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Distribution and environmental influences on freshwater gastropods from lotic systems and springs in Pennsylvania, USA, with conservation recommendations

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Abstract: We examined current distributions of and influential variables on aquatic gastropods in streams and springs across the state. Our research located 37 species representing 7 families. This inventory included rare species such as *Somatogyrus pennsylvanicus* Walker, 1904 and several populations of the Ohio Pebblesnail *Somatogyrus integra* (Say, 1829). Despite targeted surveys, no collections were made of the Buffalo Pebblesnail *Gillia altilis* (I. Lea, 1841). We also examined the influence of rapid bio-assessment habitat measurements, reach and basin hydrological variables, and selected water chemistry variables on the freshwater snail communities of Pennsylvania. Several measures of habitat quality, drainage area, and water chemistry were among the more important variables explaining patterns in species richness. Several species appear rare and 7 species are recommended for conservation consideration. Further work is needed to better understand the diversity of freshwater gastropods in Pennsylvania.

Key words: zoogeography, rare species, snails, ecology

Freshwater gastropods are of increasing conservation concern in the United States. Of the nearly 800 species in North America, 60 species of freshwater snails are believed extinct (Paul Johnson, pers. comm.) and the status of many more species is poorly known. Recent estimates by NatureServe (2008) show that over 70% of the North American gastropod fauna is imperiled (species extirpated or at-risk). Despite recent efforts by resource managers to identify species of concern in the state (PFBC and PGC 2005), Pennsylvania lacks information on the present distributional status of its aquatic gastropod fauna. The mussel fauna of the state has been better documented, with early inventory efforts by Ortmann (1919) and more recently by others (Art Bogan, pers. comm.).

Pennsylvania has a rich legacy in malacology. Most of the workers in the state have historically focused on distribution and systematics of freshwater mussels, sphaeriid clams, and land snails. A. E. Ortmann, Timothy Conrad, Henry Pilsbry, Victor Sterki, and other prominent malacologists collected freshwater snails in Pennsylvania (often incidental to mussel collecting) largely in the early 20th century. There has been little focus on the group in subsequent years and contemporary survey efforts are needed. Recent research by Evans and Ray (2008) provided support for 63 known or potential species in the state.

Pennsylvania is one of the most diverse states in the country in terms of drainage basins and contains 83,184 miles of streams (PFBC and PGC 2005) across its 67 counties. The northeastern edge of the Ohio Basin is contained in the state (Fig. 1). Nearly half of the Delaware and Susquehanna River basins flow through the state. The headwaters of the Elk and Northeast Creeks as well as the Genesee and Potomac River Basins originate in Pennsylvania.

Previous workers have determined temperature and pH to be useful determinants of freshwater snail communities (Pip 1987, Brown *et al.* 1998), while other have shown the importance of drainage area (and concomitant increase in habitat diversity) to be useful (Prezant and Chapman 2004).

To help inform the conservation effort for freshwater snails, we initiated an inventory of the Pennsylvania fauna of streams and springs. This study represents the first dedicated, modern effort aimed specifically at the entire aquatic gastropod fauna across the state of Pennsylvania, focused on lotic and spring habitats. We also wanted to examine the influence that habitat data, geology, land use, physical characteristics, and water quality data have on the lotic species in the state.

MATERIALS AND METHODS

Field sampling was primarily in streams and, to a lesser extent, accessible surface springs. Stream sampling sites were

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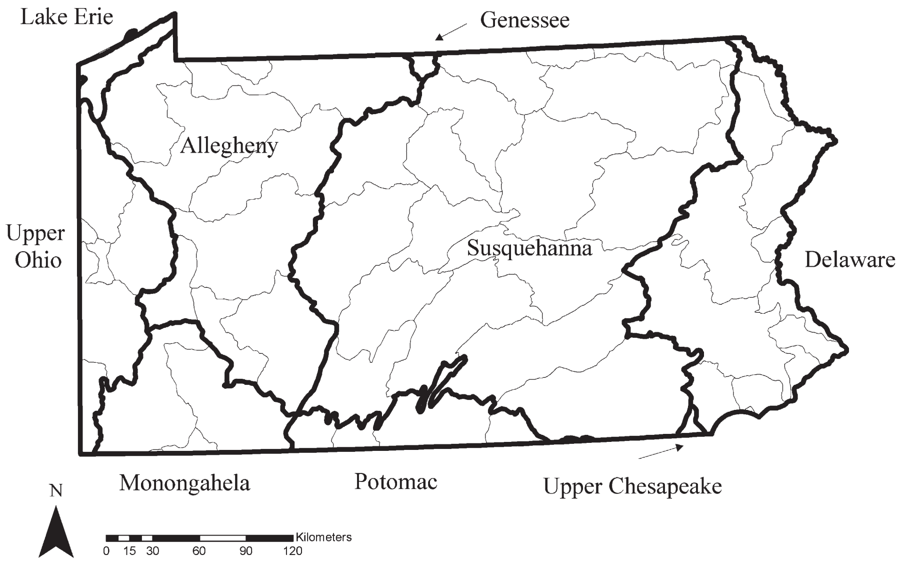

Figure 1. Major river basins of Pennsylvania.

selected based on accessibility and areas that would provide the maximum number of microhabitats for maximizing species richness. Sampling sites were initially broken into USGS HUC 8 level watersheds (which are watershed level groupings) and then chosen by using USGS 7.5 topographic maps and a Pennsylvania Gazateer (DeLorme Corporation, Maine). Our goal was to get 8-10 sampling sites per HUC 8 unit. Springs were located from USGS maps and from examining the USGS Geographic Names Information System using ArcView 9.1 and ArcView 3.2 software (ESRI, Redlands, California).

Hand collecting was done on large woody debris substrates, and handheld sieves were used to sweep vegetation and sample small accumulations of detritus. D-frame nets were used in deeper areas. Stones and trash were examined at each site for species. Although searches were not made in a standardized timed fashion, sampling was typically conducted until no new species were collected. Museum records were obtained from Academy of Natural Sciences in Philadelphia (ANSP), Carnegie Museum of Natural History (CMNH), Delaware Museum of Natural History (DMNH), Florida Museum of Natural History (FMNH), Illinois Natural History Survey (INHS) and The U.S. National Museum (Smithsonian Institution - USNM).

To examine local and landscape variables associated with gastropod species richness, sites were assigned physical variables from a modified EPA Level 3 Reach File (RF3) geographic information system (GIS) stream layer produced by The Nature Conservancy (A. Olivero, unpubl. data). This layer contains values assigned for every stream segment in the state of Pennsylvania and contains data representing various measures of land cover types, upstream dams, upstream road crossings, and watershed area for both the reach scale and HUC 12 scale of Pennsylvania streams. Dissolved oxygen, pH, temperature, calcium hardness, total hardness, and total alkalinity were measured at many sites by the investigators. At many sites, conductivity and total dissolved solids (TDS) data were also collected. Because not all parameters were collected for all sites, data were supplemented with information from the Pennsylvania Natural Heritage Program Aquatic Database, one of the largest sources of aquatic habitat and water quality data for the state of Pennsylvania (Nightingale *et al.* 2004) and averaged for the respective stream segment. To evaluate associations with physical habitat structure, a modified Rapid Bioassessment Protocol (RBP) developed by Pennsylvania Department of Environmental Protection was used (modified from Barbour *et al.* 1999). A Kruskal-Wallis test was used to examine if there were any statistical differences between species richness at the large basin (HUC 6) level. Due to limited sampling data, Lake Erie basin stream sites were excluded from all analyses.

Pearson correlations were run to examine correlations among variables. If two variables showed a correlation coefficient >0.6, the more useful of the two was retained. This reduced the dataset from 43 to 10 variables for RF3 and RBP, respectively. All 7 water chemistry variables were retained from the initial dataset to examine possible influences on community structure. Backward stepwise multiple regressions were used to examine which variables appeared strongest in explaining gastropod species richness. Analyses were conducted separately for landscape variables, land use, water chemistry variables, and habitat variables. In examining land use, species richness values were averaged at the HUC 12 level and assigned a land use value from the National Land Cover Dataset (2000 version).

To examine relationships for selected, highly significant variables on presence-absence data, we used PC-ORD software (ver. 4.32) to run Nonmetric Multidimensional Scaling (NMDS) tests. A Sørenson (Bray-Curtis) distance measure was used with 200 maximum iterations and 30 runs against a Monte-Carlo simulation. Prior to analysis, Beals Smoothing was used to minimize the influence of a large number of zero values, as is the case with presence-absence data (McCune *et al.* 2002).

Predicted versus observed species richness was examined with a species-area curve of statewide taxa (for 35 species) using a Sørensen distance measure against all stream and spring sites. Two species, *Pleurocera acuta* Rafinesque, 1831 and *Pleurocera canaliculata* (Say, 1821), were excluded from the master taxa dataset as records for these species were from contributed specimens and not a result of a dedicated survey and, thus, could artificially weight species richness data as compared to community data. We also examined species-area curves at the HUC 8 level where adequate sampling data existed. Species richness estimates were conducted using two estimators, Jackknife 1 (Palmer 1990) and Jackknife 2 (Palmer 1991):

$$\text{Jackknife 1} = \frac{S + r1(n-1)}{n}$$

where S = the observed number of species, r1 = the number of species occurring in one sample unit, and n = the number of sample units and

$$\text{Jackknife 2} = \frac{S + r1(2n-3)}{n} - \frac{r2(n-2)^2}{n(n-1)}$$

where r2 = the number of species occurring in two sample units.

Taxonomy generally followed Turgeon *et al.* (1998), Smith (2000), and Wethington and Lydeard (2007). We chose to follow the name *Galba* over *Fossaria* based on the ruling by ICZN (1998). Identifications of collections and distribution ranges were confirmed using Walker (1904), Goodrich (1940), Basch (1963), La Rocque (1968), Burch (1989), Jokinen (1992), and with comparison to museum specimens. Voucher specimens collected in the course of this study were deposited with Carnegie Museum of Natural History in Pittsburgh, Pennsylvania.

RESULTS

Survey results

We sampled a total of 398 stream and spring sites across Pennsylvania (Fig. 2) in the Delaware, Lake Erie, Ohio, Potomac, and Susquehanna River systems. Due to time constraints, no sampling occurred in the Genesee River basin. A total of 121 sites sampled (30% of total) had no snails (Fig. 2). In streams and springs that were sampled, a total of 37 species were collected (Table 1). Overall, sampling appears reasonably effective in charactering species richness across the state, with first-order jackknife estimates of 38 species and second-order jackknife estimates of 33 species (Fig. 3).

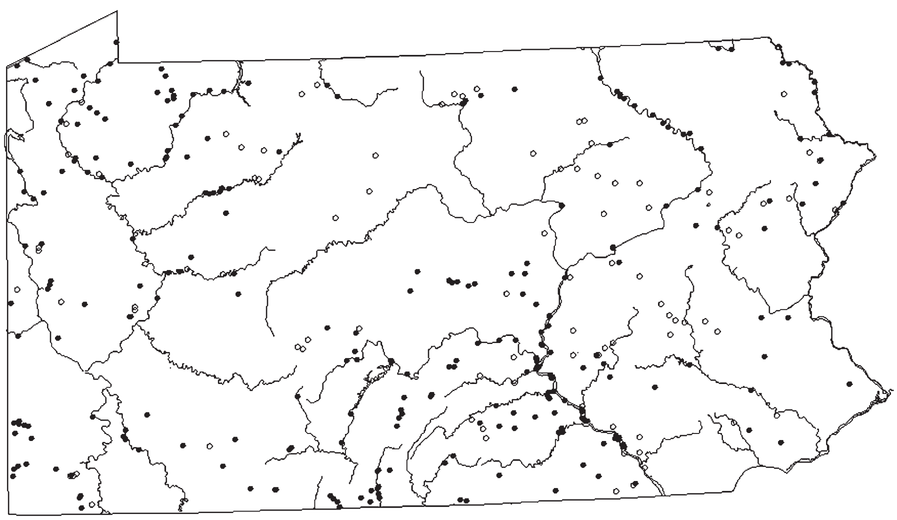

Figure 2. Sampling sites from this study, 2003-2006; null sites are indicated by open circles.

Species richness across all Pennsylvania streams was highest overall in the Ohio Basin (*N* = 25) and lowest in the Lake Erie Basin (*N* = 4). Pulmonates were more common than caenogastropods, totaling 23 species, or 62%, of the species. The most common pulmonate taxa were *Physa acuta* Draparnaud, 1805 and *Ferrissia rivularis* (Say, 1817), while *Leptoxis carinata* (Bruquiere, 1792) was the most common caenogastropod.

A significant difference was observed between major river basins in terms of species richness (Kruskal-Wallis test statistic = 17.01, *P* = 0.004). Examining richness patterns by HUC 8 region (Fig. 4), the greatest species richness was found in the Northwestern, Glaciated Plateau Physiographic Region in the French Creek watershed of northwest Pennsylvania (Allegheny River system) with 17 species present, followed by Middle Allegheny River-Tionesta Creek, Lower Susquehanna River-Swatara Cr., and Lower Juniata River each with 14 species. Despite a large number of sampling sites, only 21 species were located from the Susquehanna River system. Proportionately, the Potomac River watershed was very species rich, with 10 species located from only 23 sites. Zero species were reported from two USGS 8-digit HUCs in north-central Pennsylvania. No specimens of Pomatiopsidae were located in this study, despite investigating marginal habitats where they have been reported.

Regarding the freshwater limpets (Ancylidae; Fig. 5), *Ferrissia rivularis* (Say, 1817) was one of the most common species in the state, ranging from headwaters to larger rivers. *Ferrissia parallelus* (Haldeman, 1841), a species typical of slower-flowing stream sections or lentic environments, was reported in 3 collections: Marsh Creek (Adams County), Tobyhanna Creek, and Tunkhannock Creek (both in Monroe

Table 1. Distribution of species by major basin. List is for nominal taxa; due to taxonomic uncertainties in certain groups, not all species reported may be valid taxa.

Species	Delaware	Lake Erie	Ohio	Potomac	Susquehanna	Total no. of sites present
Amnicola limosus (Say, 1817)	x		x		x	19
Bellamya chinensis (Reeve, 1863)	x				x	6
Campeloma decisum (Say, 1817)	x		x	x	x	28
Cincinnatia integra (Say, 1829)			x			3
Elimia livescens (Menke, 1830)			x			6
Elimia virginica (Say, 1817)	x				x	45
Ferrissia fragilis (Tryon, 1863)	x		x			5
Ferrissia parallelus (Haldeman, 1841)	x			x		5
Ferrissia rivularis (Say, 1817)	x	x	x	x	x	125
Fontigens nickliniana (I. Lea, 1838)					x	3
Galba exigua (I. Lea, 1841)			x			1
Galba modicella (Say, 1825)		x	x		x	15
Galba obrussa (Say, 1825)			x			8
Galba parva (I. Lea, 1841)					x	3
Galba rustica (I. Lea, 1841)			x			2
Gyraulus deflectus (Say, 1824)	x		x			5
Gyraulus parvus (Say, 1817)	x		x			8
Helisoma anceps (Menke, 1830)	x		x	x	x	31
Laevapex fuscus (C. B. Adams, 1841)			x	x	x	16
Leptoxis carinata (Bruguière, 1792)				x	x	60
Lithasia obovata (Say, 1829)			x			17
Lyogyrus granum (Say, 1822)	x				x	7
Micromenetus dilatatus (Gould, 1841)	x		x		x	8
Physa acuta (Draparnaud, 1805)	x	x	x	x	x	133
Physa ancillaria (Say, 1825)	x		x	x	x	6
Physa gyrina (Say, 1821)	x		x	x	x	40
Planorbella campanulata (Say, 1821)	x		x			6
Planorbella trivolvis (Say, 1817)	x		x		x	12
Pleurocera acuta Rafinesque, 1831			x			1
Pleurocera canaliculata (Say, 1821)			x			1
Promenetus exacuous (Say, 1821)				x		1
Pseudosuccinea columella (Say, 1817)	x		x		x	5
Somatogyrus integra (Say, 1829)						16
Somatogyrus pennsylvanicus Walker, 1904					x	1
Stagnicola catescopium (Say, 1867)			x		x	3
Stagnicola elodes (Say, 1821)					x	1
Stagnicola emarginata (Say, 1821)			x			1
Total number of species	18	3	26	10	21	
Number of null sites	43	0	26	1	51	

County). Further sampling of low-gradient, slow-flowing stream habitats would likely yield additional specimens.

Various taxa of Lymnaeidae were located in the study (Fig. 6). In particular, species of *Galba* were common inhabitants of mud flats, cobble bars, and floodplains. *Galba exigua* (I. Lea, 1841) was reported from Enlow Fork, an upper Ohio River tributary, while *G. rustica* (I. Lea, 1841) was observed only from the Clarion River, Forest/Jefferson County and Cussewago Creek, Erie County. *Galba parva* (I. Lea, 1841) was collected from Aughwick Creek in Huntington County and Beaverdam Creek, Somerset County. Specimens of *Stagnicola*, in general, were somewhat less common in

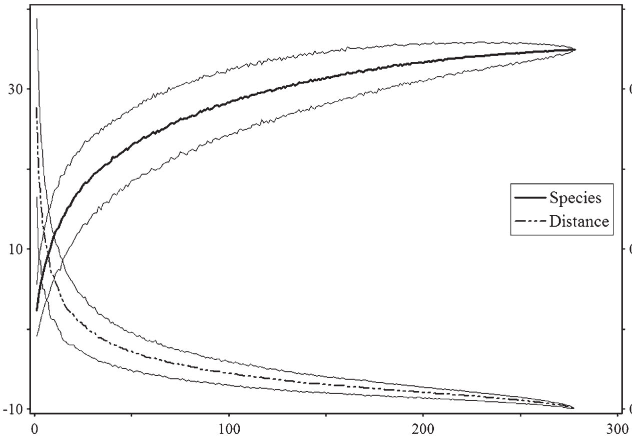

Figure 3. Species-area curve showing species versus distance. Lines around the curves represent ± 1 standard deviation.

floodplain and channel margin areas of flowing waters than *Galba* although collections were made of *Stagnicola elodes* (Say, 1821) in spring runs in Cumberland County. This species was observed to be more numerous in ditches, seeps, and seasonal pools (Evans and Ray, pers. obs.). *Stagnicola catescopium* (Say, 1867) was found in Little Sugar Creek in northwestern Pennsylvania, Aughwick Creek in Huntingdon County (central Pennsylvania) and in the lower mainstem Susquehanna River, Lancaster County. *Stagnicola emarginata* (Say, 1821) were observed in a slow-flowing, muddy section of Brokenstraw Creek in Warren County; museum records were obtained (Northampton County; CMNH #62.12594) that extended the range across the state to the Delaware River system.

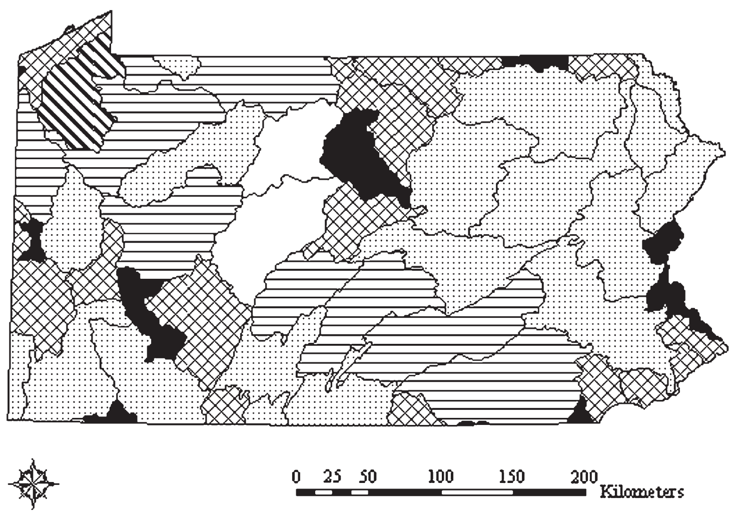

Figure 4. Species richness by HUC 8 watershed.

Planorbidae were among the more commonly encountered groups in this study (Fig. 7); *Helisoma anceps* (Menke, 1830) and *Planorbella trivolvis* (Say, 1817) were generally common and distributed nearly statewide. *Promenetus exacuous* (Say, 1821) was found at one site along a muddy edge in an upper Potomac River tributary in Bedford County. We located a few museum records for this species in the habitats of focus in this study (ANSP #21562, 27284, 122810; CMNH #62.18003; DMNH #081596). Although representatives of *Gyraulus* were less common than *Helisoma*, specimens were obtained from drainages across the state. Interestingly, most records of *Micromenetus dilatatus* (Gould, 1841) were clustered in the Juniata and lower Susquehanna drainages although other collections were made outside these areas.

Physidae were distributed statewide (Fig. 8). The Pumpkin Physa *Physa ancillaria* (Say, 1825) had the fewest records among the physids although the species was broadly distributed and located in all but the Lake Erie system. We observed *P. acuta* and *P. gyrina* (Say, 1821) in a variety of habitats, ranging from forested headwaters to lowland agricultural streams and harsh environments including extremely ephemeral waterbodies (such as small ponds).

Within the Hydrobiidae (Fig. 9), *Cincinnatia integra* (Say, 1829) was collected only from the mainstem Allegheny River and French Creek (Appendix 1) in backwater or edge habitats. In spring systems in Centre County, three collections were made of *Fontigens nickliniana* (I. Lea, 1838). One of these records (from a spring in Bellefonte, Centre County) had been previously reported (Hershler *et al.* 1990). Other records exist for the species (USNM #121387; 783938; 791479) which extend the range north to Clinton County and south to Huntingdon County, all within the Central Appalachian province. The Blue Ridge Springsnail *Fontigens orolibas* Hubricht, 1957 was not located in our sampling of springs. Database records from the Smithsonian Museum of Natural History (USNM #522087; 522846; 853173) of *Fontigens antroecetes* Hubricht, 1972 are actually *F. orolibas* (fide Robert Hershler, Smithsonian Museum of Natural History). The Shale Pebblesnail *Somatogyrus pennsylvanicus* (Walker, 1904) was collected from 1 location in the Susquehanna River from the type locality at Columbia, Lancaster County (Walker, 1904) which represents the most recent record for the species in the state. We located *Somatogyrus integra* (Say, 1829) in 16 collections from the French Creek watershed,

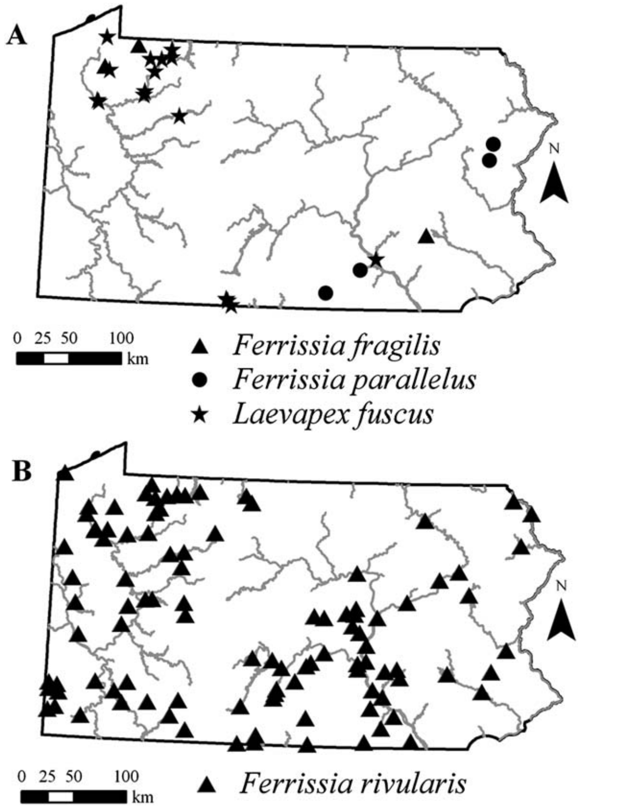

Figure 5. Distribution of Ancylidae in streams and springs of Pennsylvania.

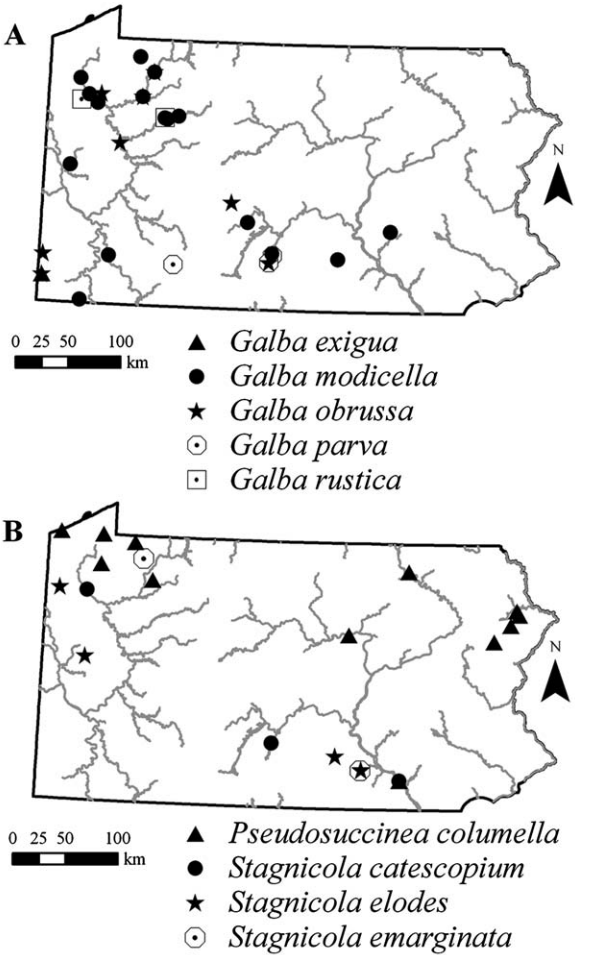

Figure 6. Distribution of Lymnaeidae in streams and springs of Pennsylvania.

Conewango Creek, Brokenstraw Creek, Oil Creek (all Allegheny River system), the Allegheny River mainstem, and Neshannock Creek (Beaver River system). It has been previously reported from the town of Warren (Warren County) by A. E. Ortmann (CMNH #62.7485) which could be a record from either the Allegheny River or Conewango Creek. Despite targeted surveys, we were unable to locate *Gillia altilis* (I. Lea, 1841) during this study. In Pennsylvania, *Gillia* has been reported from the middle Delaware River (Northampton County; FMNH #35020) to the lower Susquehanna River (Lancaster County; FMNH #88524).

The distributions of Pleuroceridae species fell out by basin (Fig. 10). In the Ohio Basin, *Pleurocera acuta* Rafinesque, 1841 was found in Muddy Creek, a tributary of the French Creek system, and along the shoreline of Lake Erie. *Pleurocera canaliculata* (Say, 1821) was reported from the mainstem Ohio River around Phyllis Island in Beaver County (fide Patty Morrison, US Fish and Wildlife Service). Museum records exist from the work of Brooks (1931) from the middle Allegheny River in Warren County (CMNH #62.7902) to the lower Allegheny River (Allegheny County; CMNH #62.6611), the lower Youghiogheny River (CMNH #62.6796), and several records for the mainstem Ohio River. Our records of *Elimia livescens* (Menke, 1830) were restricted to Beaver, Lawrence, and Crawford Counties although additional work may lead to additional contemporary records. In the Atlantic Slope, *Elimia virginica* (Say, 1817) and *Leptoxis carinata* (Bruguière, 1792) were found across the Susquehanna River basin, with *L. carinata* also occurring broadly across the upper Potomac.

Within the Viviparidae (Fig. 11), *Campeloma decisum* (Say, 1817) was distributed across the state, but principally in northwestern and south central Pennsylvania. Due to time constraints, we were not able to devote adequate time to search for *Lioplax subcarinata* (Say, 1816), known principally from the Delaware River basin. Although a record exists for the West Branch Susquehanna River (CMNH #62.7527), the species was not collected in this study. The non-native Chinese Mystery snail *Bellamya* (= *Cipangopaludina*) *chinensis* (Reeve, 1863) was located at 7 sites in the Atlantic Slope,

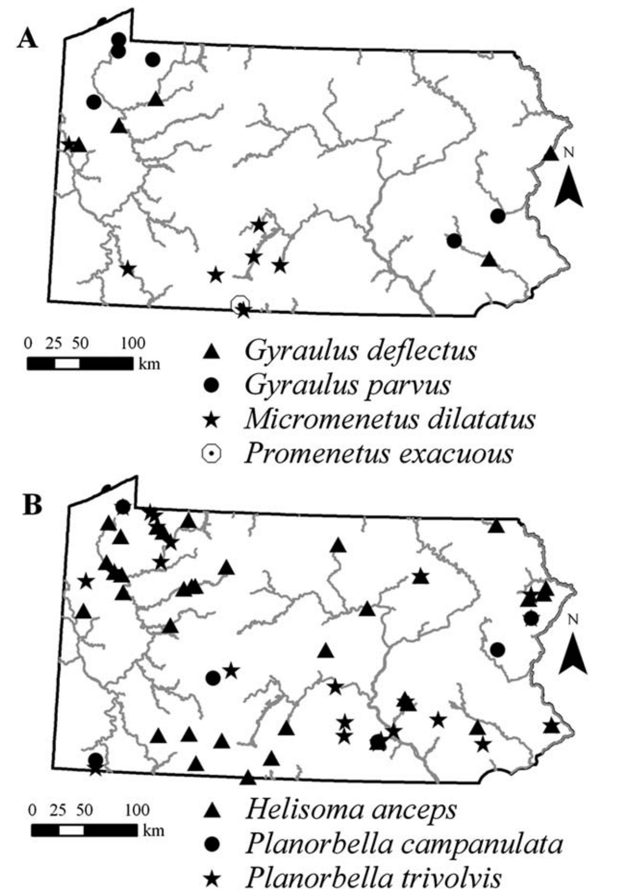

Figure 7. Distribution of Planorbidae in streams and springs of Pennsylvania.

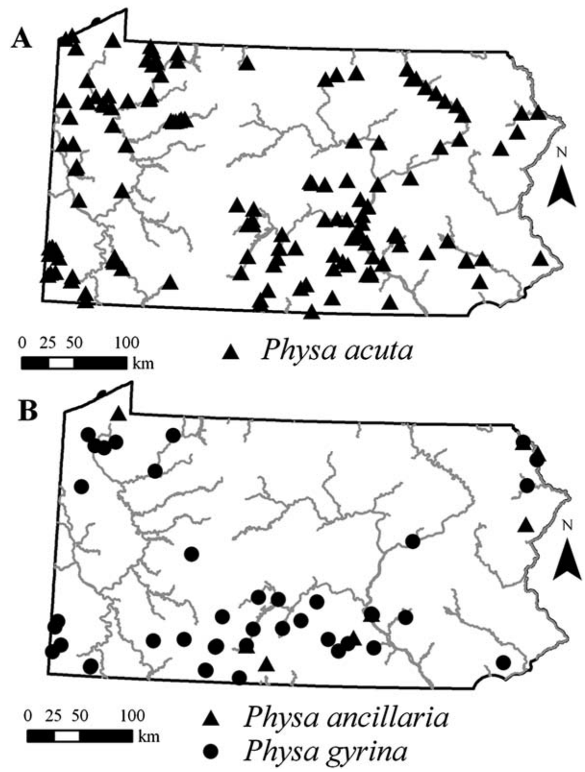

Figure 8. Distribution of Physidae in streams and springs of Pennsylvania.

Delaware, and Ohio Basin. Most notably, *B. chinensis* was particularly abundant at the mouth of Conodoguinet Creek as well as a site 16 km upstream in the mainstem Susquehanna River in Harrisburg.

Results of statistical analyses

Stepwise multiple regression models identified 23 variables that appeared to have the strongest influence on gastropod species richness (Table 2). The most important variables were total upstream area, riparian area – barren ground, total number of upstream pollution point sources, percentage of mixed forest cover at the HUC 12 level, and pH. Across all models, the water chemistry model was the strongest at explaining species richness patterns (adjusted $r^2 = 0.26$) with RF3 being the weakest model (adjusted $r^2 = 0.175$). Collectively, multiple regression models were able to explain 55.6% of the variation with regard to snail species richness.

NMDS was useful in describing the RF3 variables. As with stepwise multiple regression, the strongest trend from NMDS ordination appeared to be drainage area, with pulmonate assemblages grouping to lower-order streams and caenogastropod assemblages in higher-order streams (Fig. 12). The NMDS also showed a particular correspondence to larger drainage areas for *Elimia virginica* and *Leptoxis carinata*; these species were very common in a large number of our samples in higher order stream sites in the Atlantic Slope. In addition, the number of upstream road crossings also followed these trends and although this variable was not statistically correlated with drainage area, values increased with drainage area and its importance should be carefully interpreted. Species of *Physa* were found to be associated with increasing amounts of upstream point source pollution sources, with *Physa gyrina* showing the clearest trend along this gradient.

DISCUSSION

We found 37 species from streams, rivers, and spring habitats across the state. However, several species were found in a restricted number of locations. *Promenetus exacuous*, a species of temporary waterbodies, lakes, and sluggish sections of streams, was undersampled in this study. Additional

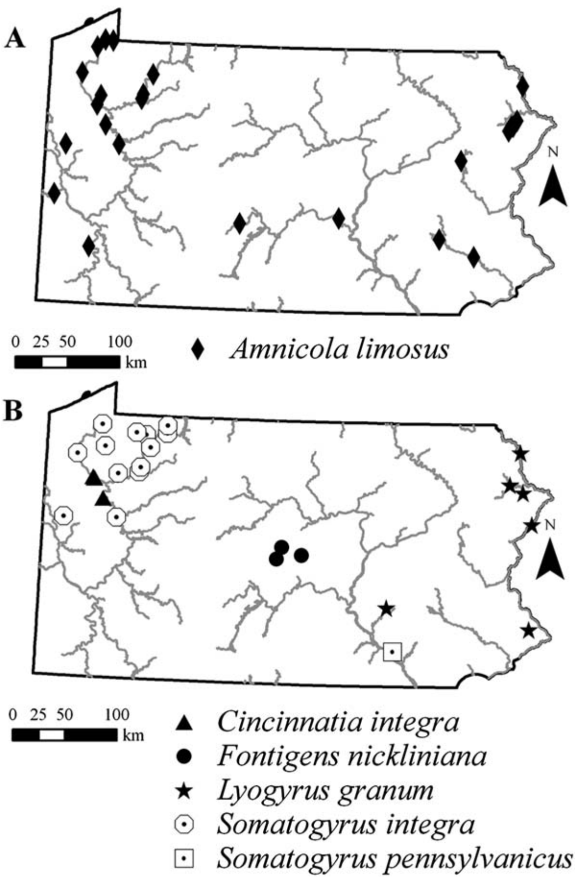

Figure 9. Distribution of Hydrobiidae in streams and springs of Pennsylvania.

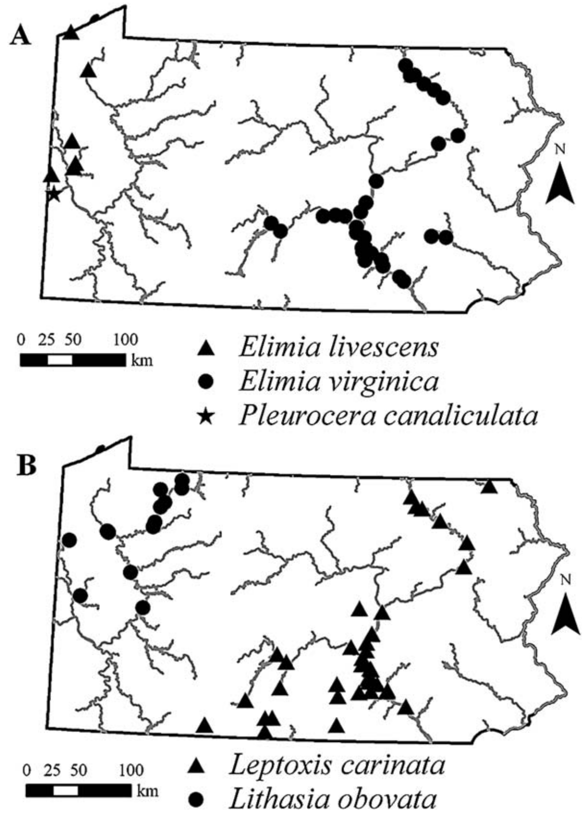

Figure 10. Distribution of Pleuroceridae in streams and springs of Pennsylvania.

sampling targeting those habitats would likely produce more records. The first modern record for *Somatogyrus pennsylvanicus* is in this study. It was located during a search for an older record of *Gillia altilis* from the Susquehanna River (Florida Museum of Natural History 88524). Specimens were found in only 1 location in the river; given the length of the mainstem Susquehanna River within the state, more field sampling is needed as well as demographic studies to derive population estimates for *S. pennsylvanicus*. Hershler *et al.* (1990) noted that *Fontigens orolibas*, which was not located in this study, was known from springs at elevations above 182 meters in Virginia, and also in caves. Few specimens of *Pleurocera*, a genus restricted to the Mississippi and Ohio River basin (Burch 1989), were found. Additional sampling efforts in the lower Allegheny River, upper Ohio River, and Monongahela Rivers, using scuba, would allow better sampling of this genus in the state.

Somatogyrus integra, a species of potential conservation concern in the Ohio Basin (unpublished list, Ohio River Valley Ecosystem Recovery Team) and listed as globally vulnerable (G3) by NatureServe (2008), was located in several streams of the Allegheny River basin, frequently in large numbers. Additional sampling in other Allegheny River system streams could yield new specimen records. Given that this species was often encountered in large numbers, and that hydrobiids are easy to overlook in surveys, this species might not be as rare as reported in the Ohio Basin. We recommend that this species be targeted for additional survey work across the upper Ohio River basin to refine its global conservation status.

Low species diversity was observed in Lake Erie tributary streams, as most sampling was from bedrock-bottomed shallow streams which typically provide limited freshwater snail habitat. Additional stream sampling in Conneaut Creek, a larger watershed that exhibits sand/gravel glacial deposits, stable substrates, and pool development, would likely reveal new species not reported from the watershed.

Because of the recent work of Walther *et al.* (2006) resolving the taxonomy of the genus *Laevapex*, specimens obtained from the Allegheny River in this study initially identified as *Laevapex diaphanus* are now considered *Laevapex*

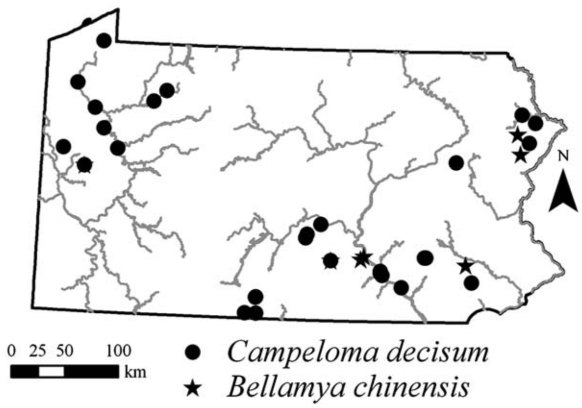

Figure 11. Distribution of Viviparidae in streams and springs of Pennsylvania.

fuscus (C. B. Adams, 1841). The degree of shell variation in North American ancylids has recently been shown to be considerable, varying not only temporally but also spatially (McMahon 2004). Albrecht *et al.* (2007) contended that the Ancylidae is a polyphyletic family that falls basally within the Planorbidae. Taxonomy of the various species of *Galba is* muddled. In a recent treatment of the freshwater gastropods of Virginia, Stewart and Dillon (2004) grouped all putative species under *Fossaria* (= *Galba*). While we followed currently accepted species names for members of the genus, the use of modern molecular taxonomic techniques as well as anatomical comparisons would allow better estimates of the true diversity of the freshwater gastropods of Pennsylvania.

Bellamya chinensis has been documented from the Delaware Basin (ANSP #392419, 401246; this study) and was sampled in this study from the Susquehanna River around Harrisburg, Dauphin County. It was also observed in several reservoirs across the state. The first records of this species in the United States were from the San Francisco Bay area in the early 20th century (Hannibal 1911). Johnson (1915) reported the first eastern United States records, and the species was first reported from Pennsylvania by Richards and Adams (1929). In stream ecosystems, little is known regarding the effects that this species can have on native fauna, underscoring the need for basic monitoring and inventories to locate other populations. Other exotic freshwater snails previously documented in Pennsylvania lotic and spring systems, including *Physa skinneri* Taylor, 1954 (Smithsonian #375998) and *Radix auricularia* (Linnaeus, 1758) (Smithsonian #47868), were not located in this study although these species were not specifically targeted. Future studies should focus on refining the knowledge of invasive species within the state.

Recent work has documented the presence of the highly invasive New Zealand Mud Snail *Potamopyrgus antipodarum* (J. E. Gray, 1853) at Presque Isle in Lake Erie (Levri *et al.* 2007) in Erie County. Additional records now exist from Lake Ontario (Zaranko *et al.* 1997) and Lake Superior (Grigorovich *et al.* 2003). This finding has significant biodiversity implications, given the negative effects that this species has had on stream macroinvertebrates (Kerans *et al.* 2005) in the western United States. Efforts to educate the public about the New Zealand Mud Snail and to monitor streams in this region for its presence will be needed to guard against further spread of the species.

The Northwestern Glaciated Plateau region of the northwestern section of the state, heavily influenced by the Wisconsin Glaciation approx. 17,000 years ago (Sevon and Fleeger 2002), exhibited the greatest species richness. The wide array of habitat types and calcareous geology in the Northwestern Glaciated Plateau is important to the rich diversity of this region. Given the unique gastropods, freshwater mussels, and fish assemblages, we recommend the Middle Allegheny River system and larger tributaries such as Conewango Creek and French Creek be priorities for conservation.

Table 2. Variables used for developing stepwise multiple regression models, with species richness used as the dependent variable. Only the variables retained in the final models are shown. All tests were evaluated at the $\alpha = 0.05$ level of significance. NS, not significant.

Variables	*F*-statistic	*P*-value
Substrate riffle/run	5.38	0.02
Sediment deposition – high gradient streams	8.21	0.005
Channel sinuosity	5.69	0.01
Total upstream drainage area	26.337	<0.001
Degree of channel alteration	2.93	NS
Riparian zone vegetation	7.88	0.006
Riparian zone width	3.59	NS
Riparian area – barren	12.35	0.001
Riparian area – forest	1.770	NS
Riparian area – wetland	2.217	NS
Upstream dam density	0.797	NS
Number of upstream pollution point sources	27.899	<0.001
Number of upstream road stream crossings	5.276	0.02
% calcareous geology – HUC 12	4.062	0.04
% unconsolidated geology – HUC 12	0.938	NS
% evergreen forest – HUC 12	1.298	NS
% mixed forest – HUC 12	17.452	<0.001
% rowcrop – HUC 12	2.312	NS
% emergent wetland in watershed – HUC 12	1.139	NS
% non-row crop agriculture – HUC 12	2.598	NS
pH	18.79	<0.001
Dissolved oxygen	3.5	NS
Specific conductance	2.71	NS

Higher species richness of snails was associated with fewer upstream point sources of pollution, fewer upstream road crossings, a higher percent of mixed forest in the watershed, and lower sediment deposition. Although our overall model for habitat measures was weak ($r^2 = 0.121$), we did not examine several potentially important microhabitat or local scale measures in detail. For instance, we observed that the amount of woody debris and microhabitats increased snail diversity although this relationship could be explained in terms of upstream drainage area, which was also found to be statistically significant. Harman (1972) found significant correlations between gastropod species richness and substrate diversity, which also occur in many other invertebrate groups (Hynes 1970).

Regarding water chemistry, pH was a strong predictor of species richness, as previously reported for freshwater gastropods (Russell-Hunter 1978, Jokinen 1987, Pip 1987, Miller *et al.* 2000). Pyron *et al.* (2009) determined that most species were found at sites with pH values ranging from 7.8 to 8. Temperature, a variable we expected to be important in influencing species richness, was not significant. Greater sampling intensity in warmer, lower-gradient stream systems could possibly reveal the importance of this variable, considered influential for freshwater snails (Aldrich 1983, McMahon 1983).

Another highly significant measure was total upstream drainage area. Total drainage area is also an important predictor of species richness in other studies of snails in streams and lakes (Dillon and Benfield 1982, Jokinen 1987, Prezant and Chapman 2004) and in freshwater mussels (Ortmann 1920, Strayer 1983). We found headwaters dominated by pulmonate species, and larger streams dominated by

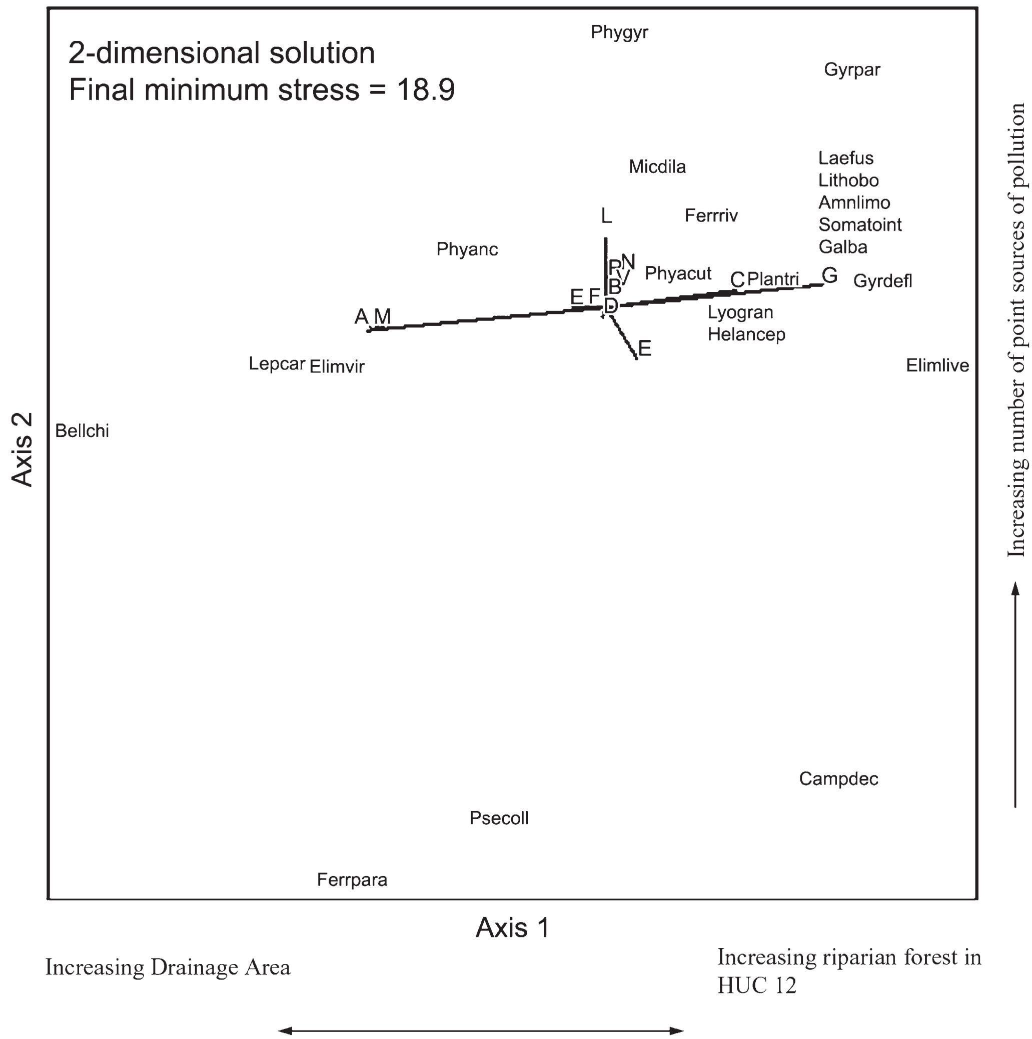

Figure 12. Plot of taxa against retained RF3 variables area using NMDS.

pleurocerids and viviparids, as reported in the literature (Brown *et al.* 1998, Minton *et al.* 2008, Pyron *et al.* 2009). Barnese *et al.* (1990) documented resource partitioning between pulmonate and prosobranch snails, while Johnson and Brown (1997) found that current regime and light penetration were important in *Elimia semicarinata* (Say, 1829). Other potentially important stream measures for snail community composition include sheer stress (Gore 1983) and spates (Stewart and Garcia 2002) for pleurocerid snails.

We also discovered that calcareous geology was a significant predictor of species richness. Huryn *et al.* (1994) found *Elimia* to be absent from streams with alkalinity values below 20 mg/L $CaCO_3$, while Pip (1987) found alkalinity to be significant in explaining species richness of gastropods. However, Økland (1983) and Miller *et al.* (2000) found snails in very low calcium environments in lakes. Snails must actively transport ions in low calcium environments, which can limit production (Allan 1995).

Increased diversity with increasing amounts of riparian forest may be attributed to greater forest cover found in smaller watersheds across the state. We were often able to collect *Galba* within small watersheds in streams that maintained an active floodplain connection, in many cases connected to intact floodplain forest. It was also associated with Ohio River species of Hydrobiidae, which could underscore the importance of forest cover to this group. Increased forest cover could maintain stream bank integrity, reduce sedimentation, shade streams, mediate spates, and increase woody debris. Several snail taxa may actually respond to stable local environments. The increased amounts of point source pollution in association with Physidae also corresponds to reported pollution tolerances for the group (Barbour *et al.* 1999). Ecoregions have also been found to be a useful variable for predicting vertebrate (McCormick *et al.* 2000) and invertebrate (Johnson 2000) diversity. We recommend future studies of ecoregion associations for aquatic gastropods, coupled with variables significant in this and other studies, as suggested by Sandin and Johnson (2000).

In the Northern Appalachian Plateau (northcentral region of the state), we suspect acid precipitation may depress freshwater snail populations; areas within the northwestern portion of the Susquehanna Basin had no species of freshwater snails. While this could have been the result of inadequate sampling, most streams in this region are of sandstone geology with poor buffering capacity. We located sampling sites with high amounts of forest cover, no acid mine drainage impacts, little human development, but few snails despite available habitat. Observed pH values can drop into the low 4 range after rain events, and chronic impacts of acid precipitation include depleted cations and elevated levels of SO_4 and NO_3 (DeWalle and Swistock 1994, Driscoll *et al.* 2001) The same reduced diversity has also been determined for fishes (Van Sickle *et al.* 1996, McClurg *et al.* 2007).

Based on our work and examination of museum records, we recommend listing 7 species of freshwater snails from lotic and spring environments as species of conservation concern (Table 3). Due to limited sampling efforts for the mainstem Delaware River, we did not feel that adequate survey data were available to give a conservation status recommendation for *Lioplax subcarinata*.

A comprehensive survey of lentic taxa is sorely needed in Pennsylvania as well as a survey of the state's stygobitic gastropod fauna and additional sampling of springs. Our inclusion here of *Fontigens orolibas* (Table 3) is based on only 1 museum record for the species from Pennsylvania (Hershler *et al.* 1990); we did not detect this species in our sampling, but given its peripheral range in the state it should be considered for conservation. *Leptoxis dilatata* (Conrad, 1835) also has a peripheral range in Pennsylvania, and given the damage caused by coal mining and impoundment of the Lower Cheat River, it should be considered endangered, if not extirpated in Pennsylvania. Schwartz and Meredith (1962) also did not collect this species in the state.

We hope this publication will be useful for conservation and planning efforts. Nightingale *et al.* (2004) for example

Table 3. Pennsylvania Species of Conservation Concern from lotic systems and springs based on results from this study as compared to historical records.

Species	Family	Current global rank*	Recommended state rank*
Cincinnatia integra	Hydrobiidae	G5	S3S4 – between Special Concern and Apparently Stable
Fontigens orolibas	Hydrobiidae	G3	S1S2 – S1S2 – Between Endangered and Threatened
Gillia altilis	Hydrobiidae	G5	S1S2 – Between Endangered and Threatened
Somatogyrus integra	Hydrobiidae	G3	S2 – Threatened
Somatogyrus pennsylvanicus	Hydrobiidae	G3	S1 – Endangered
Leptoxis dilatata	Pleuroceridae	G3	S1 – Endangered
Pleurocera acuta	Pleuroceridae	G5	S2 – Threatened

* using conservation ranking methodology of NatureServe (2008).

focused on using survey information to delineate natural community groupings and associated abiotic and biotic factors in Pennsylvania. According to NatureServe (2008), more than 275 snail species in North America are considered G1 (Globally Critically Imperiled) or G2 (Globally Threatened).

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Appendix 1. Species occurrences by USGS 8-digit HUC.

Species	HUC
Amnicola limosus	Upper Delaware R., Lehigh R., Upper Juniata R., Lower Juniata R., Middle Allegheny R.-Tionesta Cr., French Cr., Middle Allegheny R.-Redbank Cr., Lower Monongahela R., Shenango R.
Bellamya chinensis	Middle Delaware R.-Mongaup Cr.-Brodhead Cr., Lower Susquehanna R.-Swatara Cr.
Campeloma decisum	Lackawaxen R., Middle Delaware R.-Mongaup Cr.-Brodhead Cr., Upper Susquehanna R.-Lackawanna R., Lower Juniata R., Lower Susquehanna R.-Swatara Cr., Lower Susquehanna R., Conococheague Cr.-Opequon Cr., Middle Allegheny R.-Tionesta Cr., French Cr., Middle Allegheny R.-Redbank Cr.
Cincinnatia integra	Middle Allegheny R.-Tionesta Cr., French Cr.
Elimia livescens	French Cr., Shenango R., Connoquenessing Cr.
Elimia virginica	Schuylkill R., Upper Susquehanna R.-Tunkhannock Cr., Upper Susquehanna R.-Lackawanna R., Lower Susquehanna R.-Penns Cr., Upper Juniata R., Lower Juniata R., Lower Susquehanna R.-Swatara Cr., Lower Susquehanna R.
Ferrissia fragilis	French Cr., Schuylkill R.
Ferrissia parallelus	Lehigh R., Monocacy R.
Ferrissia rivularis	Upper Delaware R., Lackawaxen R., Lehigh R., Schuylkill R., Upper Susquehanna R.-Tunkhannock Cr., Upper Susquehanna R.-Lackawanna R., Lower West Branch Susquehanna R., Lower Susquehanna R.-Penns Cr., Upper Juniata R., Raystown Br., Lower Juniata R., Lower Susquehanna R.-Swatara Cr., Lower Susquehanna R., North Branch Potomac R., Cacapon R.-Town Cr., Conococheague Cr.-Opequon Cr., Chautauqua Lake-Conneaut Cr., Upper Allegheny R., Conewango Cr., Middle Allegheny R.-Tionesta Cr., French Cr., Clarion R., Middle Allegheny R.-Redbank Cr., Conemaugh R., Lower Allegheny R., Lower Monongahela R., Youghiogheny R., Shenango R., Connoquenessing Cr., Upper Ohio R.-Wheeling Cr.
Fontigens nickliniana	Bald Eagle Cr., Lower Susquehanna R.-Penns Cr.
Galba exigua	Upper Ohio R.-Wheeling Cr.
Galba modicella	Upper Juniata R., Lower Juniata R., Lower Susquehanna R.-Swatara Cr., Upper Allegheny R., Middle Allegheny R.-Tionesta Cr., French Cr., Clarion R., Lower Monongahela R., Youghiogheny R., Connoquenessing Cr.
Galba obrussa	Upper Juniata R., Lower Juniata R., Middle Allegheny R.-Tionesta Cr., Middle Allegheny R.-Redbank Cr., Upper Ohio R.-Wheeling Cr.
Galba parva	Lower Juniata R., Conemaugh R.
Galba rustica	Clarion R.
Gyraulus deflectus	Middle Delaware R.-Mongaup Cr.-Brodhead Cr., Middle Allegheny R.-Tionesta Cr., Shenango R.
Gyraulus parvus	Lehigh R., Schuylkill R., Upper Allegheny R., French Cr.
Helisoma anceps	Middle Delaware R.-Mongaup Cr.-Brodhead Cr., Crosswicks Cr.-Neshaminy Cr., Upper Susquehanna R., Pine Cr., Lower West Branch Susquehanna R., Lower Susquehanna R.-Penns Cr., Raystown Br., Lower Juniata R., North Branch Potomac R., Cacapon R.-Town Cr., Conococheague Cr.-Opequon Cr., Upper Allegheny R., Conewango Cr., Middle Allegheny R.-Tionesta Cr., French Cr., Clarion R., Middle Allegheny R.-Redbank Cr., Conemaugh R., Youghiogheny R.
Laevapex fuscus	Lower Susquehanna R.-Swatara Cr., Cacapon R.-Town Cr., Upper Allegheny R., Conewango Cr., Middle Allegheny R.-Redbank Cr., Middle Allegheny R.-Tionesta Cr., French Cr., Clarion R.
Leptoxis carinata	Upper Susquehanna R., Upper Susquehanna R.-Tunkhannock Cr., Upper Susquehanna R.-Lackawanna R., Lower Susquehanna R.-Penns Cr., Upper Juniata R., Raystown Br., Lower Juniata R., Lower Susquehanna R.-Swatara Cr., Lower Susquehanna R., North Branch Potomac R., Conococheague Cr.-Opequon Cr., Monocacy R.
Lithasia obovata	Upper Allegheny R., Conewango Cr., Middle Allegheny R.-Tionesta Cr., French Cr., Middle Allegheny R.-Redbank Cr., Shenango R., Connoquenessing Cr.
Lyogyrus granum	Upper Delaware R., Lackawaxen R., Middle Delaware R.-Mongaup Cr.-Brodhead Cr., Crosswicks Cr.-Neshaminy Cr., Lower Susquehanna R.-Swatara Cr.

Appendix 1. (continued)

Species	HUC
Micromenetus dilatatus	Upper West Branch Susquehanna R., Upper Juniata R., Raystown Br., Lower Juniata R., Cacapon R.-Town Cr., Youghiogheny R., Shenango R.
Physa acuta	Lackawaxen R., Middle Delaware R.-Mongaup Cr.-Brodhead Cr., Crosswicks Cr.-Neshaminy Cr., Brandywine Cr.-Christina R., Tioga R., Upper Susquehanna R.-Tunkhannock Cr., Upper Susquehanna R.-Lackawanna R., Pine Cr., Lower West Branch Susquehanna R., Lower Susquehanna R.-Penns Cr., Upper Juniata R., Raystown Br., Lower Juniata R., Lower Susquehanna R.-Swatara Cr., Lower Susquehanna R., Conococheague Cr.-Opequon Cr., Monocacy R., Chautauqua Lake-Conneaut Cr., Upper Allegheny R., Conewango Cr., Middle Allegheny R.-Tionesta Cr., French Cr., Clarion R., Middle Allegheny R.-Redbank Cr., Lower Allegheny R., Lower Monongahela R., Youghiogheny R., Shenango R., Connoquenessing, Upper Ohio R.-Wheeling Cr.
Physa ancillaria	Upper Delaware R., Middle Delaware R.-Mongaup Cr.-Brodhead Cr., Raystown Br., Lower Susquehanna R.-Swatara Cr., Conococheague Cr.-Opequon Cr., Upper Ohio R.
Physa gyrina	Upper Delaware R., Lackawaxen R., Lower Delaware R., Schuylkill R., Upper Susquehanna R.-Lackawanna R., Upper Juniata R., Raystown Br. Br., Lower Juniata R., Lower Susquehanna R.-Swatara Cr., North Branch Potomac R., Cacapon R.-Town Cr., Middle Allegheny R.-Tionesta Cr., French Cr., Middle Allegheny R.-Redbank Cr., Conemaugh R., Lower Monongahela R., Youghiogheny R., Shenango R., Upper Ohio R.-Wheeling Cr.
Planorbella campanulata	Middle Delaware R.-Mongaup Cr.-Brodhead Cr., Crosswicks Cr.-Neshaminy Cr.
Planorbella trivolvis	Lower West Branch Susquehanna R., Lower Juniata R., Lower Susquehanna R.-Swatara Cr., Lower Susquehanna R., Upper Allegheny R., Middle Allegheny R.-Tionesta Cr., French Cr., Lower Monongahela R., Shenango R.
Pleurocera acuta	French Cr.
Pleurocera canaliculata	Upper Ohio R., French Cr.
Promenetus exacuous	Cacapon R.-Town Cr.
Pseudosuccinea columella	Lehigh R., Upper Susquehanna R.-Tunkhannock Cr., Lower West Branch Susquehanna R., Lower Susquehanna R., French Cr.
Somatogyrus integra	Upper Allegheny R., Conewango Cr., Middle Allegheny R.-Tionesta Cr., French Cr., Middle Allegheny R.-Redbank Cr.
Somatogyrus pennsylvanicus	Lower Susquehanna R.
Stagnicola catescopium	Lower Juniata R., Lower Susquehanna R., French Cr.
Stagnicola elodes	Lower Susquehanna R.-Swatara Cr.
Stagnicola emarginata	Upper Allegheny R.