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Authors: Hilderbrand, Robert H., Utz, Ryan M., Stranko, Scott A., and Raesly, Richard L.

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Applying thresholds to forecast potential biodiversity loss from human development

Robert H. Hilderbrand[1] AND Ryan M. Utz[2]
Appalachian Laboratory, University of Maryland Center for Environmental Science, Frostburg, Maryland 21532 USA

Scott A. Stranko[3]
Monitoring and Nontidal Assessment Division, Maryland Department of Natural Resources, Annapolis, Maryland 21401 USA

Richard L. Raesly[4]
Department of Biology, Frostburg State University, Frostburg, Maryland 21532 USA

Abstract. Ecological thresholds have much potential as a tool to use for watershed management. Not all systems exhibit abrupt nonlinear responses, but the threshold concept is still useful for describing stressor responses or changes in state variables. For example, the minimum detectable negative response is an initiation-of-impact threshold that might allow for planning and management before population-scale change occurs in taxa. An extirpation threshold, which is the point where a system loses a vital component, such as a species or function, also exists. A number of taxon-specific thresholds to landuse change in watersheds have been identified in previous research. We apply these values to make watershed-level and spatially explicit forecasts regarding imperilment and loss of biodiversity in the face of watershed alterations. We show that unchecked development in the Potapsco River watershed of Maryland could result in the loss of nearly 60% of the benthic macroinvertebrate taxa by the time impervious surface cover reaches 15% of the watershed. Application of analytical thresholds to projected increases in residential development in the Middle Patuxent River watershed by 2030 indicates substantial future changes in aquatic biodiversity, with up to 50% of benthic macroinvertebrate taxa disappearing from some stream reaches and few reaches immune from projected biodiversity loss or impairment.

Key words: ecological thresholds, benthic macroinvertebrates, urbanization, land cover change, impervious surface.

The ability to forecast loss of biodiversity as human activities alter watersheds would be invaluable to planners and managers. Substantial evidence indicates that land cover conversion to various forms of urban use negatively affects many freshwater taxa (Meador et al. 2005, Roy et al. 2005, Stranko et al. 2008) and entire communities (Kennen 1999, Blakely et al. 2006, Smith and Lamp 2008). General rules of thumb exist for levels of impervious surface cover (ISC) that are associated with stream degradation (e.g., loss of biological integrity beyond 10% ISC in the watershed; reviewed by Schueler et al. 2009), but few more explicit relationships between ISC and taxon declines have been developed. Such information could help planners and managers limit further stream degradation in the face of projected human population expansion.

Ecological thresholds hold much promise as a management tool because their identification might allow preemptive actions to prevent a system from moving to an alternate state. However, a lack of

[1] Email addresses: hilderbrand@al.umces.edu

[2] Present address: Department of Ecology, Evolution and Marine Biology, University of California-Santa Barbara, Santa Barbara, California 93106 USA. E-mail: utz@lifesci.ucsb.edu

[3] sstranko@dnr.state.md.us

[4] rraesly@frostburg.edu

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evidence for abrupt nonlinear responses has led some to question if thresholds actually exist in stream ecosystems (Groffman et al. 2006, but see papers by Clements et al. 2010, Dodds et al. 2010, Gido et al. 2010, King and Baker 2010). Not all systems exhibit abrupt nonlinear responses, but the threshold concept is still valuable for describing responses to stressors or changes in state variables. For example, the point at which a stressor begins to affect an organism negatively (the minimum detectable response) is an initiation-of-impact threshold that could be used to trigger planning and management actions before population-scale change occurred. At the other end of detectable responses is the extirpation threshold—the point at which the system loses a vital structural or functional component, such as a species. Such analytical thresholds, if detectable in large data sets, could have useful applications and would provide evidence for the occurrence of ecological thresholds.

Our goal was to use data that might represent ecological thresholds for stream invertebrates to forecast potential loss of biodiversity in an area likely to experience substantial future landuse change. Utz et al. (2009) provided an extensive catalog of benthic invertebrate response thresholds to differing forms of land-cover change in Maryland watersheds. These relationships are suitable for use in forecasting losses of specific taxa and biodiversity. Our objectives were to: 1) assess potential biodiversity losses at the landscape-scale across 15 of the major basins of Maryland (listed in Heimbuch et al. 1999) along an ISC gradient and 2) generate spatially explicit forecasts of biodiversity losses given projected future residential development by 2030 (Theobald 2005) throughout a 150-km^2 watershed.

Methods

We determined responses of benthic macroinvertebrate taxa to human-created impervious surfaces in the upstream watershed by comparing cumulative frequency distributions (CFD) of observed vs expected occurrences for each individual taxon. The approach is detailed in Utz et al. (2009), where a full catalog of taxon responses to ISC, urbanization, and agriculture based on the 2001 National Land Cover Dataset (NLCD; USGS 2004) can be found in the appendices. Utz et al. (2009) used the Maryland Biological Stream Survey (MBSS) data set encompassing >2300 benthic invertebrate samples identified mostly to genus and containing relative abundance information to calculate expected responses to ISC. Because of the subsampling protocol used by MBSS for benthic samples, we based our analyses on presence/absence data for 180 taxa to determine if the distribution of a taxon was negatively associated with increasing amounts of watershed-scale ISC or urban cover (2 separate analyses). We considered a taxon unaffected if its observed CFD curve was not significantly different from the expected distribution across the ISC gradient. For those taxa negatively associated with ISC, we calculated the 95th percentile (T_{95}) of ISC for taxon occurrence. This T_{95} of ISC for a taxon's observed distribution estimated the point at which the taxon was effectively lost from the landscape. In addition, we calculated the point at which the observed and expected CFD curves departed by $\geq$1% and remained apart (D_1). D_1 is akin to a minimum detection limit in chemistry and represents the amount of ISC at which a detectable negative effect on a taxon's distribution occurs. As discussed in Utz et al. (2009), locations of these upper and lower thresholds can be altered to suit one's comfort with uncertainty. For example, a more conservative minimum detection threshold, such as 5% (D_5), departure of observed and expected curves could be used to allow for uncertainty in the data set when using values for planning purposes.

We used a Monte Carlo technique to quantify the uncertainties associated with analytical thresholds. For each sensitive taxon, we randomly withheld 25% of the occurrence data and, independently, 25% of the expected data distribution for each of 1000 runs. T_{95} and D_1, and their averages and 95% confidence intervals were calculated for each run. For any runs in which the distribution of a sensitive taxon did not differ from the expected distribution, we assigned T_{95} and D_1 values equal to the maximum ISC value in the expected data distribution.

We applied the threshold information for each taxon to derive taxon loss curves across the ISC gradient for each of the 15 major watersheds in Piedmont and Coastal Plain physiographic provinces of Maryland (Table 1). Six of these watersheds occur exclusively on the Coastal Plain, 3 occur exclusively in the Piedmont, and the remaining 6 occur across both provinces. The major watersheds range in size from 552 km^2 (Bush River) to 2926 km^2 (Lower Potomac River). We included taxa in estimates for a major basin only if they were collected within that specific major basin. ISC and urbanization are highly correlated (Pearson correlation coefficient = 0.94, $p < 0.0001$ in MBSS watersheds), but ISC better captured negative responses in less densely populated watersheds that had surfaces like roads.

To forecast future biodiversity loss, we used human residential development model predictions for 2030 with SERGoM (Theobald 2005). We chose a 150-km^2

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TABLE 1. Basin-specific loss estimates of numbers of benthic macroinvertebrate taxa based on their calculated extirpation threshold (T_{95}) (Utz et al. 2009) as impervious surface cover (ISC) increases in Maryland's major Chesapeake Bay tributary watersheds of the Eastern Piedmont and Coastal Plain physiographic provinces.

			ISC (%)				
Basin	Province	Total taxa present	5%	10%	15%	20%	30%
Bush	Coastal Plain	99	2	9	23	39	44
	Piedmont	88	14	31	50	50	50
Choptank	Coastal Plain	115	5	13	30	47	54
	Piedmont						
Chester	Coastal Plain	119	6	12	29	48	54
	Piedmont						
Elk	Coastal Plain	117	5	13	30	49	55
	Piedmont	100	19	37	57	58	58
Gunpowder	Coastal Plain	111	6	15	31	49	56
	Piedmont	100	18	37	57	58	
Lower Potomac	Coastal Plain	123	6	15	33	52	59
	Piedmont						
Middle Potomac	Coastal Plain						
	Piedmont	102	19	38	58	59	59
Nanticoke/Wicomico	Coastal Plain	113	6	11	26	44	50
	Piedmont						
Pocomoke	Coastal Plain	98	5	9	19	34	37
	Piedmont						
Potapsco	Coastal Plain	121	6	15	32	51	58
	Piedmont	102	19	38	58	59	59
Potomac/Washington	Coastal Plain	122	5	14	31	50	57
	Piedmont	101	18	37	57	58	58
Patuxent	Coastal Plain	122	6	15	32	51	58
	Piedmont	101	18	37	57	58	58
Susquehanna	Coastal Plain						
	Piedmont	100	18	36	56	57	57
Upper Potomac	Coastal Plain						
	Piedmont	101	19	38	58	59	59
West Chesapeake	Coastal Plain	119	6	14	31	50	57
	Piedmont						

watershed in the Middle Patuxent River basin in the Eastern Piedmont physiographic province (Omernik 1987) that is forecasted to be heavily altered by human population growth. The selected watershed contained 65 reaches for which we generated predicted land use in the upstream catchment. We modified the 2001 NLCD to reflect the SERGoM results where a pixel was predicted to change from agriculture or forest to urban. ISC had stronger associations with taxon responses than urbanization, but SERGoM output is in units of urbanization. We considered a pixel as converted to urban cover if the 2001 NLCD was classified as natural or agricultural cover, but the residential density predicted by Theobald (2005) was $\leq$0.7 ha of land per unit of housing by 2030. Therefore, the projected urban cover consisted of predicted residential development from SERGoM plus the existing urban covers in the 2001 NLCD, including the existing high intensity and commercial uses. Our previous results (Utz et al. 2009) indicated that benthic invertebrates in the Piedmont region were nonresponsive to increasing agriculture as a stressor, probably because the sensitive taxa already have been eliminated by centuries of intense agricultural development. Thus, we did not consider the role of agriculture in the forecasts.

We used the landuse layer modified to reflect predicted human influences in 2030 to recalculate the forecasted amount of urbanization upstream of each stream reach in our selected watershed. Stream reaches ranged between 1st and 3rd order, were variable in length, and were defined as headwaters to confluence or as entire segments between confluences. We subdivided reaches >3 km long into smaller segments to limit extrapolations to large lengths of stream. We applied the results to each stream reach to produce spatially explicit forecasts of which benthic invertebrate taxa probably will be eliminated and which probably will remain. Only taxa collected $\geq$25 times within a physiographic

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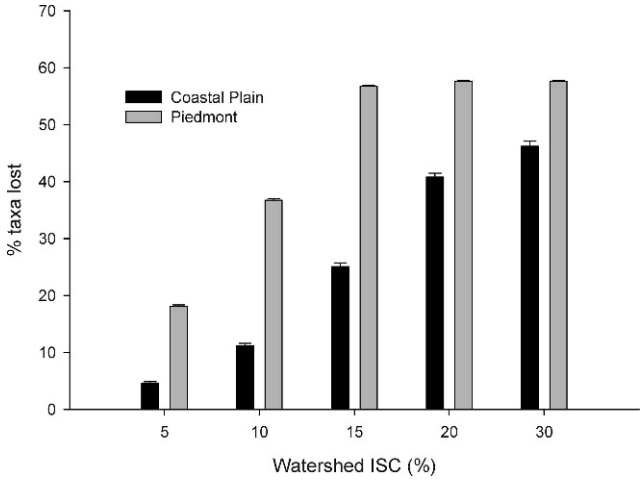


FIG. 1. Mean (+1 SE) % taxon losses of benthic macroinvertebrate taxa across the major basins of the Coastal Plain and Piedmont as watershed impervious surface cover (ISC) increases.

province during rounds I and II of the MBSS program (out of 873 and 862 collections from the Coastal Plain and Piedmont, respectively) were analyzed by Utz et al. (2009). Thus, biodiversity estimates include only those taxa assessed by Utz et al. (2009) and exclude some rare taxa. Furthermore, we included a taxon in the biodiversity estimate in the reach only if the taxon could be present based on biogeography and if the upstream watershed area exceeded the minimum among watersheds where it was collected statewide by the MBSS program.

Application of Results

Applying the analytical thresholds in Utz et al. (2009) to major watersheds indicated that ~½ of the benthic macroinvertebrate taxa collected are forecasted to be lost in Coastal Plain watersheds, and in most cases, nearly 60% of taxa in the Piedmont will be lost by the time ISC reaches 20% (Table 1). However, well before ISC reaches 20%, a number of taxa effectively will have disappeared from the landscape. Nearly 20% of taxa will have disappeared from Piedmont watersheds by the time ISC reaches 5%, and 30–40% of taxa will be lost by the time ISC reaches 10% (Fig. 1). The Piedmont portion of the Potapsco River basin, which has the highest loss rate of all the major basins, could lose 60% of its 102 taxa when ISC reaches 15% (Fig. 2A). In contrast, the Pocomoke River basin in the Coastal Plain, which has the lowest loss rate of all the major basins, could potentially lose >30% of its 98 taxa when ISC exceeds 15% (Fig. 2A). Patterns of taxon losses across the major watersheds fall within the range of these 2 extremes, with

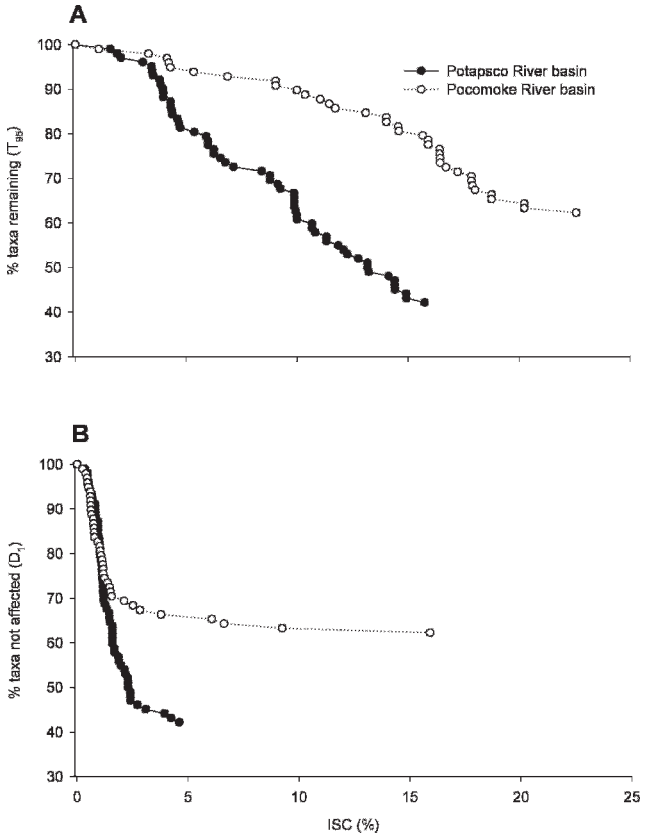


FIG. 2. Percentage of benthic invertebrate taxa remaining (based on their calculated extirpation threshold [T_{95}]) (A) and unaffected (based on their initiation-of-impact threshold [D_1]) (B) as watershed impervious surface cover (ISC) increases (values from Utz et al. 2009). Curves are shown for the Piedmont portion of the Potapsco River basin, which contains the greatest number of taxa potentially lost, and for the Pocomoke River basin in the Coastal Plain, which contains the fewest number of taxa potentially lost.

variations the result of the specific numbers and identities of taxa present. For example, the lowest loss rates were predicted for the basins with the fewest number of sensitive taxa. The confidence intervals surrounding the T_{95} were very narrow for each taxon across both physiographic provinces. The average range was <0.5% for the T_{95} (maximum range span <1%).

Both the Potapsco and Pocomoke basins showed very steep curves for the onset of negative effects. D_1 for many taxa occurred at <1% ISC as measured from the NLCD (Fig. 2B). In fact, the onset of detectable negative effects on taxa distributions occurred by ~2–3% ISC for most taxa in both basins. The average range between the upper and lower 95% confidence interval was <1% ISC for the D_1 (maximum range = 6%).

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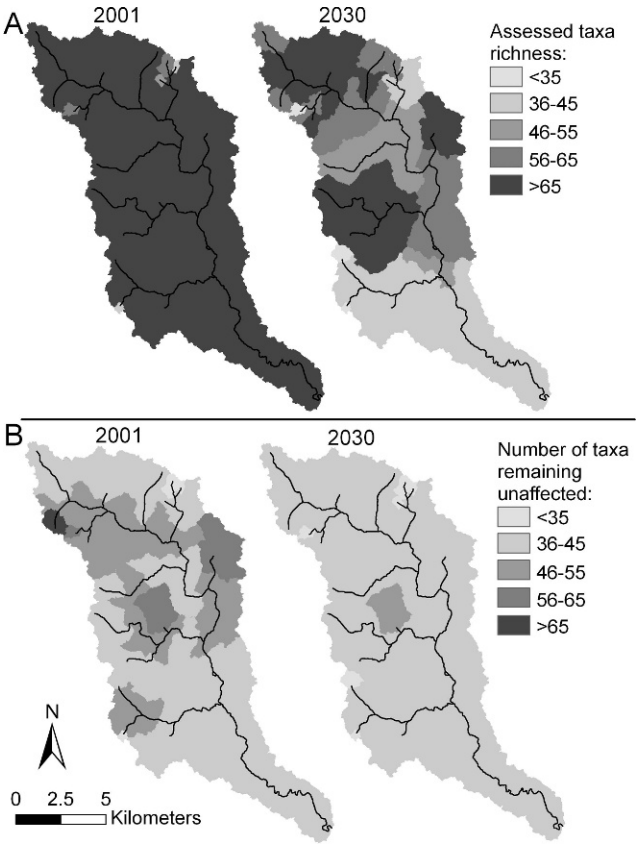


FIG. 3. A.—Forecasted number of benthic macroinvertebrate taxa in the Middle Patuxent River watershed given projected increases in human population growth in 2030. Taxon responses were projected based on effective extirpation, the point at which taxa disappear after urbanization of the upstream watershed exceeds their calculated extirpation threshold (T_{95}). B.—Forecasted local imperilment of taxa for which urbanization has exceeded the initiation-of-impact threshold (D_1) reported in Utz et al. (2009). Taxa might not disappear at D_1, but would be found at reduced frequencies and might not persist locally.

Spatially explicit application of threshold results in the Middle Patuxent River watershed resulted in a nearly 50% forecasted reduction in biodiversity (>65 taxa in 2001 to <35 taxa in 2030) in some reaches based on taxa currently present in the larger watershed (Fig. 3A). However, the taxonomic potential in most reaches already has been imperiled given current amounts of urbanization relative to each taxon's D_1 threshold, and future development in the watershed will negatively affect additional taxa with the result that only 1 reach is forecasted to have >35 taxa remaining unaffected by 2030 (Fig. 3B). The most urban-sensitive taxa (e.g., mayflies *Drunella* spp. and *Isonychia* spp.) probably will be extirpated or persist with populations reduced, whereas some taxa that are less sensitive to urbanization (e.g., *Hydropsyche* spp. and *Simulium* spp.) will remain in 2030.

Discussion

Current and potential biodiversity loss

Land conversion to urban uses has produced and will continue to produce substantial localized losses in aquatic invertebrate biodiversity in Maryland streams with the possibility of larger-scale losses as well. Nearly ½ of the benthic macroinvertebrate taxa could be lost from large portions of watersheds if growth continues as projected. Many taxa are negatively affected at very low levels of ISC, and regional fishes demonstrate a similar, but less pronounced pattern (Utz et al. 2010). Baker and King (2010) also found many taxon responses at very low urbanization levels and proposed a community-level threshold at ~5% urbanization. Their results are quite similar to the D_1 estimates in Utz et al. (2009), which represent the initiation-of-impact threshold. The weight of evidence from 2 different methods suggests the existence of an ecological threshold for benthic invertebrates as watersheds urbanize >5–10%. Above this level, and at even lower levels for ISC, taxa begin to disappear until they are effectively lost from the landscape when the T_{95} is reached.

Numerous studies in the region have reported negative effects of urbanization on biota in streams (Moore and Palmer 2005, Morgan and Cushman 2005, Goetz and Fiske 2008), but few have taken the next step to provide either landscape-scale or spatially explicit forecasts of losses. Complete conversion of a large watershed into an urban-altered landscape is unlikely because some areas will not be developed because of protected areas or terrain, such as steep slopes or wetlands, not conducive to development. Thus, extensive biodiversity loss for major basins might be unrealistic for all but the most highly urbanized areas, such as those surrounding the Washington, DC, or Baltimore metropolitan regions. However, many watersheds are at increased risk from development (Theobald et al. 2009), making our results useful for quantifying the potential magnitude of the effect should growth continue unchecked. A more realistic situation might occur where portions of smaller catchments are the targets of new development. The forecasted biodiversity losses for the Middle Patuxent River show that some stream reaches might suffer substantial taxon losses by 2030, whereas less developed reaches will retain similar macroinvertebrate assemblages over the 29-y span.

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Implications for planning and management

Many possible bridges exist for linking research on taxon response thresholds to land management and planning. Threshold responses can be used to guide development in cases where growth is inevitable. For example, a triage approach could be implemented to confine growth to watersheds already well beyond ecological thresholds to protect other areas that are still relatively intact. Guiding development to occur lower in the stream network could ease regional impacts on benthos by ensuring that headwaters remain intact (Freeman et al. 2007, Nadeau and Rains 2007), but possibly at the cost of fish diversity which tends to increase in mid-order reaches (Matthews 1986). Another use could be to determine acceptable levels of biodiversity loss. Last, futures scenarios, such as ours, can be developed by incorporating results with growth models to create what if? scenarios (e.g., Van Sickle et al. 2004). The absolute accuracy of forecasts is suspect, but the overall picture illuminates patterns that would otherwise be missed.

Despite the possibilities, applying thresholds for management will be an irrelevant academic exercise unless the consequences can be linked to regulatory triggers. Most agencies and members of the public will not be concerned if a few invertebrates disappear. However, a slight shift in focus could make the losses more relevant to those stakeholders. For example, streams in watersheds with >5% urbanization (2% ISC) effectively would lose all mayflies and stoneflies and would receive a Benthic Index of Biological Integrity (BIBI) indicative of low water quality. The low BIBI score would cause the stream to be placed on the state's list of impaired waters (Clean Water Act Section 303[d]) according to Maryland's water-quality regulations. Thus, the stream would be assigned a total maximum daily load (TMDL) under the US Clean Water Act, and this classification would require costly stream restoration and mitigation measures. A similar situation exists when a federal or state rare, threatened, or endangered species is negatively affected by some threat, which initiates a regulatory trigger.

Ecological thresholds have much promise as management tools, but caution must be used in their application. Our results might not be transferable to other regions and should be validated before use elsewhere. Even within Maryland, responses by the same taxon can differ, sometimes significantly, among physiographic provinces (Utz et al. 2010), and these differences appear to be more than artifacts of the data set. We used urbanization and ISC as surrogates for the numerous and highly interrelated stressors that affect the benthos directly, but the strength of these relationships can vary regionally. Moreover, thresholds do not exist for every pattern or process. For example, nearly ½ of the invertebrate taxa analyzed by Utz et al. (2009) did not show significant responses to land uses and, therefore, were not used in our analyses. Uncertainty exists in all ecosystem responses, and regional or local variation undoubtedly makes actual thresholds more like blurred transition zones than hard boundaries. Thus, the values derived from our analyses should not be taken as literal thresholds. Moreover, landuse data derived from the NLCD will yield different results than landuse data derived from other sources (Stranko et al. 2008) because the NLCD tends to underestimate the area of urban and suburban land cover relative to estimates based on higher resolution images (Moglen and Kim 2007). This tendency also explains why the taxon loss curves are so steep at low levels of ISC in Fig. 2. Because of the uncertainties described above, some degree of conservatism must be used when making management decisions based on thresholds, particularly when landuse data are involved.

Uncertainty in analytical thresholds also will arise from the database itself. The MBSS uses a subsampling procedure that might make detecting rare species difficult. Moreover, the data are a sample and not a full census, so the analysis could be sensitive to the underlying distributions of land uses. However, our uncertainty analysis indicated that although the range between the largest and smallest response values for each taxon was sometimes large, the 95% confidence interval around the average response was very small for both the T_{95} and the D_1 for each taxon. Such narrow confidence intervals suggest that the distribution of land uses in the database did not overly affect the stability of the results.

Our method is only one of several approaches that could be taken to threshold identification, and other methods, such as the River InVertebrate Prediction And Classification System (RIVPACS) ratio of observed to expected taxa (O/E) (Hawkins et al. 2000, Clarke et al. 2003), Bayesian or nonparametric changepoint analyses (Qian et al. 2003), or Threshold Indicator Taxa ANalysis (TITAN) (King and Baker 2010), could be adapted to produce both landscape-scale or spatially explicit predictions of taxon losses. Deriving thresholds with several techniques could address the uncertainty associated with thresholds and might increase the accuracy and precision of the results to produce a more effective conservation tool.

We must guard against the tendency or desire to manage right up to a threshold, be it maximum

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sustainable yield (Botsford et al. 1997), minimum stream flows (Stalnaker 1990), minimum viable populations (Boyce 1992), or the values used in our paper. Taxa can disappear from watersheds along the entirety of the urban stressor gradient for a number of different reasons. Management at the extirpation threshold could be catastrophic to stream biodiversity. A more useful approach would be to use D_1 as a guide. Identification of land-conversion levels at which taxa begin to disappear from a few streams could allow maintenance of pockets of biodiversity in a vastly altered region. This approach could provide a biodiversity bank that could repopulate the watershed if restoration techniques were applied. Despite the possibility of misuse, we think that analytical thresholds hold promise for watershed management.

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Literature Cited

Baker, M. E., and R. S. King. 2010. A new method for detecting and interpreting biodiversity and ecological community thresholds. Methods in Ecology and Evolution 1:25–37.

Blakely, T. J., J. S. Harding, A. R. McIntosh, and M. J. Winterbourn. 2006. Barriers to the recovery of aquatic insect communities in urban streams. Freshwater Biology 51:1634–1645.

Botsford, L. W., J. C. Castilla, and C. H. Peterson. 1997. The management of fisheries and marine ecosystems. Science 277:509–515.

Boyce, M. S. 1992. Population viability analysis. Annual Review of Ecology and Systematics 23:481–506.

Clarke, R. T., J. F. Wright, and M. T. Furse. 2003. RIVPACS models for predicting the expected macroinvertebrate fauna and assessing the ecological quality of rivers. Ecological Modelling 160:219–233.

Clements, W. H., N. K. M. Vieira, and D. L. Sonderegger. 2010. Use of ecological thresholds to assess recovery in lotic ecosystems. Journal of the North American Benthological Society 29:1017–1023.

Dodds, W. K., W. H. Clements, K. Gido, R. H. Hilderbrand, and R. S. King. 2010. Thresholds, breakpoints, and nonlinearity in freshwaters as related to management. Journal of the North American Benthological Society 29: 988–997.

Freeman, M. C., C. M. Pringle, and C. R. Jackson. 2007. Hydrologic connectivity and the contribution of stream headwaters to ecological integrity at regional scales. Journal of the American Water Resources Association 43:5–14.

Gido, K. B., W. K. Dodds, and M. E. Eberle. 2010. Retrospective analysis of fish community change during a half-century of landuse and stream flow changes. Journal of the North American Benthological Society 29: 970–987.

Goetz, S., and G. Fiske. 2008. Linking the diversity and abundance of stream biota to landscapes in the Mid-Atlantic USA. Remote Sensing of Environment 112: 4075–4085.

Groffman, P. M., J. S. Baron, T. Blett, A. J. Gold, I. Goodman, L. H. Gunderson, B. M. Levinson, M. A. Palmer, H. W. Paerl, G. D. Peterson, N. L. Poff, D. W. Rejeski, J. F. Reynolds, M. G. Turner, K. C. Weathers, and J. Wiens. 2006. Ecological thresholds: the key to successful environmental management or an important concept with no practical application? Ecosystems 9:1–13.

Hawkins, C. P., R. H. Norris, J. N. Hogue, and J. W. Feminella. 2000. Development and evaluation of predictive models for measuring the biological integrity of streams. Ecological Applications 10:1456–1477.

Heimbuch, D. G., J. C. Seibel, H. T. Wilson, and P. F. Kazyak. 1999. A multiyear lattice sampling design for Maryland-wide fish abundance estimation. Journal of Agricultural Biological and Environmental Statistics 4:443–455.

Kennen, J. G. 1999. Relation of macroinvertebrate community impairment to catchment characteristics in New Jersey streams. Journal of the American Water Resources Association 35:939–955.

King, R. S., and M. E. Baker. 2010. Considerations for analyzing ecological community thresholds in response to anthropogenic environmental gradients. Journal of the North American Benthological Society 29:998–1008.

Matthews, W. J. 1986. Fish faunal breaks and stream order in the western and central United States. Environmental Biology of Fishes 17:81–92.

Meador, M. R., J. F. Coles, and H. Zappia. 2005. Fish assemblage responses to urban intensity gradients in contrasting metropolitan areas: Birmingham, Alabama, and Boston, Massachusetts. Pages 409–423 *in* L. R. Brown, R. H. Gray, R. M. Hughes, and M. R. Meador (editors). Effects of urbanization on stream ecosystems. American Fisheries Society, Bethesda, Maryland.

Moglen, G. E., and S. Kim. 2007. Limiting imperviousness: are threshold-based policies a good idea? Journal of the American Planning Association 73:161–171.

Moore, A. A., and M. A. Palmer. 2005. Invertebrate biodiversity in agricultural and urban headwater streams: implications for conservation and management. Ecological Applications 15:1169–1177.

Morgan, R. P., and S. E. Cushman. 2005. Urbanization effects on stream fish assemblages in Maryland, USA. Journal

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of the North American Benthological Society 24: 643–655.

NADEAU, T. L., AND M. C. RAINS. 2007. Hydrological connectivity between headwater streams and downstream waters: how science can inform policy? Journal of the American Water Resources Association 43: 118–133.

OMERNIK, J. M. 1987. Ecoregions of the conterminous United States. Annals of the Association of American Geographers 77:118–125.

QIAN, S. S., R. S. KING, AND C. J. RICHARDSON. 2003. Two statistical methods for the detection of environmental thresholds. Ecological Modelling 166:87–97.

ROY, A. H., M. C. FREEMAN, B. J. FREEMAN, S. J. WENGER, W. E. ENSIGN, AND J. L. MEYER. 2005. Investigating hydrologic alteration as a mechanism of fish assemblage shifts in urbanizing streams. Journal of the North American Benthological Society 24:656–678.

SCHUELER, T. R., L. FRALEY-MCNEAL, AND K. CAPPIELLA. 2009. Is impervious cover still important? Review of recent research. Journal of Hydrologic Engineering 14:309–315.

SMITH, R. E., AND W. O. LAMP. 2008. Comparison of insect communities between adjacent headwater and mainstem streams in urban and rural watersheds. Journal of the North American Benthological Society 27:161–175.

STALNAKER, C. B. 1990. Minimum flow is a myth. Pages 31–33 *in* M. B. Bain (editor). Ecology and assessment of warmwater streams – workshop synopses. US Fish and Wildlife Service Biological Report 90(5). US Fish and Wildlife Service, Washington, DC.

STRANKO, S. A., R. H. HILDERBRAND, R. P. MORGAN, M. W. STALEY, A. J. BECKER, A. ROSEBERRY-LINCOLN, E. S. PERRY, AND P. T. JACOBSON. 2008. Brook trout declines with land cover and temperature changes in Maryland. North American Journal of Fisheries Management 28: 1223–1232.

THEOBALD, D. M. 2005. Landscape patterns of exurban growth in the USA from 1980 to 2020. Ecology and Society 10(1):32. (Available from: http://www.ecologyandsociety.org/vol10/iss1/art32/)

THEOBALD, D. M., S. J. GOETZ, J. B. NORMAN, AND P. JANTZ. 2009. Watersheds at risk to increased impervious surface cover in the conterminous United States. Journal of Hydrologic Engineering 14:362–368.

USGS (US GEOLOGICAL SURVEY). 2004. National Land Cover Dataset 2001 (NLCD). Eros Data Center, Sioux Falls, South Dakota. (Available from: http://www.mrlc.gov/index.php)

UTZ, R. M., R. H. HILDERBRAND, AND D. M. BOWARD. 2009. Identifying regional differences in threshold responses of aquatic invertebrates to land cover gradients. Ecological Indicators 9:556–567.

UTZ, R. M., R. H. HILDERBRAND, S. A. STRANKO, AND R. L. RAESLY. 2010. Regional differences in patterns of fish species loss with changing land use. Biological Conservation 143:688–699.

VAN SICKLE, J., J. BAKER, A. HERLIHY, P. BAYLEY, S. GREGORY, P. HAGGERTY, L. ASHKENAS, AND J. LI. 2004. Projecting the biological condition of streams under alternate scenarios of human land use. Ecological Applications 14:368–380.

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