
| Mean maximum daily temperature (°C) | 21.1 | 16.2 | 22.9 | 22.0 | - | 17.7 |

extant brook trout were substantially lower than those at sites where brook trout were extirpated. In the two streams with continuous temperature data and extant brook trout in 2005, the proportion of summer temperatures exceeding 20°C was 0.011 or less, whereas the three streams without brook trout had much higher proportions (0.424–0.758). None of the other in situ habitat variables measured during 2005 at the temporal trend sites showed any discernable pattern related to the presence or absence of brook trout.

## Discussion

Our findings support the idea that landscape-scale factors can substantially influence brook trout distributions (Wiley et al. 1997**;** Bulger et al. 2000; Booth et al. 2002; Kacovsky and Carline 2006). Although brook trout could be found at all levels of forested cover, most sites with relatively large forested proportions in their catchments had high numbers of brook trout, whereas few sites with little or no forest maintained brook trout. Brook trout occurrence and density at landscape scales exhibited strong negative correlations with impervious land cover but the correlations with forested land cover were even stronger. However, with one exception, brook trout were not found at sites with more than 4% impervious cover in the watershed.

Forest clearing and urbanization often result in increased water temperatures (Klein 1979; Rishel et al. 1982; Beschta and Taylor 1988; Johnson and Jones 2000; Paul and Meyer 2001), which have negative effects on brook trout (MacCrimmon and Campbell 1969; McCormick et al. 1972; Magoulick and Wilzbach 1998). Although our analyses cannot determine specific mechanisms of stream change, increased water temperatures were strongly associated with human alteration of land cover and increases in the impervious land cover percentage. Stillwater Creek, the only watershed where brook trout continued to persist despite increases in human development, maintained stream temperatures similar to heavily forested sites. We speculate that the substantial inputs of groundwater due to abundant surrounding wetlands in the catchment mediated the stream temperature increases typically associated with increases in the amount of area covered by impervious surfaces. Groundwater seepage has been implicated in similar situations elsewhere (Wiley et al. 1997; Steffy et al. 2004).

Coupling a large-scale, space-for-time substitution analysis with in-depth, long-term monitoring allowed us to more rigorously identify the importance of land conversion for brook trout populations. Large-scale analyses provided correlational evidence of factors influencing brook trout. However, by examining a subset of populations through time, we were able to better document land use levels at which brook trout were affected and to determine why Stillwater Creek brook trout remained resilient to human development in the watershed.

Our analyses indicate an upper limit of landscape modification: brook trout no longer occur in catchments exceeding 4% impervious land cover in the 2001 NLCD. Stillwater Creek is the only population to exist in a catchment exceeding the threshold. We acknowledge that certain factors (e.g., a modified hydrologic regime; Booth et al. 2002) other than those examined here may also be correlated with this relatively minor degree of landscape alteration and with brook trout loss. However, regardless of the exact mechanisms eliminating brook trout above this upper limit, the pattern appears to be real and it implies extreme sensitivity of brook trout to low levels of human disturbance. Although variable, brook trout density tended to decrease with increasing impervious land cover up to the threshold. Therefore, development below the upper limit may still have negative effects on the long-term persistence of populations. Few management alternatives are available for maintaining brook trout populations in Maryland watersheds that exceed the impervious land cover threshold.

Impervious surface estimates generated from aerial photographs were consistently higher than those from the 2001 NLCD. The results indicate that (1) relatively small impervious land cover features on the landscape are missed when using data sets of coarser resolution and (2) high-resolution aerial photographs are necessary to generate the most accurate estimates. Such differences help to explain why our landscape-level analysis identified the low threshold resulting in brook trout absence. Even with major differences between land cover estimates, very low impervious land cover amounts were associated with brook trout declines and absence in long-term monitoring sites. Because the amount of effective impervious land cover is lower still (Alley and Veenhuis 1983; Sutherland 1995; LeBlanc et al. 1997), deleterious effects associated with impervious surfaces seem to occur at very low levels of development. The measurement differences also highlight an important point: when assessing the effects of land use, the scale of observation will determine the result. Management recommendations for maximum allowable impervious surfaces could be grossly exceeded if the NLCD is used in place of high-resolution aerial imagery to measure impervious land cover percentages.

Brook trout populations have been disappearing from many central Maryland streams over the last 30 years. From 1970 to 2000, the human population in Maryland increased from $3.9 \times 10^6$ to $5.3 \times 10^6$, and the population is projected to reach $6.3 \times 10^6$ in 2025. Population growth has resulted in substantial landscape alterations in rural areas surrounding Baltimore and Washington, D.C. Such alterations may severely threaten many of Maryland's remaining brook trout populations. Maintaining forests and substantially limiting development are probably the most effective strategies for ensuring persistence of extant populations in Maryland watersheds.

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