APPENDIX D

An Evaluation of Wild Trout Abundance and Hydroecological Indices for Streams in Pennsylvania

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Introduction

There has been recent interest in developing recommendations for environmental flow standards to sustain desirable aquatic community structure and function in streams based on hydroecological indices that describe natural flow regimes in terms of magnitude, duration, frequency, timing, and rates of change of flows (Poff 1996, Olden and Poff 2003). The Hydroecological Integrity Process (HIP) developed by the U. S. Geological Survey (Kennen et al. 2007) calculates 171 hydroecological indices from U.S.G.S. water gauge records and provides options to evaluate how these indices change over time under alternative water management scenarios. An evaluation of sub basins of Pocono Creek in northeast Pennsylvania based on simulated daily flow data used 28 of these indices to develop environmental flow standards corresponding to 25th to 75th percentiles of index variation over time (J. Henriksen, J. Heasley, and M. Hartle, unpublished manuscript, Pocono Creek Hydroecological Integrity Assessment Process: Framework for Sustainable Watershed Management). The 28 indices used were low (ML1 – ML12, cfs) and high (MH1- MH12, cfs) daily flows for each month, frequency of low (FL1, number of events/year with flows <25th percentile) and high (FH1, number of events/year with flows >75th percentile) flows, and duration of low (DL16, number of days/year with flows <25th percentile) and high (DH15, number of days/year with flows >75th percentile) flows.

Although there is wide spread recognition that variation in magnitude, duration, frequency, timing, and rate changes of water flows affect aquatic communities, the use of hydroecological indices for setting environmental flow standards is not predicated on linking any specific index with some measureable attribute of the aquatic communities. However, to provide greater assurance that environmental flow standards developed using these hydroecological indices are actually likely to sustain aquatic communities, it is desirable to understand how measured attributes of the aquatic community actually respond to changes in the hydroecological indices (Arthington et al. 2006). The objective of this evaluation was to compare long-term estimates of wild trout abundance, primarily brown trout (*Salmo trutta*) but some brook trout (*Salvelinus fontinalis*), with hydroecological indices for streams in Pennsylvania. Wild trout abundance was used because sustaining wild trout populations was an important objective for developing environmental flow standards for Pocono Creek (Henriksen et al., Unpublished manuscript).

Methods

The Pennsylvania Fish and Boat Commission provided wild trout (adult and young of year) density and biomass estimates that were linked to flow records for gauges on 42 streams in Pennsylvania (Table 1). Trout abundance was sampled 1 to 40 times on the various streams. For our initial analyses, we considered each stream as a sample replicate and averaged trout density and biomass across samples within each stream. Average adult trout biomass always was at fairly low levels (<10 kg/ha) for streams with drainage areas >500 square miles but ranged from 0 to 80 kg/ha in those streams with drainage areas <500 square miles (Figure 1). Young of year trout biomass was only measured for 29 of the 42 streams and followed a similar pattern with drainage area as adults (Figure 1). Because of the reduced sample size for young of year trout, all analyses were conducted only for adult trout biomass.

The 42 streams included 16 that had some indication in the water gauge records that flows were altered or regulated to some degree. We could not distinguish the degree of flow alteration for all these regulated streams. The regulated streams had low to high trout biomass similar to the unregulated streams and include small to very large drainage areas (Figure 1). Twenty-one of the 42 streams were included in a recent HIP stream classification made for The Nature Conservancy: 9 were classified as stable ground water; 8 as low volume, perennial runoff; 2 as moderate volume, perennial runoff; and 2 as high volume, perennial runoff streams. Because all 42 streams were not classified and there were a small number of streams in each class, we did not try to use these stream classes in our statistical analyses.

Flow records from U.S.G.S. gauges often did not completely coincide with years in which trout were sampled in the various streams. We considered three different periods of record for flows to use in computing the 171 hydroecological indices given in Kennen et al. (2007). (1) We used the entire period of record for the gauges, regardless of how it coincided with trout sampling. (2) We used the period of record within the 15 years prior to the last year trout were sampled. (3) We used the period of record within the 15 years prior to the last year trout were sampled or the period of record contained within the 3 years prior to the first year trout were sampled to the last year trout were sampled, whichever was longer. Flow indices calculated for (2) and (3) were very similar and we only report the results for (1) and (3). Because 6 streams had no flow records within 15 years of when the trout were sampled, sample sizes for flow period of records (2) and (3) were $n = 36$ compared to $n = 42$ for the entire period of record (1). For Pocono Creek (station 1441500) that only had daily flow records before 1920, we used simulated daily flow values for 1975 to 2005 provided by M. Hantush to calculate indices for period (3).

All 171 hydroecological indices were computed for streams for the two periods of record (1) and (3). We initially focused statistical analyses on the 28 indices previously used for the Pocono Creek HIP but examined relationships for all the other indices too. We expected there to be considerable heterogeneity in trout abundance with any of the flow indices because hydrology is only one of many factors that limit trout populations (Terrell et al. 1996, Cade et al. 1999, Cade et al. 2005). So we used quantile regression (Cade and Noon 2003, Koenker 2005) to estimate changes in the 25^{th} to 75^{th} percentiles (0.25 to 0.75 quantiles) of adult trout biomass in simple linear regression models with the various hydroecological indices as predictor variables. Quantile regression estimates changes in all parts (the quantiles) of the response variable (y = trout biomass) distribution conditional on the linear predictors (hydrological indices), providing a comprehensive view of regression relationships when there is structured heterogeneity in the response variable as commonly occurs with ecological limiting factors (Terrell et al. 1996, Cade et al. 1999, Cade et al. 2005). Quantile regression extends the conventional linear model to estimates of all (or any selected subset) of the conditional quantiles of the response variable distribution rather than just the mean. Recent examples of quantile regression analyses of fish habitat relationships are Terrell et al. 1996, Dunham et al. 2002, and Zoellick and Cade (2006). Because of our relatively small samples and the need for weighted quantile regression estimates, we only expected to obtain reasonably precise estimates and associated confidence intervals for quantiles from 0.25 to 0.75 (Cade et al. 2006). Confidence intervals were based on rank score inversion and quantile bandwidth adjustments for heterogeneous variances. Although we estimated quantiles by percentile increments between 0.25 and 0.75, we only graphed the linear functions for 0.25, 0.50, and 0.75 quantiles (corresponding to 1st, 2nd, and 3rd quartiles). Quantile regression estimates were obtained from the quantreg package for R. We used weighted quantile regression models based on the number of times streams were sampled for trout, where weights were equal to number of samples ÷ 10 for streams sampled ≤ 10 times or 1.0 for streams sampled >10 times. This weighting procedure gave less weight to streams only sampled a few times, but did not give inordinately high weights to those streams sampled 10 or more times. We felt this was desirable because those streams sampled >10 times were always streams with highest trout abundance, whereas streams sampled <10 times had low to high abundance of trout.

We report results for simple linear regression models for those hydroecological indices that provided any reasonable evidence of nonzero relationships (90% confidence intervals exclude zero) for some portion of the 25th to 75th percentiles of trout biomass. Many of the hydroecological indices; e.g., median (MA2) annual daily flow, monthly low (ML1-ML12), or monthly high (MH1 – MH12) flows; were strongly correlated (r = 0.94 – 0.99) with drainage area and, thus, had the same disjunct relationship as between trout biomass and drainage area (Figure 1). To provide more reasonable quantile regression estimates for these variables, we excluded all the streams with drainage areas >500 square miles and estimated piecewise linear models using b-spline functions on the $\log_{10}$ of the flow indices. We eyeballed break points (knots) for the piecewise linear functions because we lacked sufficient samples to try and estimate break points. Selection of the piecewise linear rather than simple linear models was justified based on reductions in Akaike's information criterion (AIC) calculated as in Cade et al. (2005). The sharp breaks in the piecewise linear functions of these estimates should be interpreted as only indicating regions of the predictor variables where there were transitions between positive and negative rates of change. With larger sample sizes, a more smooth transition rather than a sharp break between the linear pieces would provide more ecologically reasonable estimates of transitions between states. We also considered quantile regression models with multiple predictor variables, e.g., $\log_{10}$(ML8) + DL16. However, we found either similar coefficient estimates with only minor changes in precision (90% confidence intervals) as the models with a single hydroecological index or that precision of the estimates in the multiple regression models became excessively large.

Results

When we used period of record (3) most closely coincident with the time frame of the trout sampling, we found that those hydroecological indices strongly correlated with drainage area, mean and median (MA2) annual daily flow, monthly low (ML1 – ML12) flows, and monthly high (MH1 – MH12) flows, all had similar multiplicative patterns of highest trout biomass occurring at intermediate values of the indices, declining to lower values as those indices increased or decreased. We present results only for median (MA2) annual daily flow (Figure 2) and low flow (ML8) in August (Figure 3). Highest quantiles of trout biomass occurred at about 100 cfs of median annual flow but 50% of the highest biomass was still maintained as median flows decreased to 10 cfs or increased to 300 cfs (Figure 2). There was evidence of nonzero effects of MA2, as indicated by 90% confidence intervals that excluded zero, for 0.60 to 0.75 quantiles (Figure 2). With August low flow, highest biomass occurred around 60 cfs but 50% of the highest biomass was still maintained as August low flows decreased to 1 cfs or increased to 100 cfs (Figure 3). The outlying value of 0.01 cfs for August low flow was actually a flow of 0 cfs that was assigned 0.01 so that we could take logarithms. This 0 cfs low flow was for station 1432000 (Wallenpaupack Creek) that has flows regulated by Lake Wallenpaupack. This outlying value is one reason confidence intervals (90%) for ML8 estimates were rather unstable (the sawtooth like pattern of CI) and indicated only weak evidence of nonzero relationships for some quantiles (actually had to use an asymptotic variance/covariance method rather than the rank score inversion method for estimating CI because of the unstability). When we considered these same indices calculated on the entire flow record (1), there were similar patterns but increases in trout biomass as median annual flow (Figure 9) increased to 100 cfs were not supported although decreases above 100 cfs were supported. A similar pattern with low flow in August (Figure 10) was evident but without the impact of the outlying flow of 0 cfs because the flow record now included years prior to station 143200 being regulated. Negative changes in trout biomass with August low flows increasing above 63 cfs were primarily supported for 0.30 to 0.55 quantiles and positive changes as August low flows increased to 63 cfs were very weakly supported for 0.73 to 0.75 quantiles (Figure 10).

Hydroecologogical indices that were not strongly correlated with drainage area that had evidence of nonzero linear relationships with any of the 25th to 75th percentiles of trout biomass were the ratio of minimum to median annual flow, ML16 (Figures 4 and 11); the number of days with flows <25th percentile of flow, DL16 (Figures 5 and 12); the ratio of the minimum of 30-day moving average to median flow, DL13 (Figures 6 and 13); the coefficient of variation of number of days >75th percentile of flow, DH16 (Figures 7 and 14); and the number of days >75th percentile of flow, DH15 (Figures 8 and 15). Quantiles of trout biomass near the 75th percentile increased with increasing values of DL13 and DL16 and decreased with increasing values of DL16, indicating increased biomass of trout on streams having fewer days with extreme low flows. The estimated patterns were similar whether the indices were calculated using the shorter period of record (3) coinciding better with the years trout were sampled or the entire period of flow record (1). However, the increased sample size for the entire flow record (1) led to more precise estimates with 90% confidence intervals excluding zero for more quantiles near the 75th percentile. Lower quantiles of trout biomass conditional on ML16, DL16, and

DL13 changed in a fashion similar to the quantiles near 0.75 but 90% confidence intervals overlapped zero because the estimates were less precise partly due to the lower sampling weights associated with most streams that had low trout abundance. Note that ML16 and DL13 were strongly correlated ($r = 0.93$) and DL16 and DL13 were weakly, inversely related ($r = –0.43$).

Percentiles of trout biomass near the 0.75 quantile increased with increasing DH16 (Figures 7 and 14) and decreasing DH15 (Figures 8 and 15) similarly for the two different periods of record used for flows. Again, the increased sample size for the entire period of flow records (1) led to slightly more precise estimates and more confidence intervals excluding zero for quantiles near 0.75. Collectively, the relationships for these two indices indicate weak increases in trout biomass for streams having shorter, more variable, duration of high flow events (>75th percentile of flow). These two hydroecological indices were negatively correlated ($r = –0.63$).

Discussion

The estimated nonzero effects of these hydroecological indices indicated highly variable effects across the 25th to 75th percentiles of adult wild trout biomass. For example, doubling the number of days with flow <25th percentile of flow from 5 to 10 (an interval containing the majority of streams in Figure 12), decreased the estimated 25th to 75th percentiles of trout biomass from 25-80 kg/ha to 3-45 kg/ha. So while there was a substantial reduction in biomass with a doubling of days of low flow, considerable biomass remained such that the intervals for 25th to 75th percentiles overlapped. The precision of the lower percentile estimates in our models were often poor because of the lower sampling weights applied to streams with low trout abundance. These could be improved by increasing the sampling intensity for streams with lower abundance of trout. But all indications are that trout biomass will be highly variable across a substantial range of values for any of these hydroecological indices.

It is important to appreciate the different temporal and spatial scales that are applicable to the hydroecological indices and our statistical analyses of trout biomass. Our analyses used temporally averaged values for both the trout biomass and hydroecological indices, where the statistical variation modeled was associated with among stream variation (i.e., spatial). This spatial variation of time averaged values is consistent with the spatial, among stream variation that is incorporated in both the procedures for stream classification and selection of primary and secondary hydroecological indices in HIP applications (Olden and Poff 2003, Kennen et al. 2007). However, this spatial variation of time averaged values is not consistent with the scale of annual variation among hydroecological indices within a single stream, the statistical variation that is often used for setting environmental flow standards by the default computations in HIP (Kennen et al. 2007) and was used for setting flow standards in sub basins of Pocono Creek (Henriksen et al., unpublished report). The temporal variation of the hydroecological indices within any single stream will typically be less than the variation in the indices among streams. For example, in the synthetic daily flow data we used for Pocono Creek, the index ML8, August low flow, has annual variation in flows ranging from 5 to 54 cfs (25th percentile = 9 cfs, 75th percentile = 23 cfs). The variation among Pennsylvania streams with drainage areas <500 square miles for ML8 (Figure 3) was 0 to 150 cfs (25th percentile = 8 cfs, 75th percentile = 53 cfs), considerably greater than the annual variation within Pocono Creek.   Average adult wild trout biomass varied from 0.2 to 76.7 kg/ha in streams that had low flows in August of 8 to 53 cfs, corresponding to 25^{th} to 75^{th} percentiles of ML8 among streams (Figure 3). The trout biomass in Pocono Creek varied from 16.8 to 78.2 kg/ha among years that had low flows in August of 9 to 23 cfs, corresponding to 25^{th} to 75^{th} percentiles of annual variation for this time period. Thus, among stream variation in average trout biomass exceeded (by including lower or higher biomass) variation of biomass within a single selected stream, and among stream variation in the hydroecological indices exceeded the annual variation of the indices within a single stream.

It might be possible to conduct additional statistical analyses where temporal variation among years within a stream are included with the among stream variation in both hydroecological indices and trout biomass. This combination of a cross-sectional and longitudinal analysis would, however, only increase the variation to be modeled in both trout biomass (the dependent variable y in the regression) and the hydroecological indices (the predictor variables X in the regression), further supporting our basic interpretation that low to high trout biomass occurs across a large range of values for the indices. Furthermore, as many of the hydroecological indices are strongly correlated with drainage area, many of the observed patterns of trout biomass as a function of these indices will continue to be dictated by the relationship with drainage area (Figure 1). However, the additional sample size and ability to incorporate previous year (or multiple years) values in a temporal autocorrelated regression model might improve the precision of our quantile regression estimates and, thus, clarify the pattern of variability.

Literature Cited

Arthington, A. H., S. E. Bunn, N. L. Poff, and R. J. Naiman. 2006. The challenge of providing environmental flow rules to sustain river ecosystems. Ecological Applications 16: 1311-1318.

Cade, B. S., and B. R. Noon. 2003. A gentle introduction to quantile regression for ecologists. Frontiers in Ecology and the Environment 1: 412-420.

Cade, B. S., B. R. Noon, and C. H. Flather. 2005. Quantile regression reveals hidden bias and uncertainty in habitat models. Ecology 86: 786-800.

Cade, B. S., J. D. Richards, and P. W. Mielke, Jr. 2006. Rank score and permutation testing alternatives for regression quantile estimates. Journal of Statistical Computation and Simulation 76: 331-355.

Cade, B. S., J. W. Terrell, and R. L. Schroeder. 1999. Estimating effects of limiting factors with regression quantiles. Ecology 80: 311-323.

Dunham, J. B., B. S. Cade, and J. W. Terrell. 2002. Influences of spatial and temporal variation on fish-habitat relationships defined by regression quantiles. Transactions of the American Fisheries Society 131: 86-98.

Kennen, J.G., J.A. Henriksen, and S.P. Nieswand. 2007. Development of the hydroecological integrity assessment process for determining environmental flows for New Jersey streams. Scientific Investigations Report 2007-5206. U.S. Geological Survey. 55 p.

Koenker, R. 2005. Quantile Regression. Econometric Society Monographs. Cambridge University Press. 349pp.

Olden, J. D., and N. L. Poff. 2003. Redundancy and the choice of hydrologic indices for characterizing streamflow regimes. River Research and Applications 19: 101-121.

Poff, N. L. 1996. A hydrogeography of unregulated streams in the United States and an examination of scale-dependence in some hydrological descriptors. Freshwater Biology 36: 71-91.

Terrell, J. W., B. S. Cade, J. Carpenter, and J. M. Thompson. 1996. Modeling stream fish habitat limitations from wedge-shaped patterns of variation in standing stock. Transactions of the American Fisheries Society 125: 104-117.

Zoellick, B. W., and B. S. Cade. 2006. Evaluating redband trout habitat in sagebrush desert basins in southwestern Idaho. North American Journal of Fisheries Management 26:268-281.

Table 1. U.S. Geological Survey gauge station numbers, stream name, square miles of drainage area (DA), starting year for flow records (POR_S), ending year of flow records (POR_E), number of trout samples (N), first year of fish sampling (FISH_S), last year of fish sampling (FISH_E), average adult wild trout biomass (AD_KGHA), and average young of year wild trout biomass (YOY_KGHA).

STATION	NAME	DA	POR_S	POR_E	N	FISH_S	FISH_E	AD_KGHA	YOY_KGHA
1428750	West Branch Lackawaxen River near Aldenville, PA	40.6	1986	2007	1	1982	1982	19.13	2.96
1432000	Wallenpaupack Creek at Wilsonville, PA	228.0	1909	2007	6	1978	1993	39.04	8.73
1432500	Shohola Creek near Shohola, PA	83.6	1920	1928	1	1977	1977	1.79	
1440400	Brodhead Creek near Analomink, PA	65.9	1957	2007	1	1978	1978	32.71	5.37
1441000	McMichaels Creek at Stroudsburg, PA	65.3	1912	1937	8	1977	2004	12.19	
1441500	Pocono Creek near Stroudsburg, PA	41.0	1912	1919	29	1978	2002	49.29	
1442500	Brodhead Creek at Minisink Hills, PA	259.0	1950	2007	4	1978	1991	2.79	0.07
1446600	Martins Creek near East Bangor, PA	10.4	1962	1977	17	1976	2001	45.49	
1447500	Lehigh River at Stoddartsville, PA	91.7	1943	2007	1	1977	1977	6.03	0.07
1447680	Tunkhannock Creek near Long Pond, PA	16.8	1965	2007	2	2002	2002	4.02	0.23
1447800	Lehigh R below F E Walter Res nr White Haven, PA	290.0	1957	2007	1	1977	1977	2.52	0.23
1448500	Dilldown Creek near Long Pond, PA	2.4	1949	1996	1	1979	1979	18.81	
1449000	Lehigh River at Lehighton, PA	591.0	1982	2007	1	2000	2000	4.19	0.14
1449360	Pohopoco Creek at Kresgeville, PA	49.9	1966	2007	1	1995	1995	47.77	28.93
1449500	Wild Creek at Hatchery, PA	16.8	1941	1978	1	1979	1979	3.91	
1449800	Pohopoco Cr below Beltzville Lake nr Parryville, PA	96.4	1967	2007	16	1977	2004	36.25	2.94
1450500	Aquashicola Creek at Palmerton, PA	76.7	1939	2007	9	1976	2001	55.87	6.13
1451000	Lehigh River at Walnutport, PA	889.0	1946	2007	1	1977	1977	3.18	0.37
1451500	Little Lehigh Creek near Allentown, PA	80.8	1947	2007	1	1978	1978	0.00	0.05
1451650	Little Lehigh Cr at Tenth St Br at Allentown, PA	98.2	1986	2007	33	1977	2004	81.64	2.28
1452500	Monocacy Creek at Bethlehem, PA	44.5	1948	2007	40	1976	2001	76.72	5.54
1453000	Lehigh River at Bethlehem, PA	1279.0	1909	2007	1	1977	1977	6.59	0.98
1453500	Saucon Creek at Lanark, PA	12.1	1948	1953	26	1976	2004	63.49	
1454000	South Branch Saucon Creek at Friedensville, PA	10.3	1948	1953	4	1976	2006	14.48	
1454500	Saucon Creek at Friedensville, PA	26.6	1948	1953	1	1998	1998	64.08	
1454700	Lehigh River at Glendon, PA	1359.0	1966	2007	6	1977	2006	4.29	0.13
1468500	Schuylkill River at Landingville, PA	133.0	1973	2007	1	2000	2000	1.33	0.13

1469500	Little Schuylkill River at Tamaqua, PA	42.9	1919	2007	10	1976	2003	6.99	0.28
1470500	Schuylkill River at Berne, PA	355.0	1947	2007	1	2002	2002	1.60	0.61
1470756	Maiden Creek at Virginville, PA	159.0	1973	1994	2	1976	1976	0.23	
1471510	Schuylkill River at Reading, PA	880.0	1977	2007	1	2002	2002	0.36	0.66
1472000	Schuylkill River at Pottstown, PA	1147.0	1927	2007	1	2000	2000	4.20	0.17
1472174	Pickering Creek near Chester Springs, PA	6.0	1967	1982	4	1977	1992	6.07	
1472198	Perkiomen Creek at East Greenville, PA	38.0	1981	2007	3	1979	1995	31.84	2.69
1472199	West Branch Perkiomen Creek at Hillegass, PA	23.0	1981	2007	13	1978	2002	61.29	3.99
1473000	Perkiomen Creek at Graterford, PA	279.0	1914	2007	1	1995	1995	54.18	14.56
1473169	Valley Cr at PA Turnpike Bridge nr Valley Forge, PA	20.8	1982	2007	8	1982	1990	43.46	4.09
1473500	Schuylkill River a Norristown, PA	1760.0	2001	2007	1	2002	2002	0.68	0.00
1474500	Schuylkill River at Philadelphia, PA	1893.0	1931	2007	6	2000	2002	8.22	0.13
1475300	Darby Creek at Waterloo Mills near Devon, PA	5.1	1972	1997	1	1976	1976	3.14	
1475510	Darby Creek near Darby, PA	37.4	1964	1990	3	1976	1986	2.41	
1475850	Crum Creek near Newtown Square, PA	15.8	1981	2007	3	1999	1999	14.65	2.08

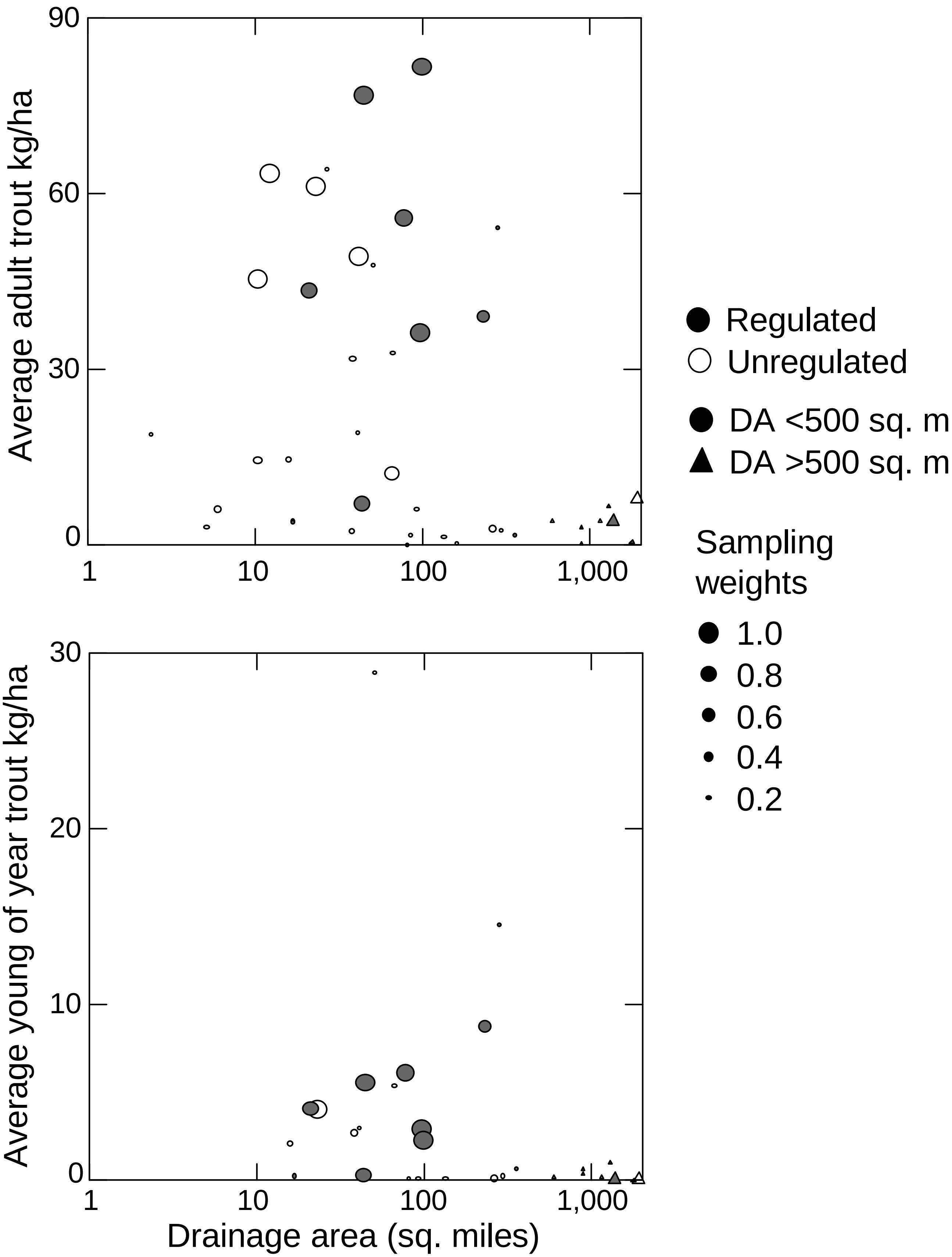


Figure 1. Young of year (*n* = 29) and adult (*n* = 42) wild trout biomass and drainage areas of streams in Pennsylvania. Sampling weights are the minimum of (number of times trout were sampled ÷ 10, or 1.0). Regulated streams (solid symbols) were those with any indication of human manipulation of flow and unregulated (open symbols) were the converse.

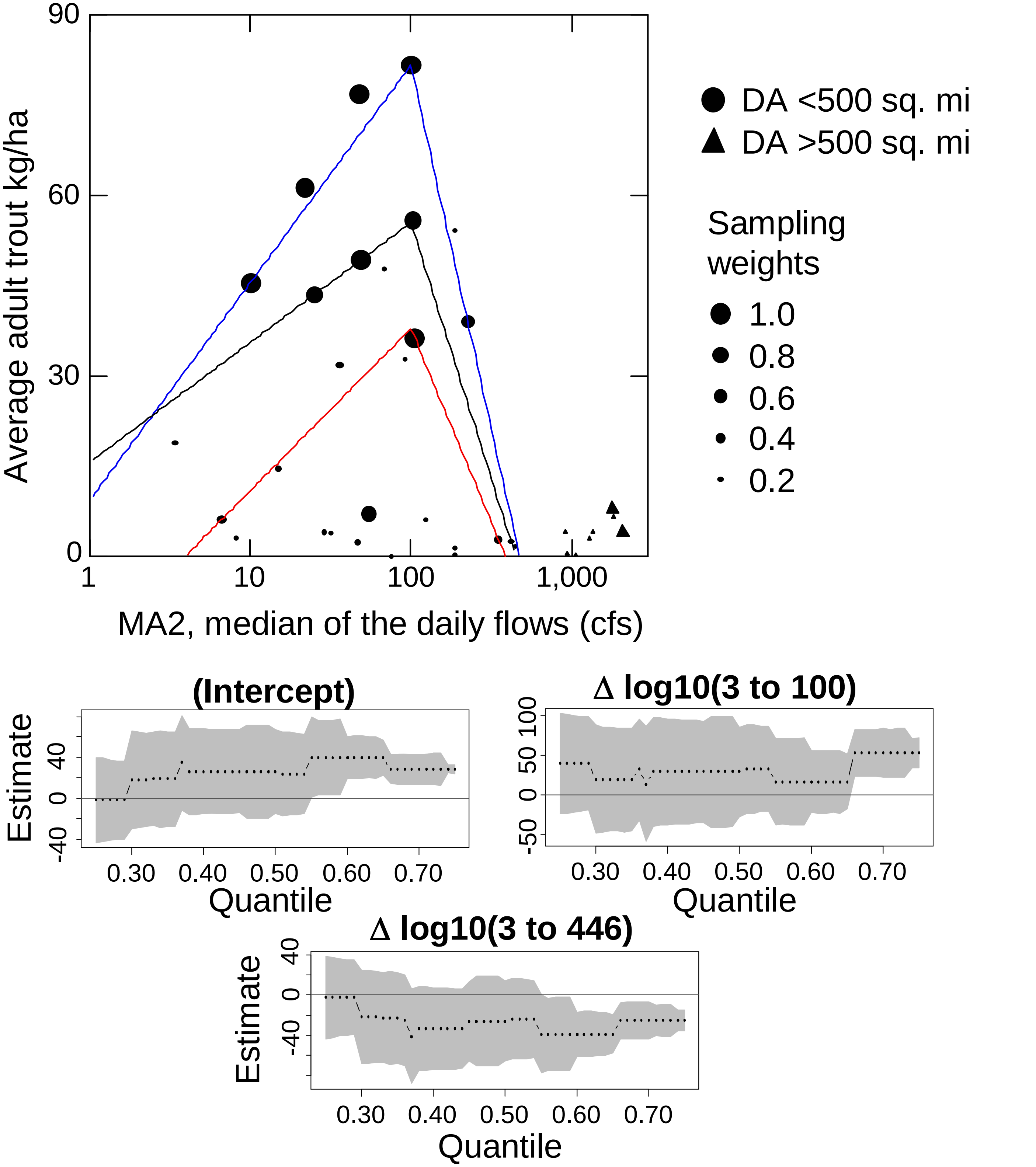


Figure 2 Quantile (0.25 – 0.75) regression estimates of wild trout biomass as a piecewise (break point at 100 cfs) linear function of log10 ML2, median daily flow, based on the 15 years of flow prior to last year trout were sampled or years of trout sampling plus previous 3 years (whichever is longer) for *n* = 36 streams in Pennsylvania. In the upper panel the blue line is 0.75, black line is 0.50, and red line is 0.25 quantile. Sampling weights are the minimum of (number of times trout were sampled ÷ 10, or 1.0). Streams with drainage areas >500 sq. miles were not used in estimation. In lower panels, points are estimates by increments of 0.01 from 0.25 – 0.75 quantiles and grey shaded bands bound 90% confidence intervals.

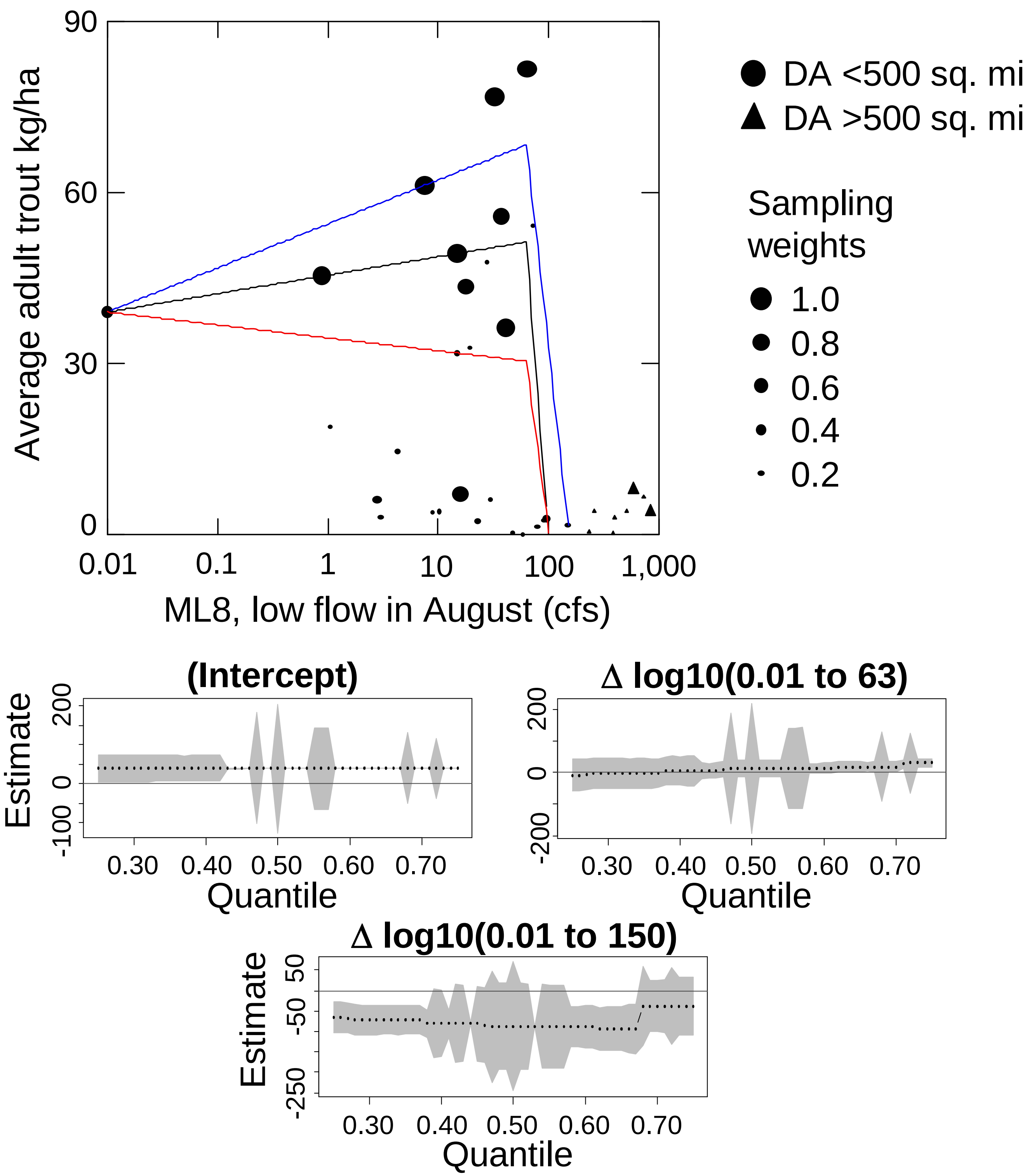


Figure 3 Quantile (0.25 – 0.75) regression estimates of wild trout biomass as a piecewise (break point at 63 cfs) linear function of log10 ML8, low flow in August, based on the 15 years of flow prior to last year trout were sampled or years of trout sampling plus previous 3 years (whichever is longer) for *n* = 36 streams in Pennsylvania. In the upper panel the blue line is 0.75, black line is 0.50, and red line is 0.25 quantile. Sampling weights are the minimum of (number of times trout were sampled ÷ 10, or 1.0). Streams with drainage areas >500 sq. miles were not used in estimation. In lower panels, points are estimates by increments of 0.01 from 0.25 – 0.75 quantiles and grey shaded bands bound 90% confidence intervals.

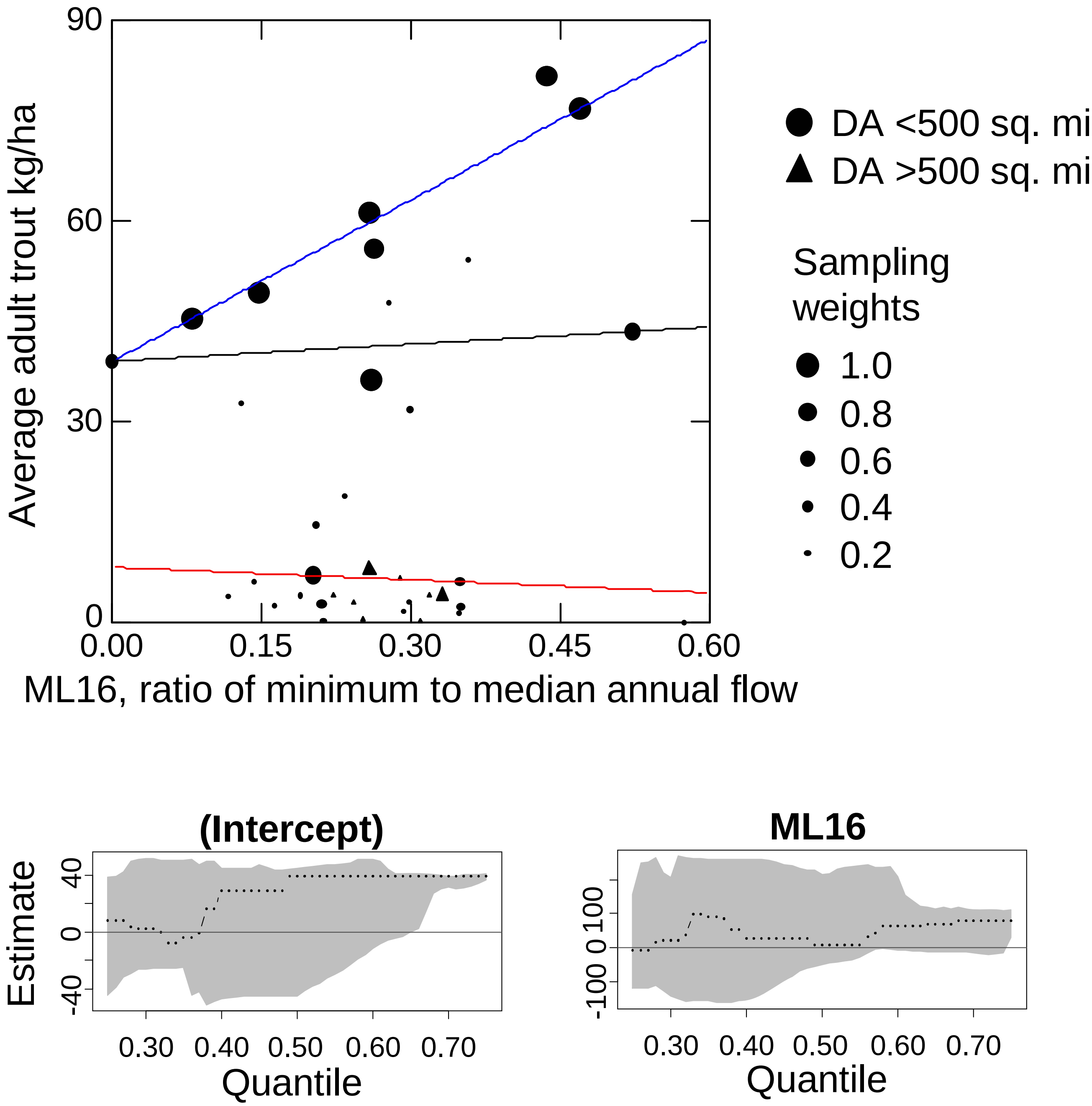


Figure 4. Quantile (0.25 – 0.75) regression estimates of wild trout biomass as a function of ML16, ratio of minimum to median annual flow, based on the 15 years of flow prior to last year trout were sampled or years of trout sampling plus previous 3 years (whichever is longer) for *n* = 36 streams in Pennsylvania. In the upper panel the blue line is 0.75, black line is 0.50, and red line is 0.25 quantile. Sampling weights are the minimum of (number of times trout were sampled ÷ 10, or 1.0). In lower panels, points are estimates by increments of 0.01 from 0.25 – 0.75 quantiles and grey shaded bands bound 90% confidence intervals.

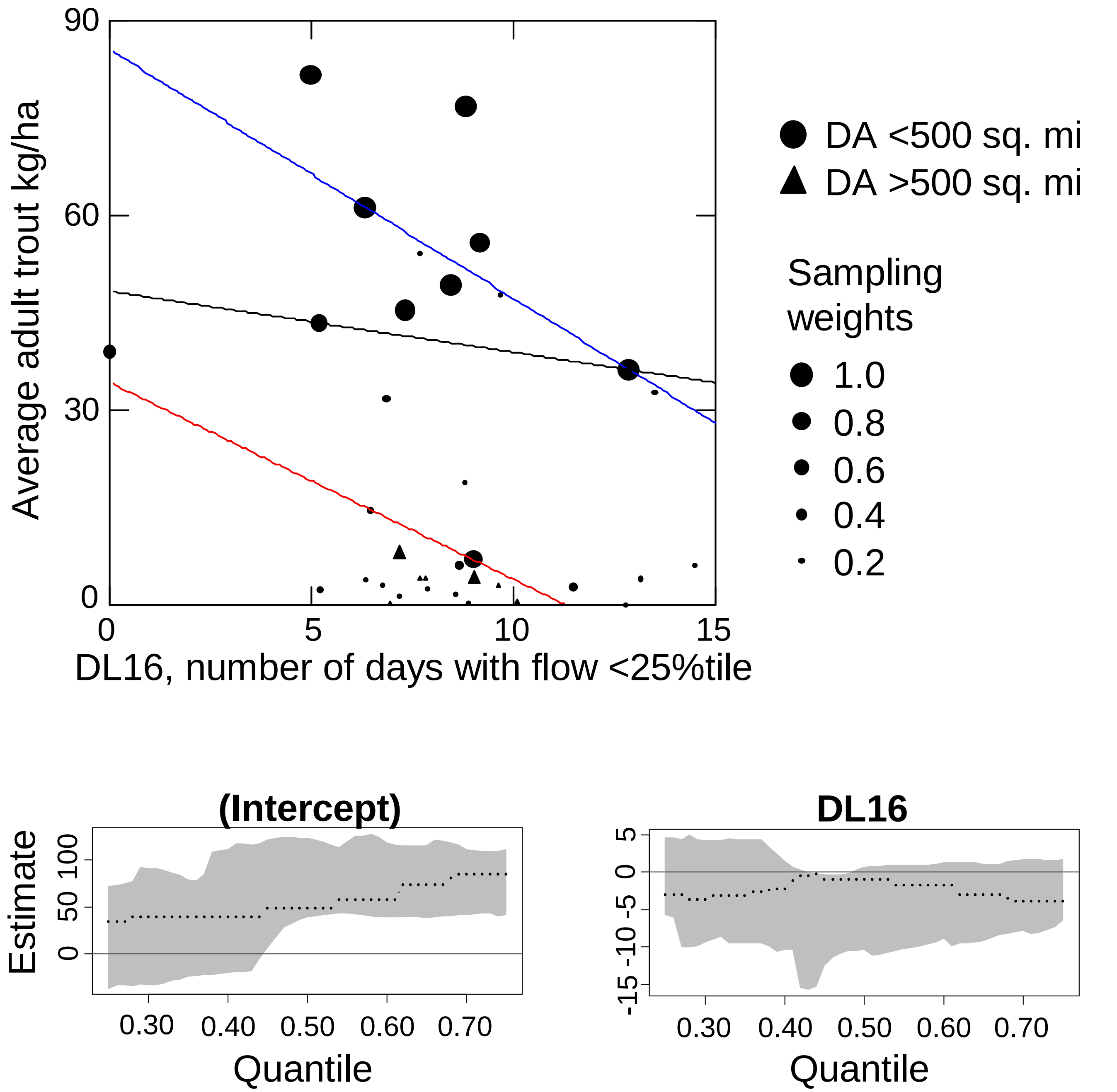


Figure 5. Quantile (0.25 – 0.75) regression estimates of wild trout biomass as a function of DL16, average number of days with flow <25%tile, based on the 15 years of flow prior to last year trout were sampled or years of trout sampling plus previous 3 years (whichever is longer) for n = 36 streams in Pennsylvania. In the upper panel the blue line is 0.75, black line is 0.50, and red line is 0.25 quantile. Sampling weights are the minimum of (number of times trout were sampled ÷ 10, or 1.0). In lower panels, points are estimates by increments of 0.01 from 0.25 – 0.75 quantiles and grey shaded bands bound 90% confidence intervals.

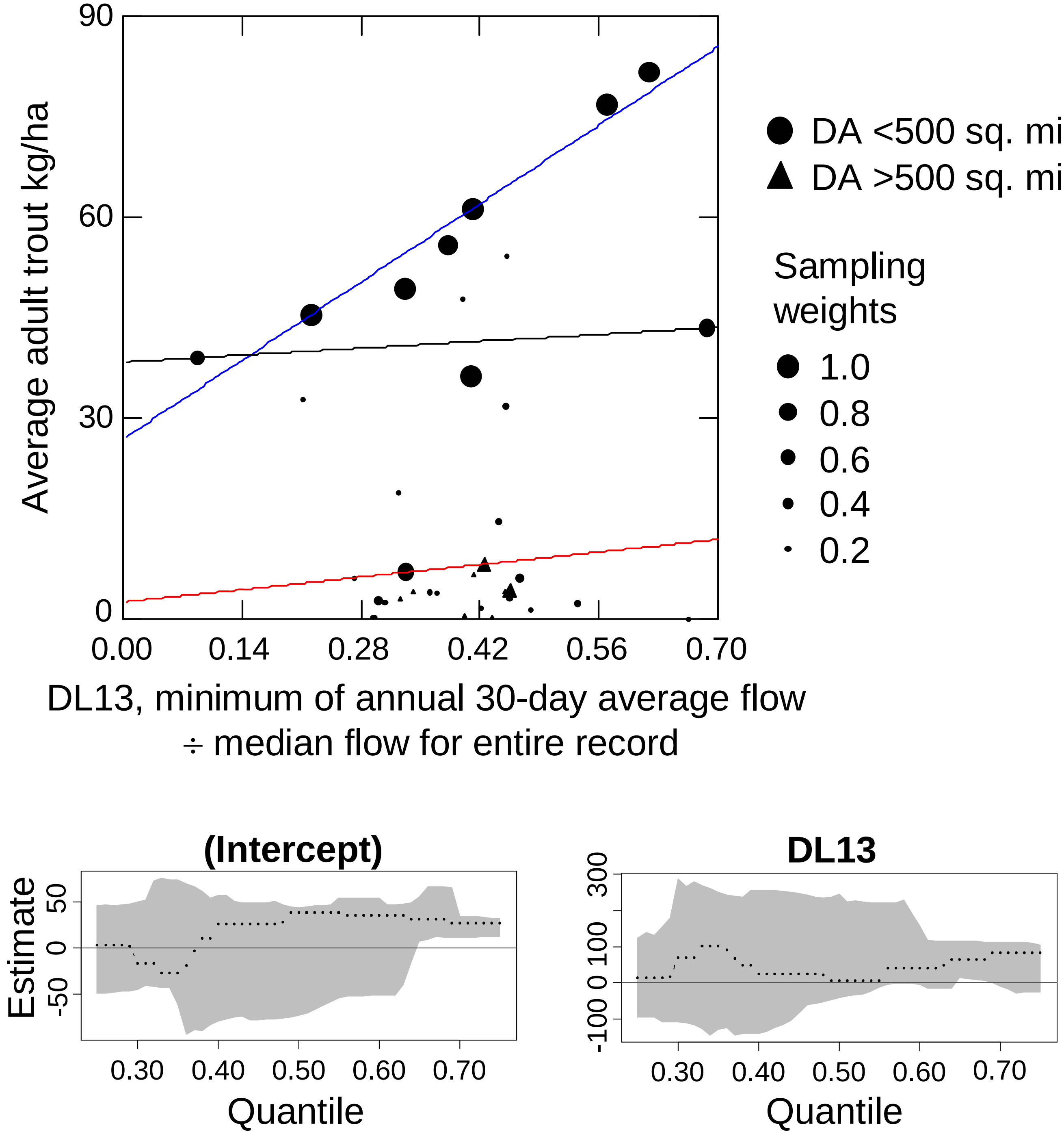


Figure 6. Quantile (0.25 – 0.75) regression estimates of wild trout biomass as a function of DL13, minimum of annual 30-day average flow ÷ median flow for entire record, based on the 15 years of flow prior to last year trout were sampled or years of trout sampling plus previous 3 years (whichever is longer) for *n* = 36 streams in Pennsylvania. In the upper panel the blue line is 0.75, black line is 0.50, and red line is 0.25 quantile. Sampling weights are the minimum of (number of times trout were sampled ÷ 10, or 1.0). In lower panels, points are estimates by increments of 0.01 from 0.25 – 0.75 quantiles and grey shaded bands bound 90% confidence intervals.

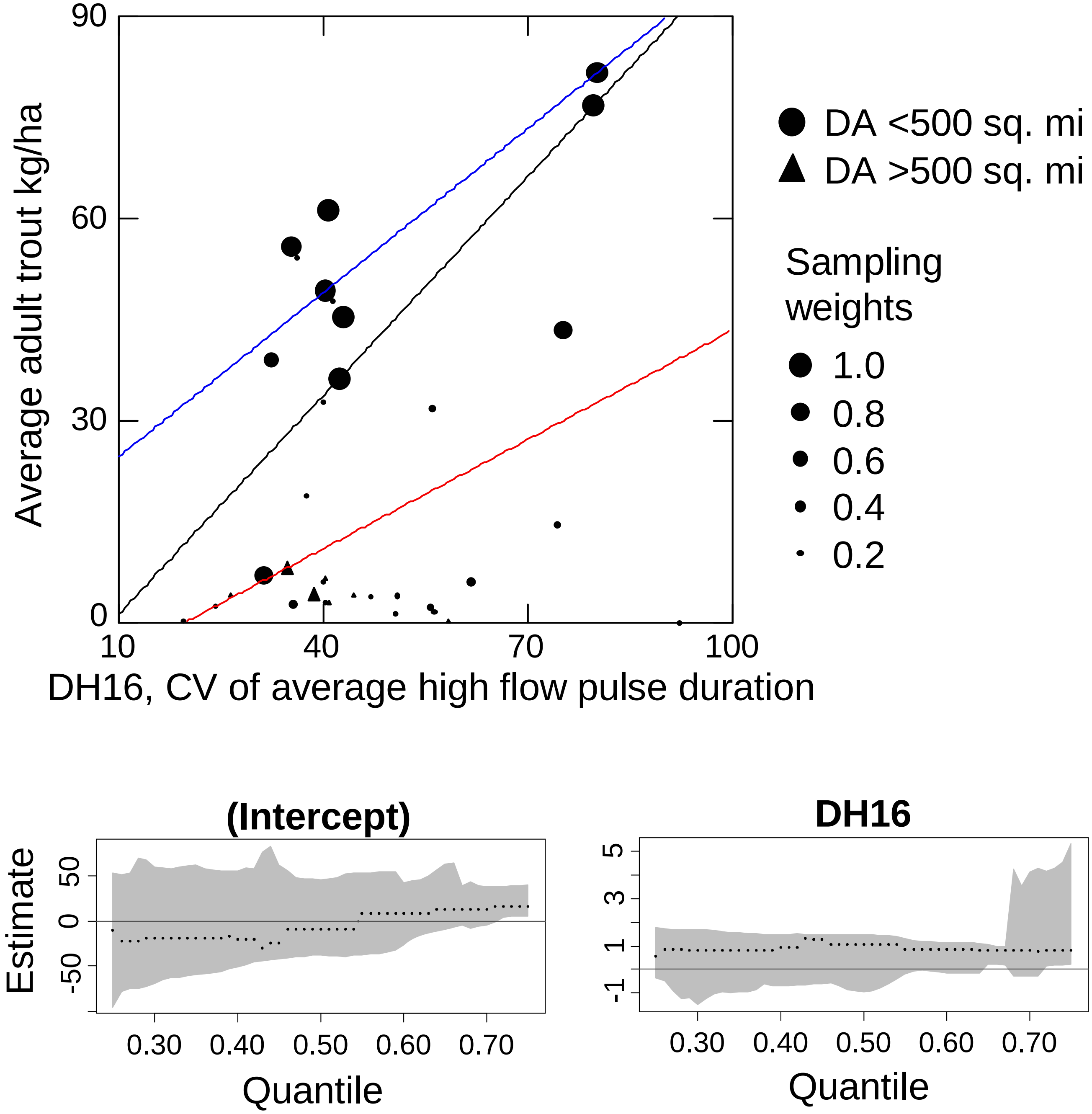


Figure 7. Quantile (0.25 – 0.75) regression estimates of wild trout biomass as a function of DH16, coefficient of variation of average high flow pulse durations, based on the 15 years of flow prior to last year trout were sampled or years of trout sampling plus previous 3 years (whichever is longer) for *n* = 36 streams in Pennsylvania. In the upper panel the blue line is 0.75, black line is 0.50, and red line is 0.25 quantile. Sampling weights are the minimum of (number of times trout were sampled ÷ 10, or 1.0). In lower panels, points are estimates by increments of 0.01 from 0.25 – 0.75 quantiles and grey shaded bands bound 90% confidence intervals.

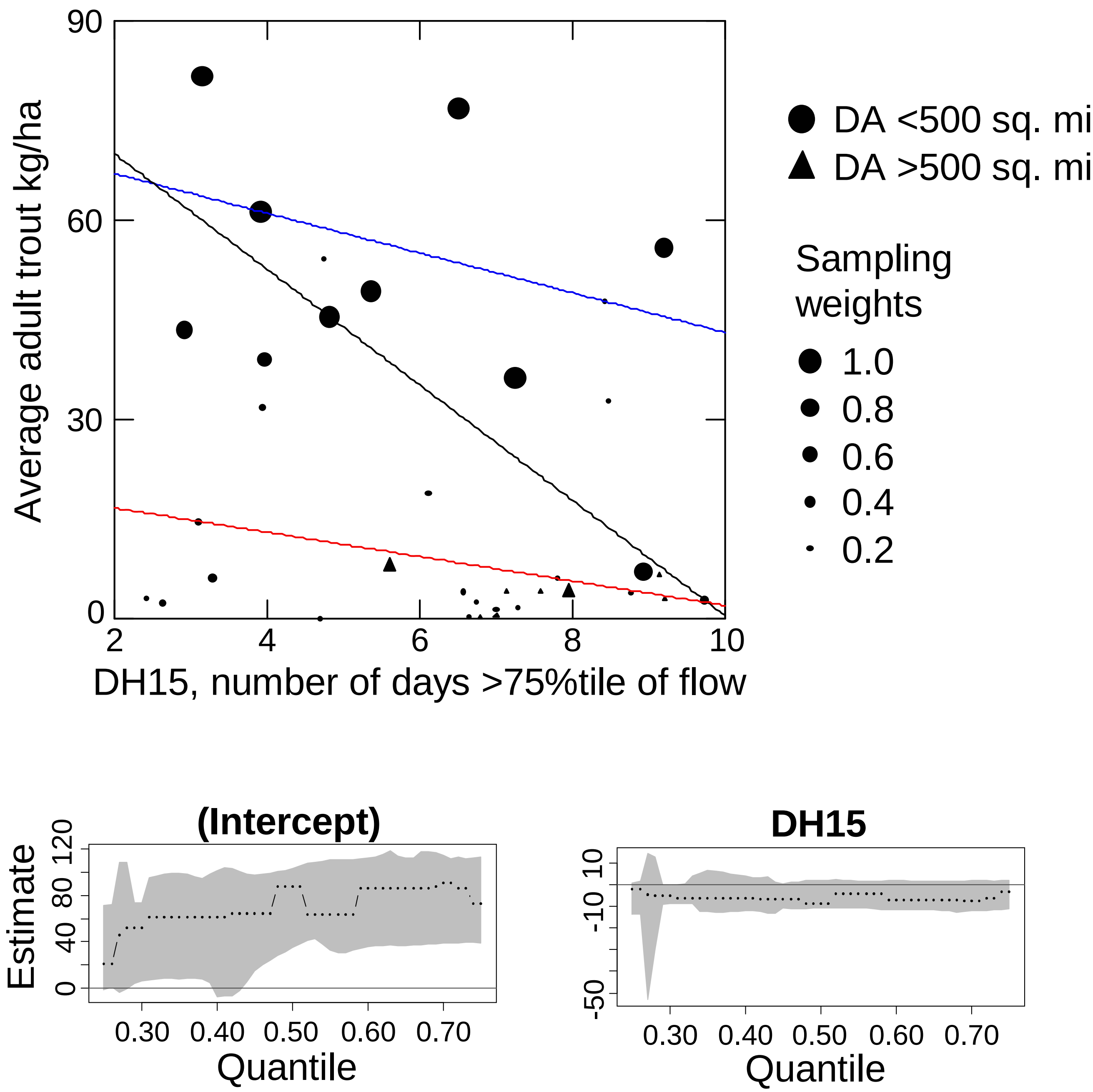


Figure 8. Quantile (0.25 – 0.75) regression estimates of wild trout biomass as a function of DH15, number of days >75%tile of flow, based on the 15 years of flow prior to last year trout were sampled or years of trout sampling plus previous 3 years (whichever is longer) for *n* = 36 streams in Pennsylvania. In the upper panel the blue line is 0.75, black line is 0.50, and red line is 0.25 quantile. Sampling weights are the minimum of (number of times trout were sampled ÷ 10, or 1.0). In lower panels, points are estimates by increments of 0.01 from 0.25 – 0.75 quantiles and grey shaded bands bound 90% confidence intervals.

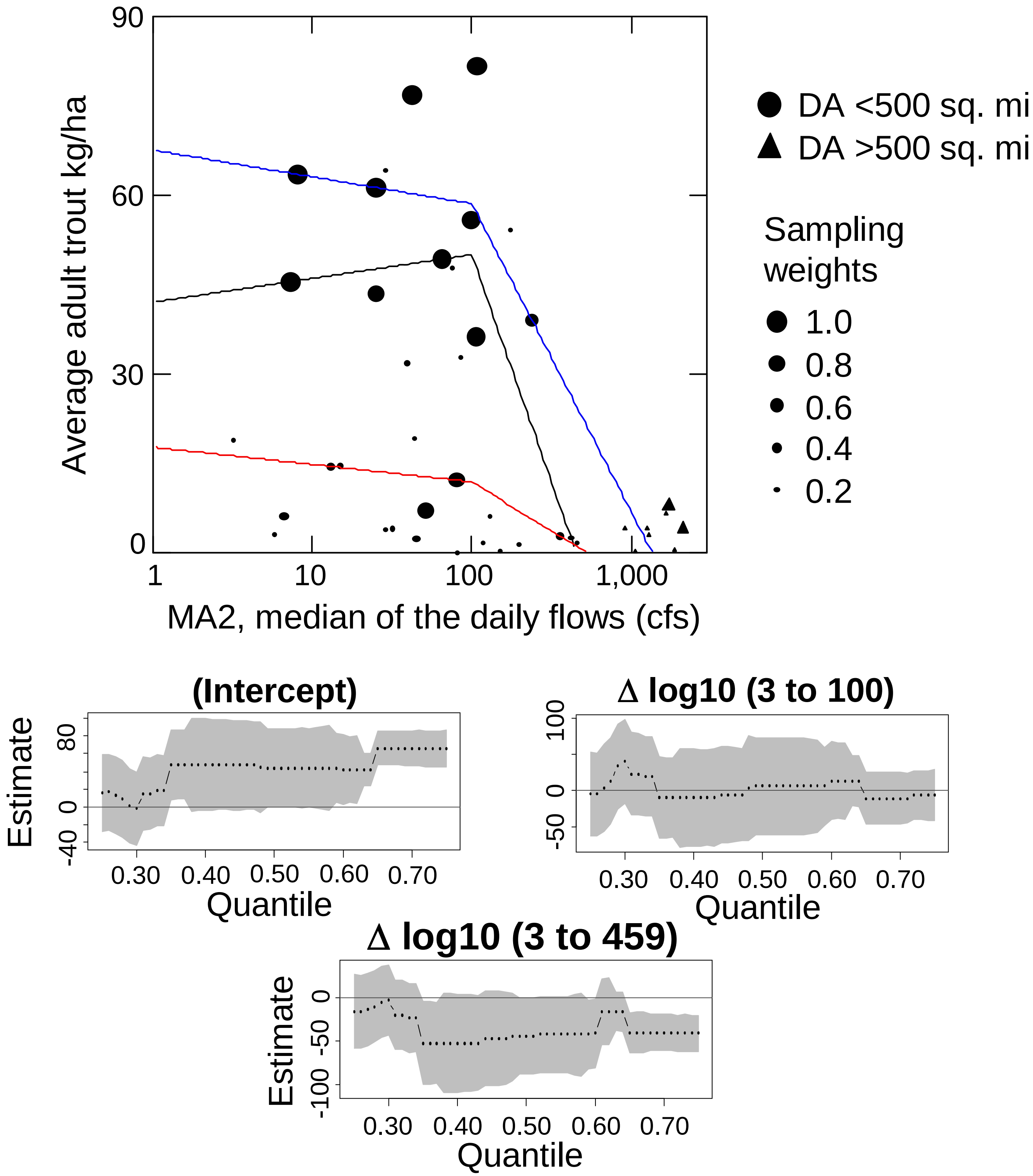


Figure 9. Quantile (0.25 – 0.75) regression estimates of wild trout biomass as a piecewise (break point at 100 cfs) linear function of log10 MA2, median daily flow, based on the entire flow record for gauges for n = 42 streams in Pennsylvania. In the upper panel the blue line is 0.75, black line is 0.50, and red line is 0.25 quantile. Sampling weights are the minimum of (number of times trout were sampled ÷ 10, or 1.0). Streams with drainage areas >500 sq. miles were not used in estimation. In lower panels, points are estimates by increments of 0.01 from 0.25 – 0.75 quantiles and grey shaded bands bound 90% confidence intervals.

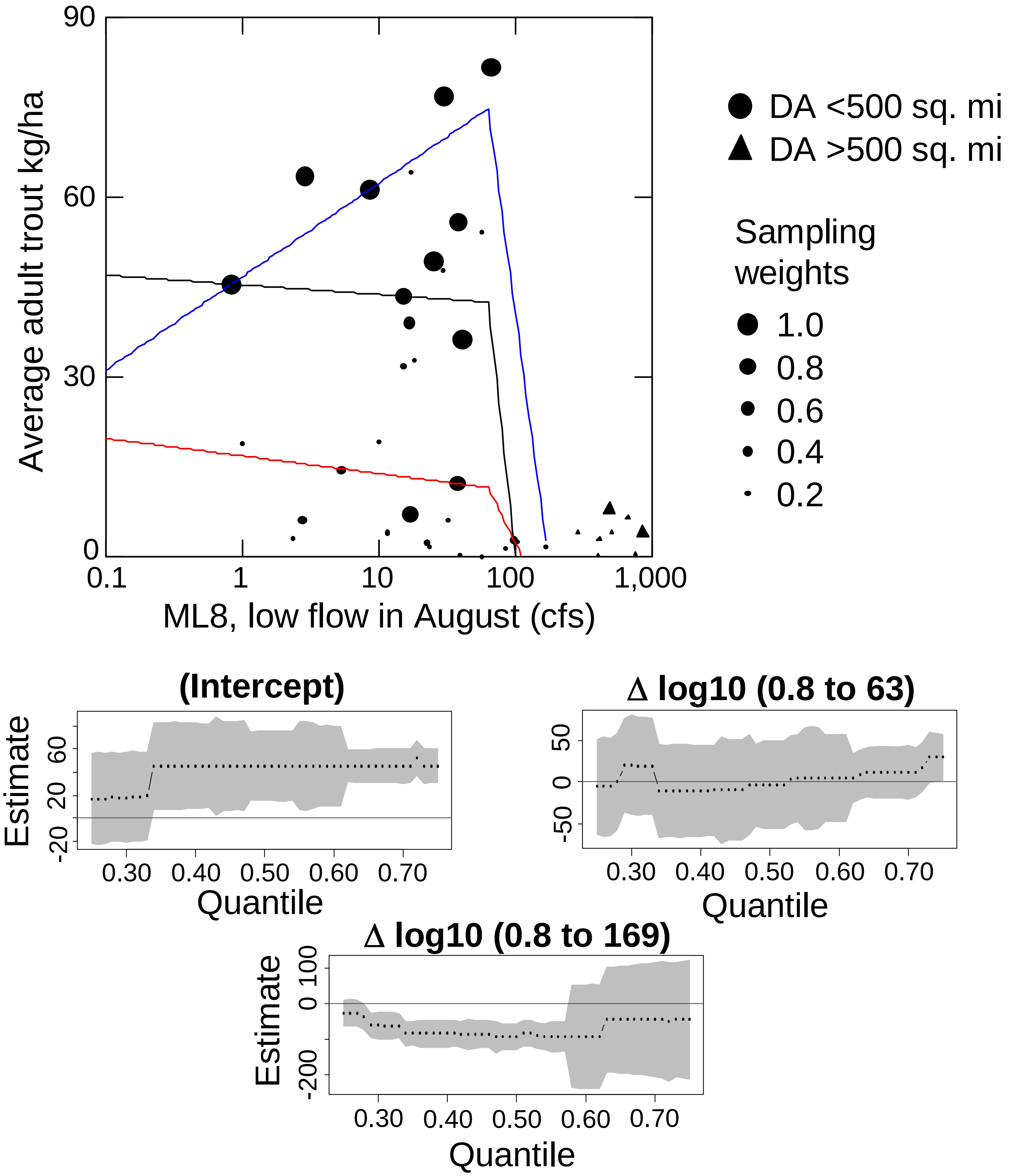


Figure 10. Quantile (0.25 – 0.75) regression estimates of wild trout biomass as a piecewise (break point at 63 cfs) linear function of log10 ML8, low flow in August, based on the entire flow record for gauges for *n* = 42 streams in Pennsylvania. In the upper panel the blue line is 0.75, black line is 0.50, and red line is 0.25 quantile. Sampling weights are the minimum of (number of times trout were sampled ÷ 10, or 1.0). Streams with drainage areas >500 sq. miles were not used in estimation. In lower panels, points are estimates by increments of 0.01 from 0.25 – 0.75 quantiles and grey shaded bands bound 90% confidence intervals.

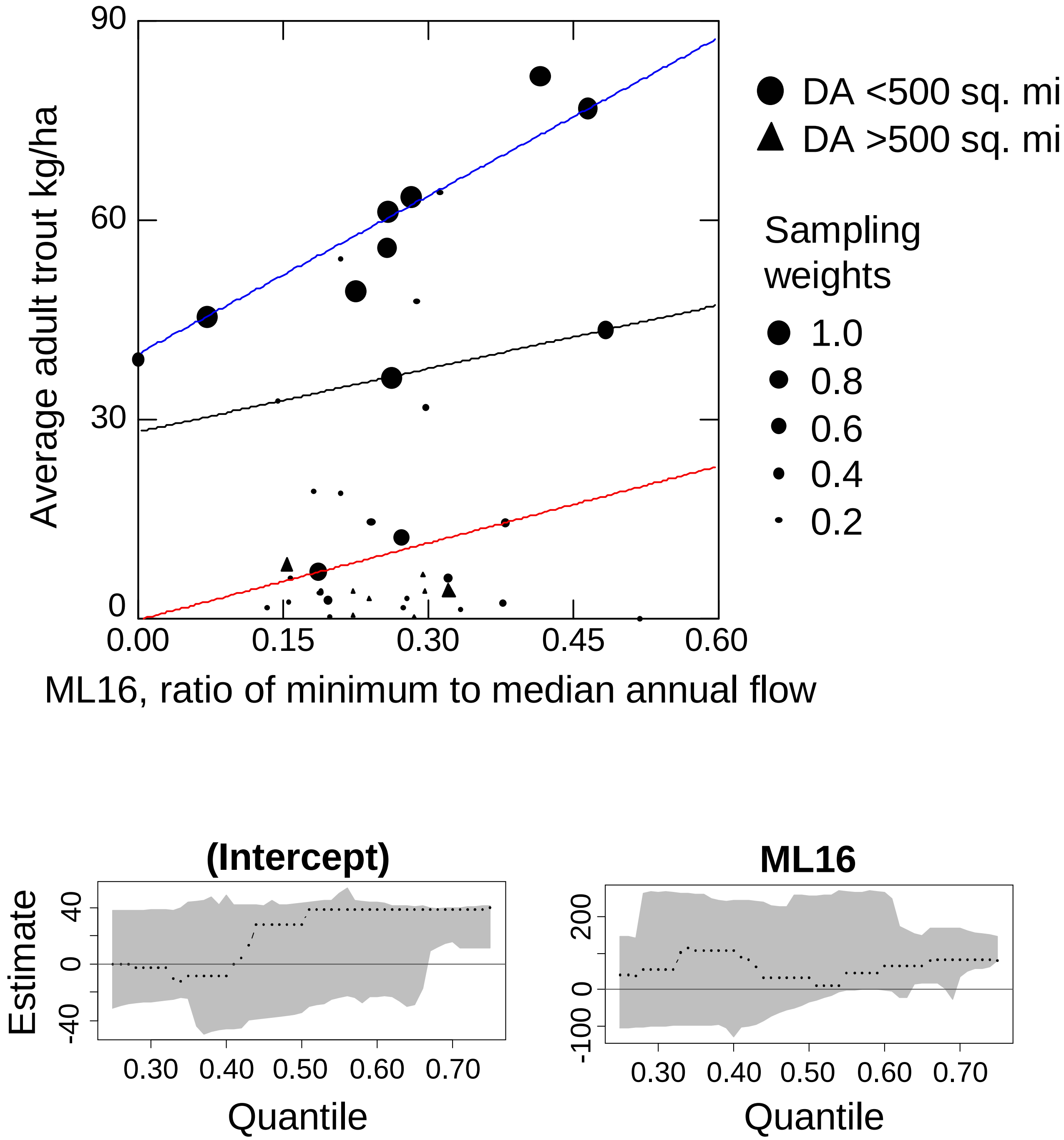


Figure 11. Quantile (0.25 – 0.75) regression estimates of wild trout biomass as a function of ML16, ratio of minimum to median annual flow, based on the entire flow record for gauges for *n* = 42 streams in Pennsylvania. In the upper panel the blue line is 0.75, black line is 0.50, and red line is 0.25 quantile. Sampling weights are the minimum of (number of times trout were sampled ÷ 10, or 1.0). In lower panels, points are estimates by increments of 0.01 from 0.25 – 0.75 quantiles and grey shaded bands bound 90% confidence intervals.

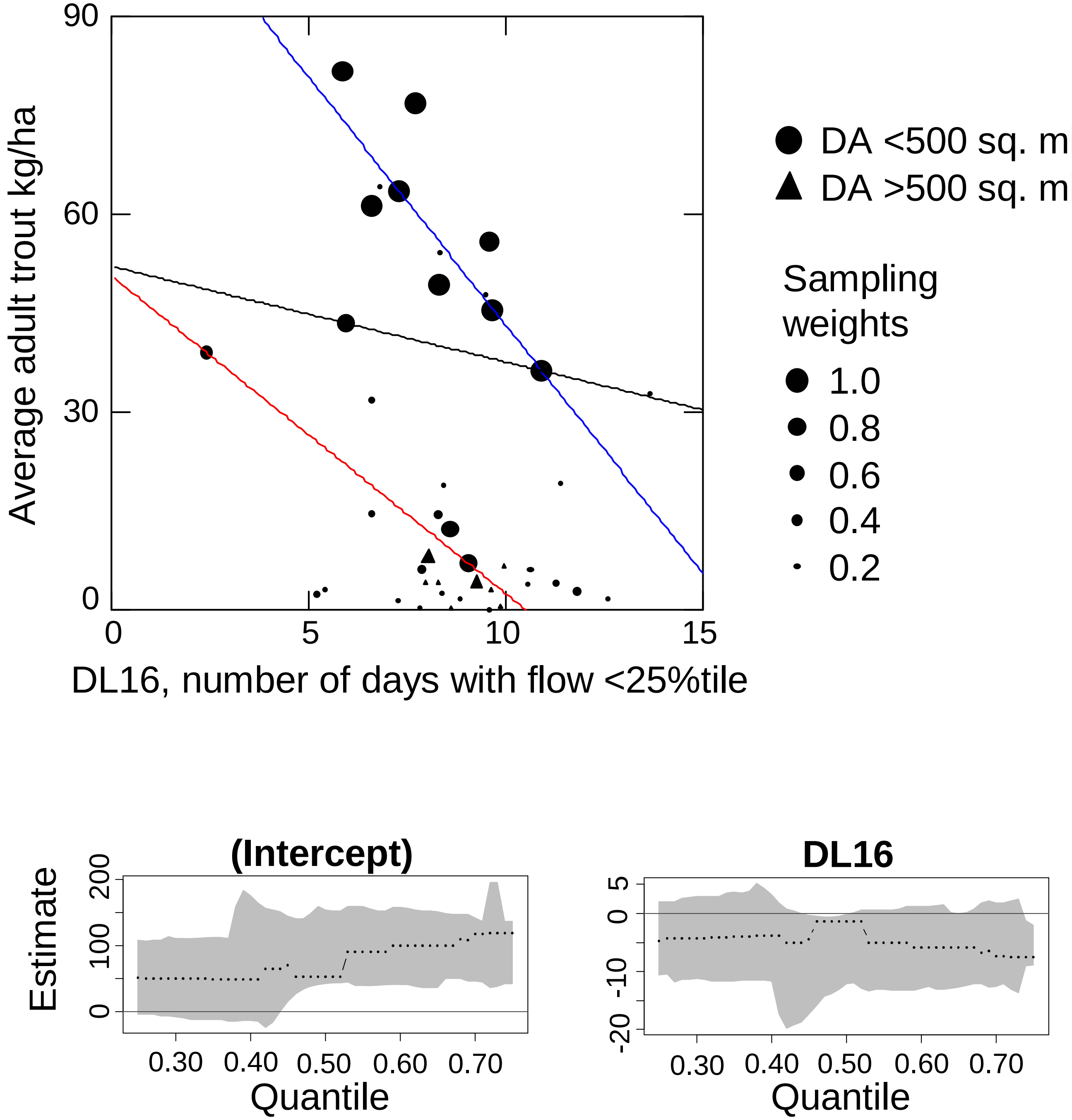


Figure 12. Quantile (0.25 – 0.75) regression estimates of wild trout biomass as a function of DL16, average number of days with flow <25%tile, based on the entire flow record for gauges for *n* = 42 streams in Pennsylvania. In the upper panel the blue line is 0.75, black line is 0.50, and red line is 0.25 quantile. Sampling weights are the minimum of (number of times trout were sampled ÷ 10, or 1.0). In lower panels, points are estimates by increments of 0.01 from 0.25 – 0.75 quantiles and grey shaded bands bound 90% confidence intervals.

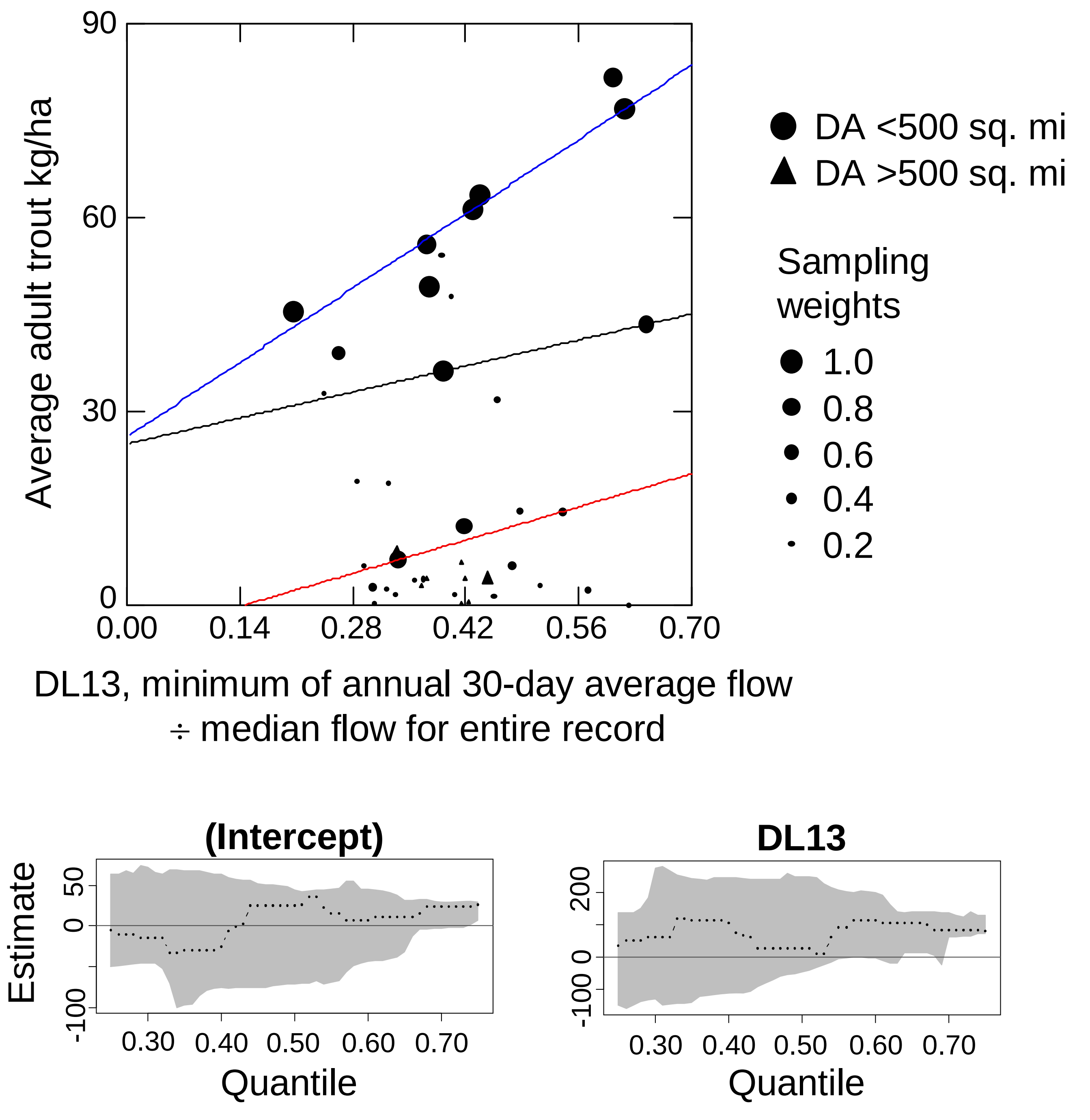


Figure 13. Quantile (0.25 – 0.75) regression estimates of wild trout biomass as a function of DL13, minimum of annual 30-day average flow ÷ median flow for entire record, based on entire flow record for gauges for *n* = 42 streams in Pennsylvania. In the upper panel the blue line is 0.75, black line is 0.50, and red line is 0.25 quantile. Sampling weights are the minimum of (number of times trout were sampled ÷ 10, or 1.0). In lower panels, points are estimates by increments of 0.01 from 0.25 – 0.75 quantiles and grey shaded bands bound 90% confidence intervals.

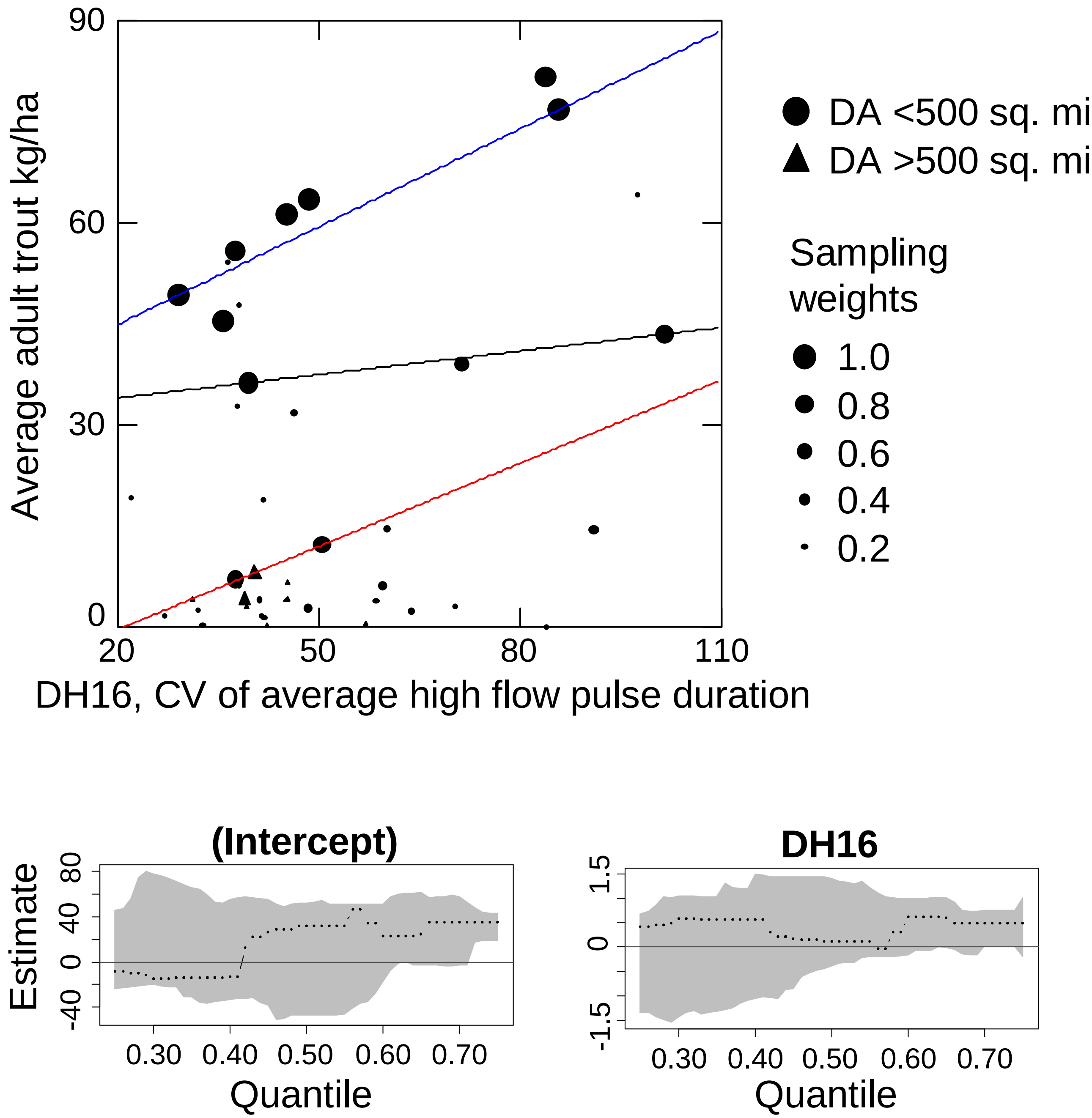
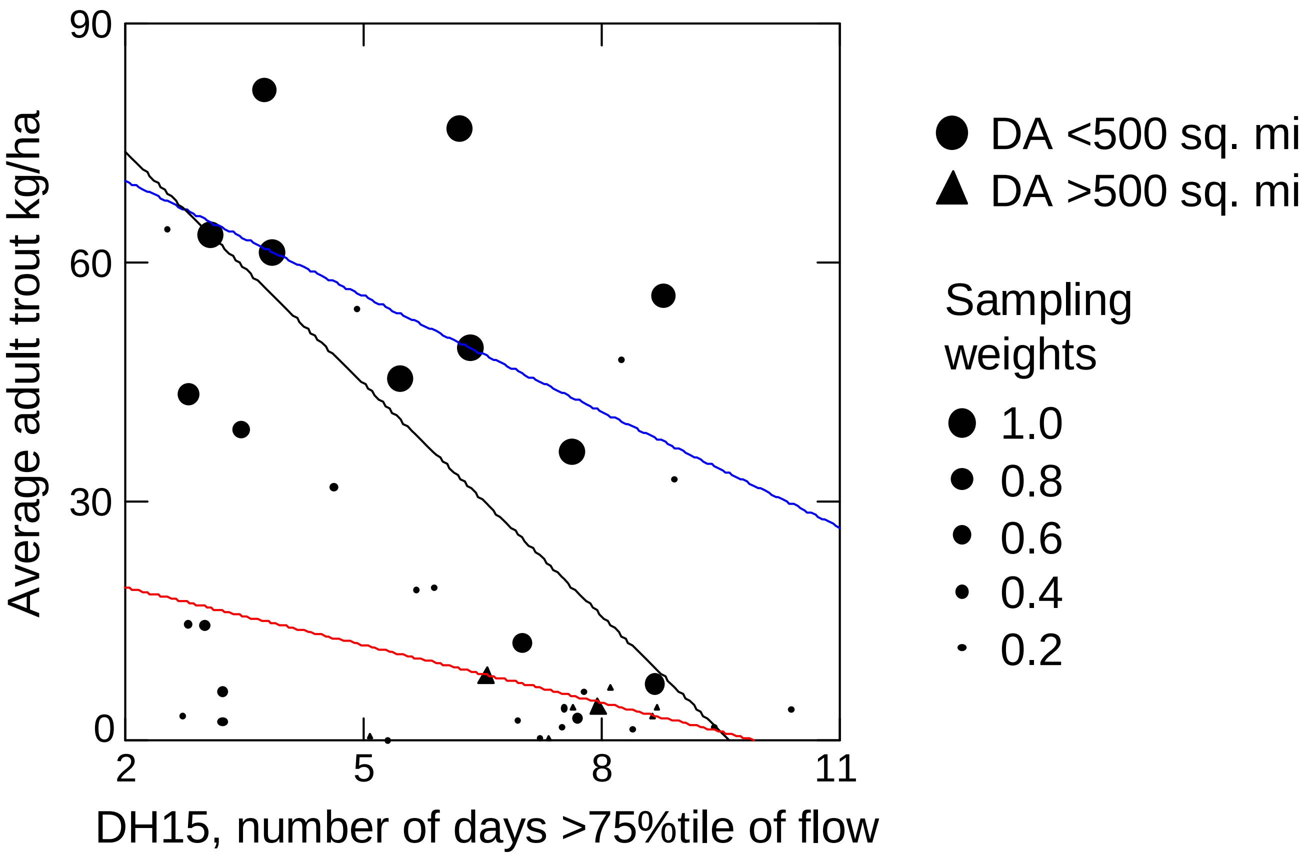


Figure 14. Quantile (0.25 – 0.75) regression estimates of wild trout biomass as a function of DH16, coefficient of variation of average high flow pulse durations, based on the entire flow record for gauges for *n* = 42 streams in Pennsylvania. In the upper panel the blue line is 0.75, black line is 0.50, and red line is 0.25 quantile. Sampling weights are the minimum of (number of times trout were sampled ÷ 10, or 1.0). In lower panels, points are estimates by increments of 0.01 from 0.25 – 0.75 quantiles and grey shaded bands bound 90% confidence intervals.



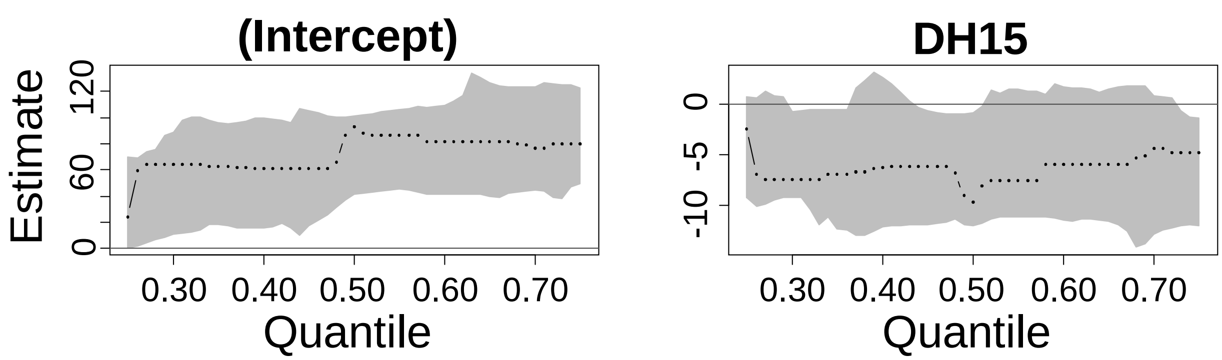


Figure 15. Quantile (0.25 – 0.75) regression estimates of wild trout biomass as a function of DH15, number of days >75%tile of flow, based on the entire flow record for gauges for *n* = 42 streams in Pennsylvania. In the upper panel the blue line is 0.75, black line is 0.50, and red line is 0.25 quantile. Sampling weights are the minimum of (number of times trout were sampled ÷ 10, or 1.0). In lower panels, points are estimates by increments of 0.01 from 0.25 – 0.75 quantiles and grey shaded bands bound 90% confidence intervals.