THE LONG GAME: THE IMPORTANCE OF LTM FOR FRESHWATER MUSSEL POPULATION ASSESSMENTS

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LONG-TERM MONITORING (LTM) OF MUSSEL POPULATIONS

Monitoring:

- "The repeated collection and analysis of observations and measurements to evaluate changes in populations of species and environmental conditions" (Dallmeier et al. 2013)
- Demographic data collected over repeated events and extended time-scales
  - Within-year repeated surveys
  - Multi-year repeated surveys

Temporal scale for "LTM" can be relative to:

- Study objectives and goals
- Biology of the species biology (life-span, generation time)

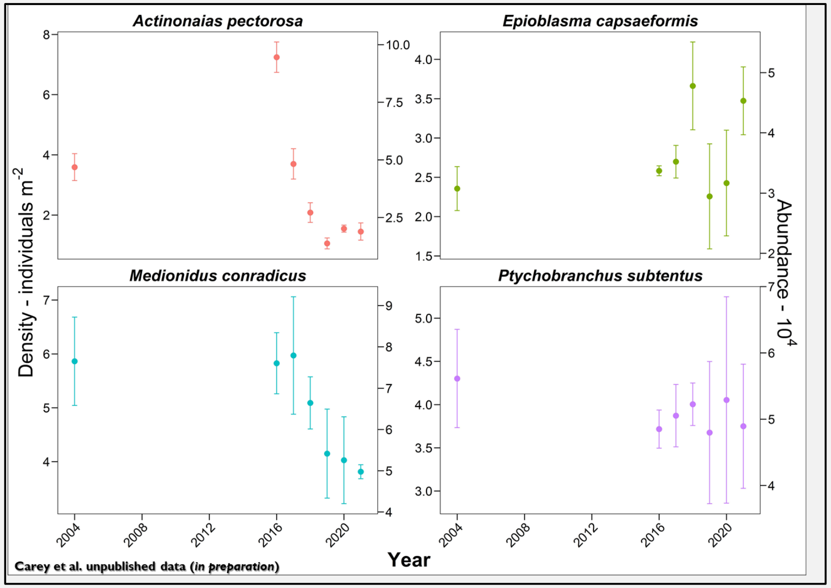
Dallmeier et al. 2013. Framework for assessment and monitoring of biodiversity. Encyclopedia of Biodiversity (Second Edition). Academic Press: 545-559

LONG-TERM MONITORING (LTM) OF MUSSEL POPULATIONS

Importance of collecting demographic data over repeated and long time-scales:

Population Dynamics

- Estimating key demographic parameters and vital rates to understand species-specific population dynamics (over temporal- and spatial-scales)
- Assessing population trends over time; evaluating effects of changing environmental conditions and anthropogenic disturbances



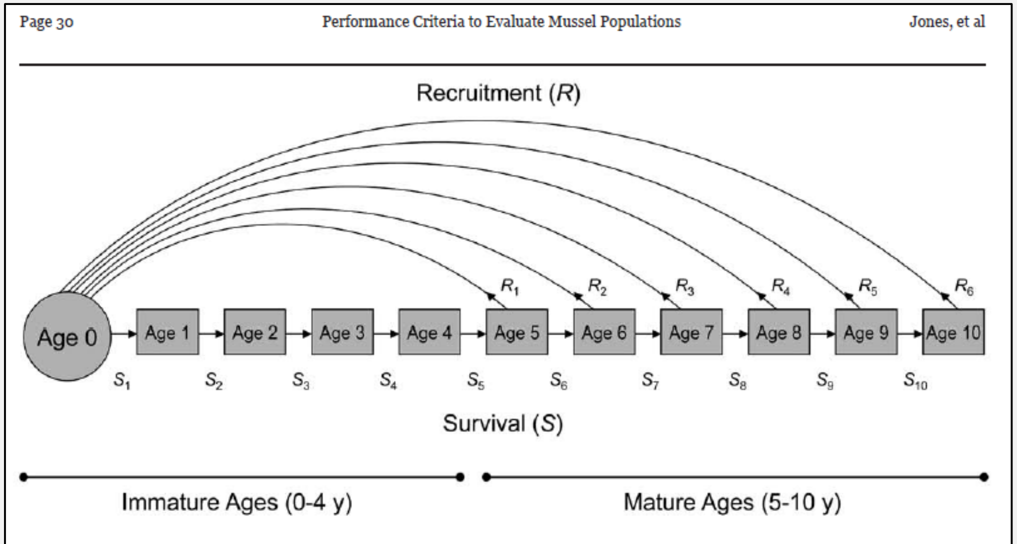


FIGURE 1
A general life-cycle diagram depicting the demography of a freshwater mussel species living to a maximum of 10 y, such as *Epioblasma capsaeformis*. Species living longer can be accommodated in the model by adding age classes, such as five more for *E. brevidens*. Nodes (circle and boxes) represent age-class stages, and arrows between nodes represent transitions (survival) between stages. Recruitment is shown as the number of age-0 individuals produced by adults in mature age classes.

Carey et al. unpublished data (*in prep.*); Jones et al. 2012

LONG-TERM MONITORING (LTM) OF MUSSEL POPULATIONS

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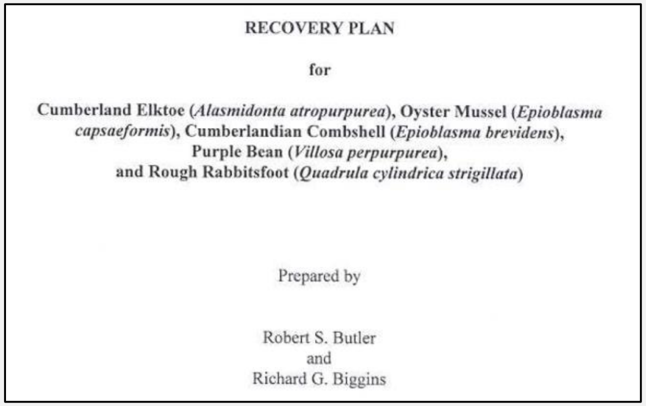
- Assessing population trends over time; evaluating effects of changing environmental conditions and anthropogenic disturbances

Species Recovery Documents

- Defining objective, measurable recovery criteria and delisting thresholds for T&E recovery plans
- Informing Species Status Assessments (SSAs), 5-year Reviews, SWAPs, recovery efforts



RECOVERY PLAN

for

Cumberland Elktoe (*Alasmidonta atropurpurea*), Oyster Mussel (*Epioblasma capsaeformis*), Cumberlandian Combshell (*Epioblasma brevidens*), Purple Bean (*Villosa perpurpurea*), and Rough Rabbitsfoot (*Quadrula cylindrica strigillata*)

Prepared by

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and
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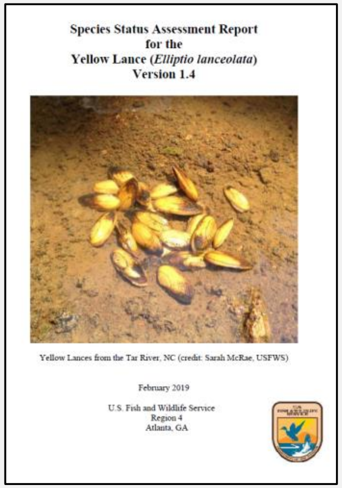

Species Status Assessment Report for the Yellow Lance (*Elliptio lanceolata*) Version 1.4

Yellow Lances from the Tar River, NC (credit: Sarah McRae, USFWS)

February 2019

U.S. Fish and Wildlife Service
Region 4
Atlanta, GA

LONG-TERM MONITORING (LTM) OF MUSSEL POPULATIONS

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Population Dynamics

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- Assessing population trends over time; evaluating effects of changing environmental conditions and anthropogenic disturbances

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- Defining objective, measurable recovery criteria and delisting thresholds for T&E recovery plans
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Evaluations

- Evaluating effectiveness of recovery efforts (e.g., captive propagation, reintroductions, augmentations) and providing feedback to improve future efforts
- Evaluating population performance (viability) & species recovery

LONG-TERM MONITORING (LTM) OF MUSSEL POPULATIONS

LTM Datasets & Sampling Designs:

- Quantitative
  - Quadrat surveys (simple/systematic/stratified random sampling; adaptive cluster sampling)
  - Capture-mark-recapture (unique markings, tags; PIT tags)
- Semi-quantitative
  - Timed-searches (within defined sampling units)
- Qualitative
  - Informal timed-searches over substrate surface or banks (sampling unit not defined)

LONG-TERM MONITORING (LTM) OF MUSSEL POPULATIONS

LTM Demographic Data From…

Semi-quantitative & Qualitative Data:

CPUE

Surface density

Species list

- **Examine temporal changes in species presence across drainage** or CPUE over time <u>within a site</u>
- **Detect mass-mortality events and intra-annual trends in mortality**
- **Complements quantitative surveys to obtain complete species list at a site**
- Identify areas to allocate more-intensive quantitative sampling efforts
- Inform *presence-only SDMs, JSDMs, habitat suitability models (*probabilistic semi-quantitative survey could be designed for use in presence-absence modelling approaches)

Some limitations:

- Probability of detecting individuals or species at the substrate surface is a function of its availability for detection and its detectability by a surveyor
- **Detection is influenced by….** survey conditions, surveyor experience, habitat type, shell size + aperture characteristics, life-histories and reproductive behaviors, etc.
- **Non-detections ≠ true absence**
- CPUE rates generally are not comparable across sites

LTM Demographic Data From…

Quantitative data:

Population sizes/densities

Population growth (λ)

Age(size)-class structures

Survival + mortality rates

Recruitment

Diversity

- **Establish species- and site-level baseline conditions**
- **Species-specific population dynamics**
- Distinguish/quantify natural from disturbance-caused population fluctuations
- Assess temporal (+spatial) variability
- **Detect population trends, direction + magnitude of change**
- Estimate detection rates
- Conduct time-series or **demographic explicit PVAs**
- SDMs + JSDMs, habitat suitability models

CASE STUDY: LONG-TERM MONITORING IN THE CLINCH AND POWELL RIVERS, VIRGINIA & TENNESSEE

Clinch & Powell Rivers

- Upper Tennessee River Basin; upstream of Norris Reservoir
- Highly diverse mussel assemblage
- Historically supported 55 species (24 FE; 3 extinct; 6 extirpated; 7 UR)
- Currently ~46 extant

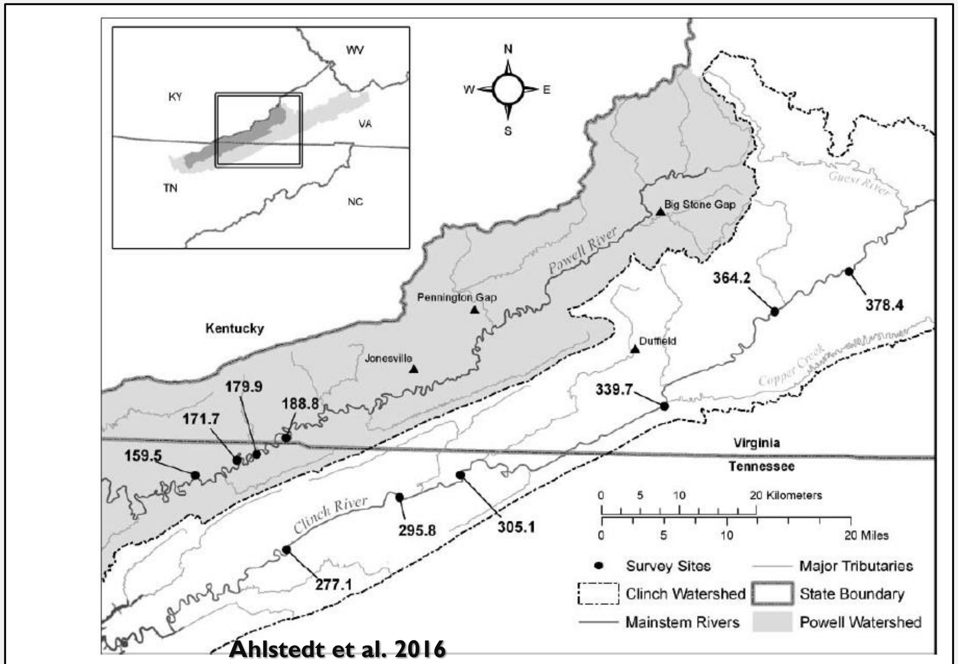


Figure 1. The Clinch and Powell river watersheds showing locations of sites (in RKM) sampled from 1979–2004.

CASE STUDY:
CLINCH & POWELL RIVER LTM

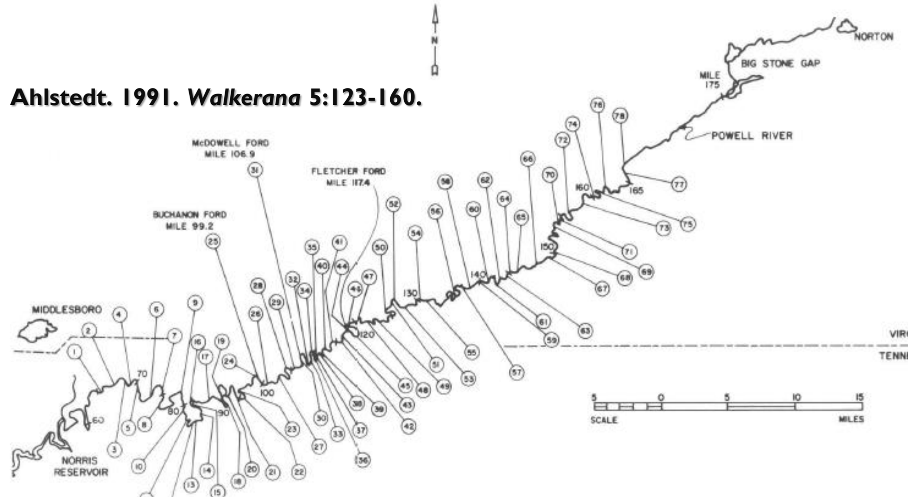
Historical Surveys in the Powell River

Qualitative Monitoring:

- 1800's – early 1900's (Adams, Goodrich, Ortmann, Walker [Ortmann 1918])
- 1970's – present (Ahlstedt & Brown 1979; Neves et al. 1980; Dennis 1981; Jenkinson & Ahlstedt 1988; Wolcott & Neves 1994; Virginia Tech, VDWR, Daguna grey literature/unpub data)

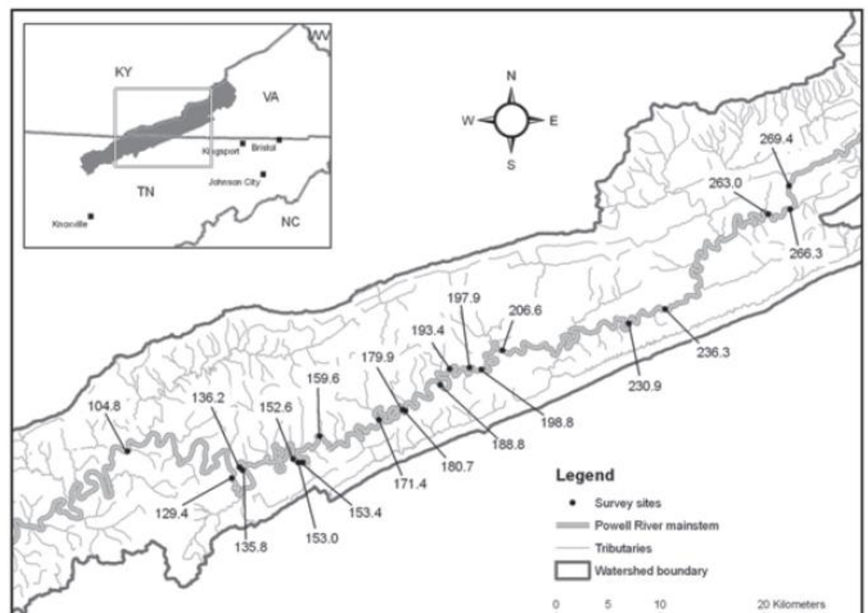
Quantitative Monitoring:

- **<u>1979 – 2004 on a semi-regular basis</u>** (Ahlstedt 1986, 1991; Wolcott & Neves 1994; Ahlstedt et al. 2016)
- **<u>1970's – present at non-regular intervals</u>** (Dennis 1981; Johnson et al. 2012; Virginia Tech, VDWR, grey literature/unpub data)



Ahlstedt. 1991. *Walkerana* 5:123-160.

FIG. 1. Powell River mussel sampling sites.



Johnson et al. 2012. *Freshwater Mollusk Conservation Society 15:83-98.*

FIGURE 1
Sites surveyed using random timed search, systematic search, and quadrat sampling methods in the Powell River.

CASE STUDY:
CLINCH & POWELL RIVER LTM

Historical Surveys in the Clinch River

Qualitative Monitoring:

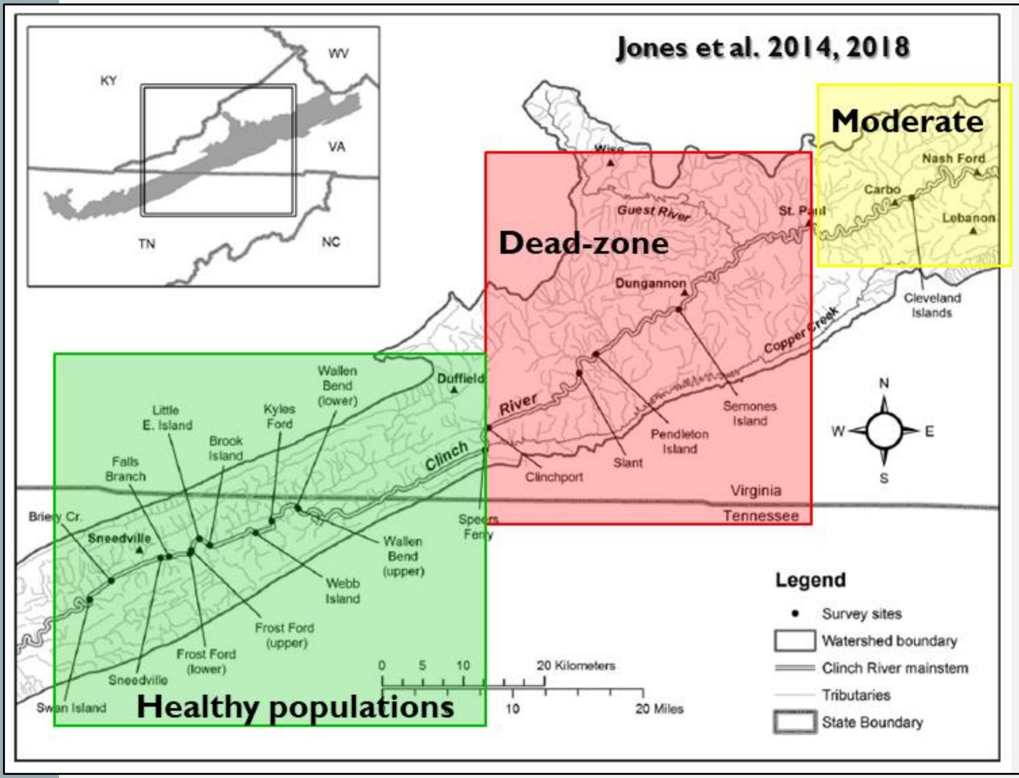
- 1800's – early 1900's (Adams, Goodrich, Ortmann, Walker [Ortmann 1918])
- 1970's – present (Stansbery 1973; Neves et al. 1980; Bates & Dennis 1978; Dennis 1989; Ahlstedt 1991; Virginia Tech, VDWR, Daguna grey literature/unpub. data

Quantitative Monitoring (>140 sites)

- 1979–2004 on a semi-regular basis (Ahlstedt 1986, 1991; Ahlstedt et al. 2016)
- 1979–present at non-regular intervals (Ahlstedt 1986, 1991, 2005; Ahlstedt & Tuberville 1997; Ahlstedt et al. 2016; Jones et al. 2014, 2018; Virginia Tech, VDWR, Daguna grey literature/unpub data)

Annual Quantitative Monitoring:

- 2004 – 2014 & 2017 – present across 3 sites (Jones et al. 2014, 2018; Carey & Ostby 2018 – 2021 annual reports; Virginia Tech/Daguna grey literature/unpub data)
- 2004 & 2016 – present at 1 additional site (Jones et al. 2014, 2018; Phipps & Hyde 2017; Carey & Ostby 2018 – 2021 annual reports; Virginia Tech/Daguna grey literature/unpub data)



CASE STUDY:
CLINCH & POWELL RIVER LTM

Qualitative Survey Methods, Data, +Inferences

- Timed-searches
- Focused in suitable habitat
- Snorkeling, viewscopes, tactile/visual, SCUBA, muskrat middens, hand-raking
- Species lists

THE NAIADES OF THE CLINCH RIVER
ABOVE NORRIS RESERVOIR

C - Cumberlandian
O - Ohioan
U - Undetermined

P - Previously recorded (Ortmann, 1918) (Collected by Adams, 1899 and Ortmann, 1912-1915)
R - Recently recorded (Stansbery, 1972) (Collected by Stansbery and others, 1963-1971)
E - Believed extinct (Stansbery, 1970, 1971)

	Fauna	Recorded
FAMILY MARGARITIFERIDAE Ortmann, 1911.		
1. *Cumberlandia monodonta* (Say, 1829).	U	R
FAMILY UNIONIDAE (Fleming, 1828) Ortmann, 1911.		
SUBFAMILY ANODONTINAE (Swainson, 1840) Ortmann, 1910.		
2. *Strophitus undulatus shaefferianus* (Lea, 1852).	C	P R
3. *Alasmidonta marginata* Say, 1818.	U	P R
4. *Alasmidonta viridis* (Rafinesque, 1820).	U	P R
5. *Pegias fabula* (Lea, 1836).	C	R
6. *Lasmigona costata* (Rafinesque, 1820).	U	P R
7. *Lasmigona holstonia* (Lea, 1838).	C	P R
SUBFAMILY AMBLEMINAE Morrison, 1955.		
igillata (Wright, 1898).	C	P R
1841).	C	R
onrad, 1836).	C	P R
ea, 1831).	U	P R
a (Say, 1817).	U	P R
lesueuriana (Lea, 1840).	C	P R
ea, 1840).	C	P R
ea, 1840).	C	P R
Lea, 1838).	C	P R
(Rafinesque, 1820).	U	P R
des (Lea, 1840).	C	P R
Rafinesque, 1820).	U	P R
Conrad, 1834).	C	P R
(Conrad, 1836).	U	P R
ea, 1840).	U	P R
um (Lea, 1831).	U	P R
marck, 1819).	U	P R
nesque, 1820).	U	P R
ue, 1820).	U	P R

Table I

Mussel Species collected at Pendleton Island, Clinch River, September, 1987

Species	Live	Dead only
Actinonaias carinata	X	
Actinonaias pectorosa	X	
Amblema costata	X	
Conradilla caelata	X	
Cyclonaias tuberculata	X	
Cyprogenia irrorata	X	
Dysnomia brevidens		X
Dysnomia capsaeformis		X
Dysnomia triquetra	X	
Dysnomia torulosa gubernaculum		X (relic)
Elliptio dilatatus	X	
Fusconaia barnesiana	X	
Fusconaia cuneolus	X	
Fusconaia edgariana	X	
Fusconaia pilaris	X	
Lampsilis fasciola	X	
Lampsilis ventricosa	X	
Lasmigona costata	X	
Leptodea fragilis	X	
Lexingtonia dolabelloides	X	
Ligumia recta latissima	X	
Medionidus conradicus	X	
Plethobasus cyphyus	X	
Pleurobema cordatum	X	
Pleurobema oviforme	X	
Proptera alata	X	
Ptychobranchus fasciolaris	X	
Ptychobranchus subtentum	X	
Quadrula cylindrica	X	
Quadrula pustulosa	X	
Truncilla truncata	X	
Villosa trabalis	X	
Villosa nebulosa (complex)	X	
Totals: (Grand = 33)	30	3

Table 2. Mussel species collected in the Powell River, Virginia, 1988 and 1989.

Scientific name	Common name
Actinonaias ligamentina (Lamarck)	mucket
Actinonaias pectorosa (Conrad)	pheasantshell
Amblema plicata plicata (Conrad)	threeridge
Cyclonaias tuberculata (Rafinesque)	purple wartyback
Dromus dromas (Lea)[1]	dromedary pearlymussel
Elliptio dilatata (Rafinesque)	spike
Epioblasma brevidens (Lea)[2]	cumberlandian combshell
Epioblasma capsaeformis (Lea)[2]	oyster mussel
Epioblasma triquetra (Rafinesque)[2]	snuffbox
Fusconaia barnesiana (Lea)	Tennessee pigtoe
Fusconaia cor (Conrad)[1]	shiny pigtoe
Fusconaia subrotunda (Lea)	long-solid
Lampsilis fasciola (Rafinesque)	wavy-rayed lampmussel
Lampsilis ovata (Say)	pocketbook
Lasmigona costata (Rafinesque)	fluted-shell
Lemiox rimosus (Rafinesque)	birdwing pearlymussel
Ligumia recta (Lamarck)[2]	black sandshell
Medionidus conradicus (Lea)	Cumberland moccasinshell
Plethobasus cyphyus (Rafinesque)[2]	sheepnose
Pleurobema oviforme (Conrad)	Tennessee clubshell
Potamilus alatus (Rafinesque)	pink heelsplitter
Ptychobranchus fasciolaris (Rafinesque)	kidneyshell
Ptychobranchus subtentum (Say)	fluted kidneyshell
Quadrula cylindrica strigillata (Wright)	rough rabbitsfoot
Quadrula intermedia (Conrad)[1]	Cumberland monkeyface
Quadrula sparsa (Lea)[1]	Appalachian monkeyface
Villosa iris (Lea)	rainbow
Villosa vanuxemensis vanuxemensis (Lea)	mountain creekshell

[1]Federal endangered species
[2] State endangered species

Ortmann (1918); Dennis (1989); Wolcott & Neves (1994)

CASE STUDY:
CLINCH & POWELL RIVER LTM

Qualitative Survey Data & Inferences

- Species lists
- Spatial variation in species distributions

TABLE 3. Number of each naiad species found during qualitative sampling of the Clinch River between 1978 and 1983.

Mussel Species	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
	Collecting Sites [1]																												
Actinonaias ligamentina	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Actinonaias pectorosa[2]	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Alasmidonta marginata	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Amblema plicata	2	3	4	1	–	–	–	–	–	–	–	–	–	1	–	2	–	–	–	–	–	–	–	–	–	–	–	–	–
Anodonta grandis	2	–	–	1	–	–	–	–	–	1	–	2	–	–	–	1	–	–	1	–	–	2	2	4	1	1	–	–	–
Anodonta suborbiculata	–	–	–	–	–	–	–	–	–	–	–	1	–	–	–	–	–	–	–	–	1	–	–	–	1	–	–	–	–
Cumberlandia monodonta	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Cyclonaias tuberculata	1	–	2	2	–	–	1	2	–	–	–	–	–	3	–	–	2	–	–	–	–	–	1	–	1	–	–	–	–
Cyprogenia stegaria	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Dromus dromas[2,3]	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Elliptio crassidens	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Elliptio dilatata	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Epioblasma brevidens[2]	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Epioblasma capsaeformis[2]	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Epioblasma triquetra	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Fusconaia barnesiana[2]	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Fusconaia cor[2,3]	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Fusconaia cuneolus[2,3]	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Fusconaia subrotunda	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Hemistena lata	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Lampsilis abrupta[3]	–	–	–	–	–																								
Lampsilis fasciola	–	–	–	–	–																								
Lampsilis ovata	–	–	–	–	–																								
Lasmigona complanata	–	–	–	–	–																								
Lasmigona costata	–	–	–	–	–																								
Lemiox rimosus[2,3]	–	–	–	–	–																								
Leptodea fragilis	–	–	–	–	–																								
Lexingtonia dolabelloides[2]	–	–	–	–	–																								
Ligumia recta	–	–	–	–	–																								
Medionidus conradicus[2]	–	–	–	–	–																								
Plethobasus cyphyus	–	–	–	–	–																								
Pleurobema cordatum	1	–	–	–	–																								
Pleurobema plenum[3]	–	–	–	–	–																								
Pleurobema rubrum	1	–	–	–	–																								
Pleurobema oviforme[2]	–	–	–	–	–																								
Potamilus alatus	–	–	–	–	–																								
Ptychobranchus fasciolaris	–	–	–	–	–																								
Ptychobranchus subtentum[2]	–	–	–	–	–																								
Quadrula cylindrica	–	–	–	–	–																								
Quadrula metanevra	–	–	–	1	–																								
Quadrula pustulosa	3	1	9	3	6																								
Quadrula sparsa[2,3]	–	–	–	–	–																								
Strophitus undulatus	–	–	–	–	–																								
Truncilla truncata	–	–	–	–	–																								
Villosa nebulosa[2]	–	–	–	–	–																								
Villosa perpurpurea[2]	–	–	–	–	–																								
Villosa vanuxemensis[2]	–	–	–	–	–																								
Total number of species	6	2	3	5	1																								

[1] Collecting sites (1-63 lower Clinch, 64-204 upper Clinch); [2] C

Page 94 Freshwater Mussels of the Powell River Johnson, et al.

TABLE 3
Numbers and relative abundances of each species collected during random timed search and systematic search at selected sites in the Powell River. Total numbers of mussels collected, catch-per-unit-effort (CPUE), and total species collected are also provided for each site.

	Powell River Site (PRKM and Site Number)									
	269.4	266.3	263.0	236.3	230.9	206.6	198.8	197.9	193.4	188.8
Species	1	2	3	4	5	6	7	8	9	10
Actinonaias ligamentina	-	-	-	7	11	23	9	609	192	235
Actinonaias pectorosa	1	-	-	28	53	34	9	1573	1287	443
Amblema plicata	-	-	-	-	2	3	1	8	11	34
Cyclonaias tuberculata	-	-	-	-	2	4	1	9	9	24
Dromus dromas	-	-	-	-	-	-	-	2	7	6
Elliptio crassidens	-	-	-	-	-	-	-	-	-	-
Elliptio dilatata	-	1	-	2	3	7	-	246	137	56
Epioblasma brevidens	-	-	-	-	-	-	-	-	1	6
Epioblasma triquetra	-	-	-	-	-	-	-	-	-	-
Fusconaia cor	-	-	-	-	-	-	-	12	4	-
Fusconaia subrotunda	-	-	-	1	6	2	-	7	9	3
Lampsilis fasciola	1	-	-	-	1	2	-	1	11	5
Lampsilis ovata	-	-	-	-	1	-	-	1	2	12
Lasmigona costata	-	-	-	-	-	1	-	1	-	-
Lemiox rimosus	-	-	-	-	-	-	-	3	2	4
Ligumia recta	-	-	-	-	-	-	-	-	-	-
Medionidus conradicus	-	-	-	-	-	1	1	49	33	63
Plethobasus cyphyus	-	-	-	-	-	-	1	5	1	6
Pleuronaia barnesiana	-	-	-	-	-	-	-	3	-	-
Pleuronaia dolabelloides	-	-	-	-	-	-	-	3	1	-
Potamilus alatus	-	-	-	-	-	-	-	-	-	-
Ptychobranchus fasciolaris	2	1	1	-	-	2	-	8	14	23
Ptychobranchus subtentum	-	-	-	-	-	-	-	26	1	-
Quadrula c. strigillata	-	-	-	-	3	-	-	-	-	-
Quadrula intermedia	-	-	-	-	1	-	-	7	6	6
Quadrula pustulosa	-	-	-	-	-	-	-	2	-	-
Quadrula sparsa	-	-	-	-	1	-	-	-	1	2
Villosa iris	-	-	-	-	1	-	3	3	9	14
Villosa vanuxemensis	-	-	-	-	-	-	-	1	-	6
Total Number	4	2	1	38	85	79	25	2579	1738	948
CPUE (mussels/p-h)	1.33	0.67	0.33	5.07	4.53	9.03	2.78	20.97	7.79	5.02
Total Species	3	2	1	4	12	10	7	22	20	18

4 STERKIANA No. 71, January 1981

TABLE III
MUSSEL RECORDS, POWELL RIVER — ORTMANN, 1918

	Big Stone Gap Wise Co., Va.	Olinger Lee Co., Va.	Dryden Lee Co., Va.	Pennington Gap Lee Co., Va.	Jonesville Lee Co., Va.	Rose Hill Lee Co., Va.	Shawnanee Claiborne Co., Tn.	Bryant Shoals Claiborne Co., Tn.	Lower Powell River
Unionidae									
Unioninae									
Amblema costata	—	—	—	—	—	—	X	X	X
Elliptio crassidens	—	—	—	—	X	—	X	—	X
Elliptio dilatatus	—	X	X	X	—	X	X	X	X
Fusconaia barnesiana	X	—	X	—	—	—	—	—	X
Fusconaia barnesiana bigbyensis	X	X	X	X	—	X	X	—	X
* *Fusconaia cuneolus*	—	X	—	—	—	—	X	—	X
Fusconaia edgariana	—	—	—	X	—	X	X	X	X
* *Fusconaia pilaris*	X	X	X	X	X	X	X	X	X
* *Lexingtonia dolabelloides*	X	X	X	X	—	—	—	X	X
* *Plethobasus cyphyus*	—	—	—	—	—	—	—	X	X
Pleurobema oviforme	X	X	X	X	X	X	X	X	X
Quadrula cylindrica strigillata	—	—	—	X	—	—	—	X	X
Quadrula pustulosa	—	—	—	—	—	—	—	X	—
Andontinae									
Alasmidonta marginata	—	X	X	—	—	X	—	X	X
* *Alasmidonta minor*	X	—							
* *Lasmigona holstonia*	X	—							
Lasmigona costata	—	X							
Strophitus rugosus	X	—							
Lampsilinae									
Actinonais carinata	—	—							
Actinonais pectorosa	—	—							
* *Carunculina moesta*	X	—							
Conradilla caelata	—	—							
Dromus dromas	—	—							
Dysonomia brevidens	—	—							
Dysnomia capsaeformis	—	—							
* *Dysnomia haysiana*	—	—							
* *Dysnomia lewisi*	—	—							
* *Dysnomia torulosa*	—	—							
Dysnomia triquetra	—	—							
Lampsilis fasciola	X	—							
Lampsilis ovata ventricosa	—	X							
Leptodea fragilis	—	—							
Ligumia recta latissima	—	—							
Medionidus conradicus	X	X							
* *Micromya fabalis*	—	X							
Micromya nebulosa	X	X							
* *Micromya perpurpurea*	—	X							
Micromya vanuxemensis	X	—							
* *Pegias fabula*	—	—							
Proptera alata	—	—							
Ptychobranchus fasciolaris	—	—							
Ptychobranchus subtentum	X	X							
Total species represented - 42 Totals	14	13							

*Species not found in present study

18 STERKIANA NO. 69-70, MARCH 1978

TABLE V - MUSSEL SPECIES DISTRIBUTION: CLINCH RIVER, 1973-1975

Species	Site Number 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Margaritanidae															
Cumberlandia monodonta	-	-	-	-	-	-	-	-	X	-	-	-	X	-	-
Unioninae															
Amblema costata	-	-	-	-	-	-	-	-	X	X	-	-	-	X	-
Cyclonaias tuberculata	-	-	-	-	X	-	-	-	X	X	-	-	-	-	-
Elliptio crassidens	-	-	X	-	-	-	-	-	X	-	X	-	-	-	-
Elliptio dilatatus	-	-	-	-	-	-	-	-	X	-	-	X	X	-	X
* Fusconaia barnesiana **	-	-	-	-	-	-	-	-	X	X	X	X	X	-	X
* Fusconaia b. bigbyensis	-	-	-	-	-	-	-	-	X	-	-	-	-	-	-
Fusconaia edgariana **	-	-	-	-	-	-	-	-	-	-	-	X	X	-	-
Lastena lata	-	-	X	-	-	-	-	-	X	-	-	-	-	-	-
Plethobasus cyphyus	-	-	-	-	-	-	-	-	X	-	-	-	-	-	-
Pleurobema cordatum	-	-	-	-	-	-	-	-	X	X	-	-	-	-	-
Pleurobema oviforme **	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Quadrula cylindrica	-	-	-	-	-	-	-	-	X	-	-	-	-	-	X
Quadrula pustulosa	-	-	-	-	-	-	-	-	X	-	-	X	-	-	-
Anodontinae															
Alasmidonta marginata	-	-	-	-	-	-	-	-	X	-	-	-	-	-	-
Lasmigona costata	-	-	X	-	-	-	X	-	X	X	-	-	-	-	-
Strophitus rugosus	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Lampsilinae															
* Actinonaias carinata	-	-	-	-	-	-	-	-	X	-	-	-	-	-	X
* Actinonaias c. gibba	-	X	X	-	X	-	X	-	X	X	X	X	-	-	X
Actinonaias pectorosa **	-	X	X	-	-	-	X	-	X	-	-	X	X	-	X
Cyprogenia irrorata	-	-	-	-	-	-	-	-	X	X	-	-	-	X	-
Conradilla caelata **	-	-	-	-	-	-	-	-	X	-	-	-	-	-	-
Dromus dromas **	-	-	-	-	-	-	-	-	X	-	-	-	X	-	-
Dysnomia brevidens **	-	-	-	-	-	-	-	-	X	-	-	-	-	-	X
Dysnomia capsaeformis **	-	-	-	-	-	-	-	-	X	-	X	-	X	-	X
Dysmonia torulosa ** gubernaculum	-	-	-	-	-	-	-	-	X	-	-	-	-	-	-
Dysnomia triquetra	-	-	-	-	-	-	-	-	X	-	-	-	X	-	-
Lampsilis fasciola	-	-	-	-	-	-	-	-	X	-	X	X	-	-	-
Lampsilis ovata	-	-	-	-	-	-	X	-	X	X	-	-	-	-	X
Legumia recta latissima	-	-	-	-	-	-	-	-	X	X	-	-	-	-	-
Leptodea fragilis	-	-	-	-	-	-	-	-	X	X	-	-	-	-	-
Medionidus conradicus **	-	X	-	-	-	-	X	-	X	-	X	X	-	X	X
Micromya (Villosa) ** nebulosa	-	-	-	-	-	-	-	-	X	-	X	-	-	-	-
Micromya vanuxemensis **	-	-	-	-	-	-	-	-	X	-	X	-	-	-	X
Proptera alata	-	-	X	-	-	-	-	-	X	X	-	-	-	-	-
Ptychobranchus fasciolaris	-	-	-	-	-	-	-	-	X	X	-	-	-	-	X
Ptychobranchus subtentum **	-	X	-	-	-	-	X	-	X	X	X	X	X	-	X
Truncilla truncata	-	-	-	-	-	X	-	-	X	-	X	X	-	-	X
		4	6		2	1	6		33	13	10	10	9	3	13

* these two forms have been counted as one species. **Cumberlandian species.

Ahlstedt (1991a); Johnson et al. (2012); Bates & Dennis (1978); Dennis (1981)

CASE STUDY:
CLINCH & POWELL RIVER LTM

Qualitative Survey Data & Inferences:

- Species lists
- Spatial variation in species distributions
- Spatio-temporal variation in observed species richness (within drainage)

TABLE 4. Longitudinal distribution of freshwater mussel species in 32-km (20-mile) reaches of the Clinch River with historical record
(1918) and recent collections from 1978 to 1983 by Ahlstedt (A).

	Collecting Sites (kilometer/mile reach)																	
	Lower Clinch River							Upper Clinch River										
Mussel Species	km 16 mi. 10	48 30	80 50	113 70	145 90	177 110	209 130	241 150	273 170	306 190	338 210	370 230	402 250	434 270				
Actinonaias ligamentina	O	–	O,A	O,A	O	–	O	A	A	O,A	O,A	A	O,A	A				
Actinonaias pectorosa	–	–	–	–	–	–	O	A	A	O,A	O,A	A	O,A	O,A				
Alasmidonta marginata	O	–	O	O	–	–	O	A	A	A	O,A	A	O,A	O,A				
Alasmidonta viridis	–	–	–	–	–	–	–	–	–	–	O	–	O	O				
Amblema plicata	O,A	–	OA	O,A	–	–	O	A	A	A	O,A	O,A	O,A	O,A				
Anodonta grandis	A	A	A	A	–	–	–	–	–	–	–	–	–	–				
Anodonta suborbiculata	A	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Cumberlandia monodonta	–	–	O,A	O,A	O	O	O	A	A	A	A	–	–	–	–	–	–	–
Cyclonaias tuberculata	A	–	O,A	O	O	–	O	A	A	O,A	O,A	A	A	–	–	–	–	–
Cyprogenia stegaria	–	–	O	O	O	–	O	–	A	A	A	A	–	–	–	–	–	–
Dromus dromas	–	–	O	O	O	—	O	–	A	A	–	–	–	–	–	–	–	–
Elliptio crassidens	O,A	–	O,A	O,A	–	–	O	A	A	A	O	A	A	–	–	–	–	–
Elliptio dilatata	O	–	O,A	O,A	O	—	O	A	O,A	O,A	O,A	A	O,A	O,A	A	O	O	–
Epioblasma arcaeformis	–	–	–	–	–	–	O	–	–	–	–	–	–	–	–	–	–	–
Epioblasma brevidens	–	–	O	–	–	–	O	–	A	A	O,A	A	–	–	–	–	–	–
Epioblasma capsaeformis	–	–	O	O	–	–	O	–	A	O,A	O,A	A	O	O	–	O	O	–
Epioblasma haysiana	–	–	O	O	–	–	O	–	–	–	–	–	–	–	–	O	–	–
Epioblasma lenior	–	–	–	–	–	–	–	–	–	–	O	–	–	–	–	–	–	–
Epioblasma propinqua	O	–	O	O	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Epioblasma stewardsoni	–	–	–	O	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Epioblasma torulosa gubernaculum	–	–	–	–	–	O	O	–	–	O	O	O	–	–	–	–	–	–
Epioblasma triquetra	–	–	O	O	–	–	O	–	A	O,A	O,A	A	–	–	–	–	–	–
Fusconaia barnesiana	O	–	O	O	O	–	O	A	A	O,A	O,A	A	O,A	A	A	O	O,A	O
Fusconaia cor	O	–	O	–	–	–	O	–	O,A	A	O,A	A	O,A	O,A	–	–	–	–
Fusconaia cuneolus	–	–	O	O	–	–	O	A	A	O,A	O,A	A	A	A	A	–	A	–
Fusconaia subrotunda	O	–	O,A	O,A	O	–	O	–	O,A	O,A	O,A	A	O,A	O,A	A	O,A	O,A	–
Hemistena lata	–	–	O	O	–	–	O	–	A	A	O,A	–	O	O	–	–	–	–
Lampsilis abrupta	A	–	O	O	–	–	–	–	–	A	–	–	–	–	–	–	–	–
Lampsilis fasciola	O	–	O	O	–	–	O	A	A	A	O,A	A	O,A	O,A	A	O	O,A	–
Lampsilis ovata	–	–	O	O	–	–	O	A	A	A	O,A	A	O,A	O,A	A	O	O	–
Lasmigona complanata	A	A	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Lasmigona costata	–	–	O	O	–	–	O	A	A	O,A	O,A	A	O,A	O,A	A	O,A	O	–

Table 10. Species diversity reported in mussel surveys conducted at selected sites in the Powell River, Virginia.

Site (PRM)	Survey*							
		A	B	C	D	E	F	G
FLET (117.3)		28	12	17	27	15	10	19
YELL (117.9)	-	-	26	10	0	-	3	
833B (120.4)		24	21	18	11	-	-	18
SNOD (123.0)	-	-	-	-	-	-	22	
HALL (128.5)	-	-	5	18	-	-	14	
FLAN (130.6)	4	8	13	-	6	5	9	
HURR (138.3)	-	1	6	-	-	-	7	
SEWE (143.5)	-	-	2	-	-	-	15	
POTE (144.6)		9	12	5	-	-	-	16
CHEE (146.8)	0	-	-	-	-	-	11	
TRAS (153.4)	-	-	2	-	-	-	11	
ROCK (158.3)	-	-	0	-	-	-	7	
SWIM (163.4)	-	-	1	-	-	-	3	
619B (165.7)		2	1	-	-	-	-	3
DRYD (167.4)	1	1	4	-	-	-	5	

*A = 1973-1978 (Dennis 1981)
B = 1975-1978 (Ahlstedt and Brown 1979)
C = 1979 (Ahlstedt 1986)
E = 1983 (Jenkinson and Ahlstedt 1988)
F = 1988 (Jenkinson and Ahlstedt 1988)
G = 1988-1989 (present study)

Ahlstedt (1991a); Wolcott & Neves (1994)

CASE STUDY:
CLINCH & POWELL RIVER LTM

(Non-annual) Quantitative Surveys & Methods:

Semi-regular intervals 1979 – 2004

- 10 Clinch & Powell river sites monitored on 4 - 6 sampling occasions over a 26-year period at 3 - 5 year intervals
- Simple random sampling with 0.25-m^2 quadrat units

Non-regular intervals 1970's – present

- >140 Clinch River and >75 Powell River sites
- Simple random sampling with varying sized (0.25 – 1.0-m^2) quadrat units
- Systematic random sampling (≥3 random starts) with 0.25-m^2 quadrat units
- # monitoring events per site variable (1 – 6 years of data)

Other:

- Capture-mark-recapture (CMR) studies with Hallprint shellfish and PIT tags

CASE STUDY:
CLINCH & POWELL RIVER LTM

(Non-annual) Quantitative Survey Data & Inferences:

- Population size/density
- Temporal and spatial trends in diversity and species' densities over time

Table 3, continued.

	Sample Year							
	1979	1983	1988	1994	1999	2004	Mean	±95% CI
Semones Island, VA (CRKM 378.4)								
Per meter squared	-	7.7	4.6	6.5	4.2	1.7	4.9	2.0
Species (17)	-	14	11	10	9	6	10.0	2.6
Endangered Species (5)	-	2	3	2	1	1	1.8	0.7
Powell River Site (PRKM)								
Buchanan Ford, TN (PRKM 159.5)								
Per meter squared	10.9	21.8	3.5	5.5	5.1	8.0	9.1	5.4
Species (24)	14	15	7	9	7	11	10.5	2.8
Endangered Species (8)	2	5	-	2	2	1	2.4	1.2
McDowell Shoal, TN (PRKM 171.7)								
Per meter squared	5.5	2.3	3.3	1.8	2.8	1.4	2.9	1.2
Species (22)	16	10	13	8	10	7	10.7	2.7
Endangered Species (8)	6	2	3	1	1	1	2.3	1.6
Bales Ford, TN (PRKM 179.9)								
Per meter squared	7.2	4.8	2.6	4.4	4.2	2.2	4.2	1.4
Species (19)	12	8	8	10	9	6	8.8	1.6
Endangered Species (7)	4	2	2	4	2	1	2.5	1.0
Fletcher Ford, VA (PRKM 188.8)								
Per meter squared	11.2	10.3	5.6	7.0	5.2	1.4	6.8	2.9
Species (23)	16	14	11	10	8	7	11.0	2.8
Endangered Species (8)	4	3	2	2	2	1	2.3	0.8

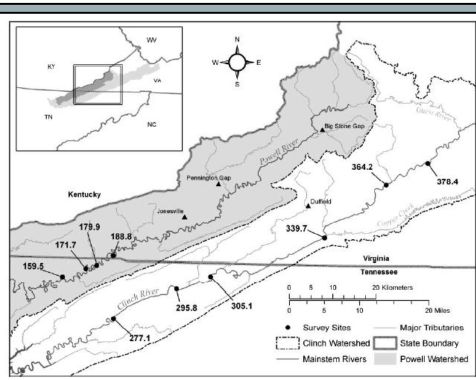


Figure 1. The Clinch and Powell river watersheds showing locations of sites (in RKM) sampled from 1979–2004.

Ahlstedt et al. 2016

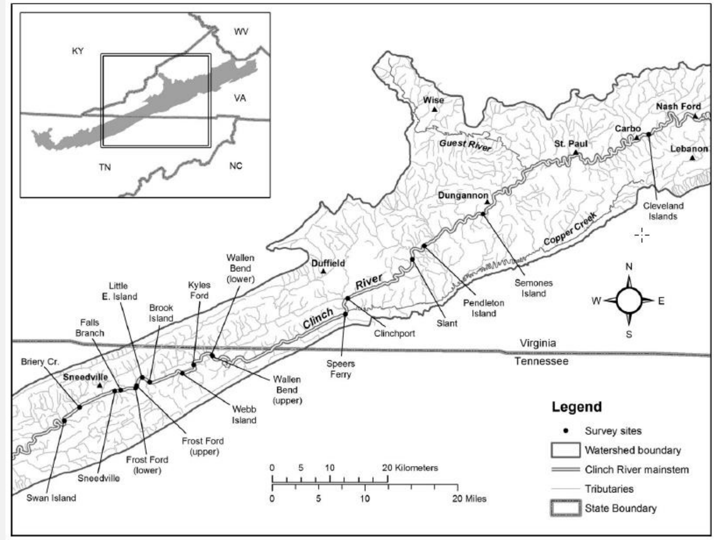


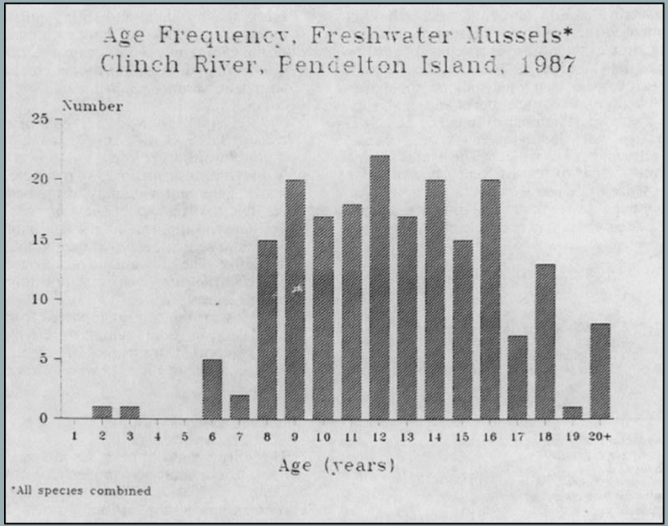
TABLE 2. Sampling Site, Area Size, and Mussel Density at Sites Sampled from 2004 to 2009 in the Clinch River, Tennessee and Virginia.

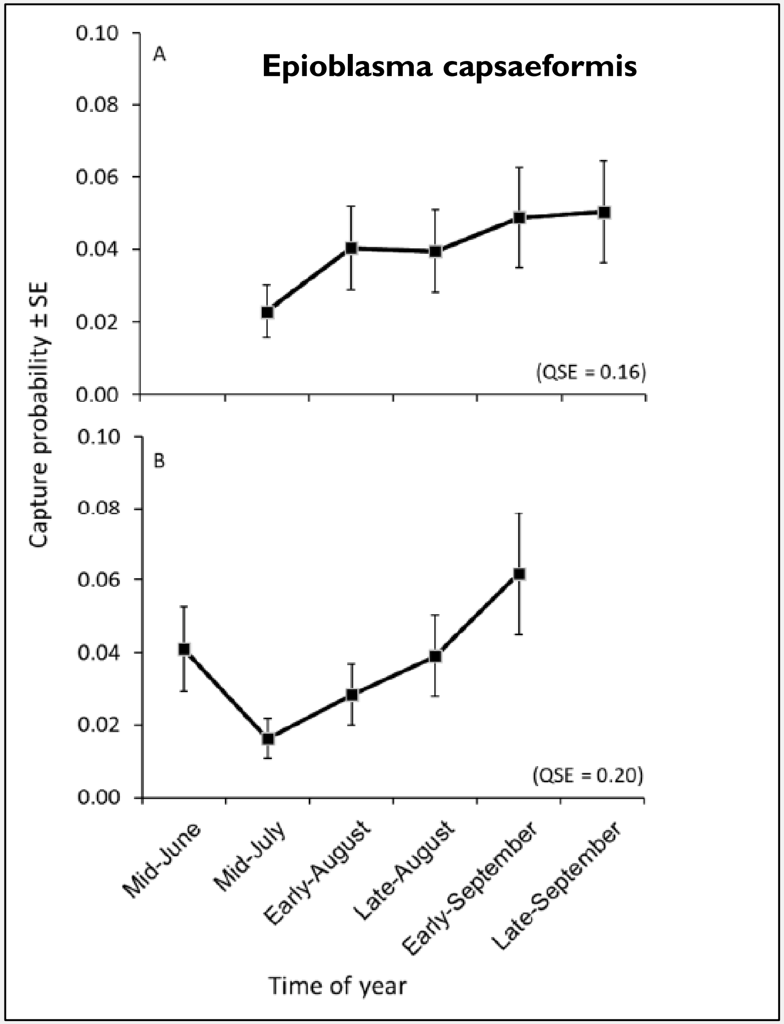
Site Location Name	River Kilometer (River Mile)	Total Site Area (m²)	Year(s) Sampled	No. (n) 0.25 m² quadrats yr⁻¹	Mean Density m⁻² (SE)	Lower 95% CI	Upper 95% CI
(2) Briery Creek, Tennessee	280.8 (174.5)	6,600	2006	40	12.0 (1.6)	8.9	15.1
(3) Sneedville, Tennessee	287.6 (178.7)	2,016	2006	40	11.8 (1.6)	8.5	15.0
(4) Falls Branch, Tennessee	288.7 (179.4)	5,334	2006	40	34.9 (4.3)	26.4	43.2
(7) Little E. Island, Tennessee	293.7 (182.5)	11,200	2005	60	19.3 (1.6)	16.2	22.4
(8) Brooks Island, Tennessee	295.3 (183.5)	~6,000	2005	60	21.5 (4.0)	13.6	29.2
(9) Webb Island, Tennessee	301.7 (187.5)	4,576	2006	60	22.8 (2.2)	18.4	27.2
(10) Kyles Ford, Tennessee	305.1 (189.6)	~15,000	2004	146	43.8 (4.1)	35.8	51.8
(13) Speers Ferry, Virginia	339.7 (211.1)	~4,000	2009	80	5.0 (0.7)	3.6	6.4
(14) Clinchport, Virginia	343.1 (213.2)	10,173	2006	220	1.9 (0.2)	1.6	2.2
(15) Slant, Virginia	359.7 (223.5)	9,000	2005	201	3.8 (0.3)	2.6	5.0
(16) Pendleton Island, Virginia	364.2 (226.3)	~20,000[1]	2009	360	0.66 (0.1)	0.5	0.9
(17) Semones Island, Virginia	378.3 (235.1)	~10,000	2009	124	0.61 (0.2)	0.3	0.9
(18) Cleveland Islands, Virginia	435.7 (270.8)	16,930	2008	478	6.6 (0.4)	5.9	7.3

CASE STUDY:
CLINCH & POWELL RIVER LTM

(Non-annual) Quantitative Survey Data & Inferences:

- Population size/density
- Temporal and spatial trends in diversity and species' densities over time
- Snapshots of age-class distributions
- Survival, mortality, and detection rates from CMR datasets





Dennis (1989); Carey et al. (2019)

CASE STUDY:
CLINCH & POWELL RIVER LTM

(Non-annual) Quantitative Survey Data & Inferences:

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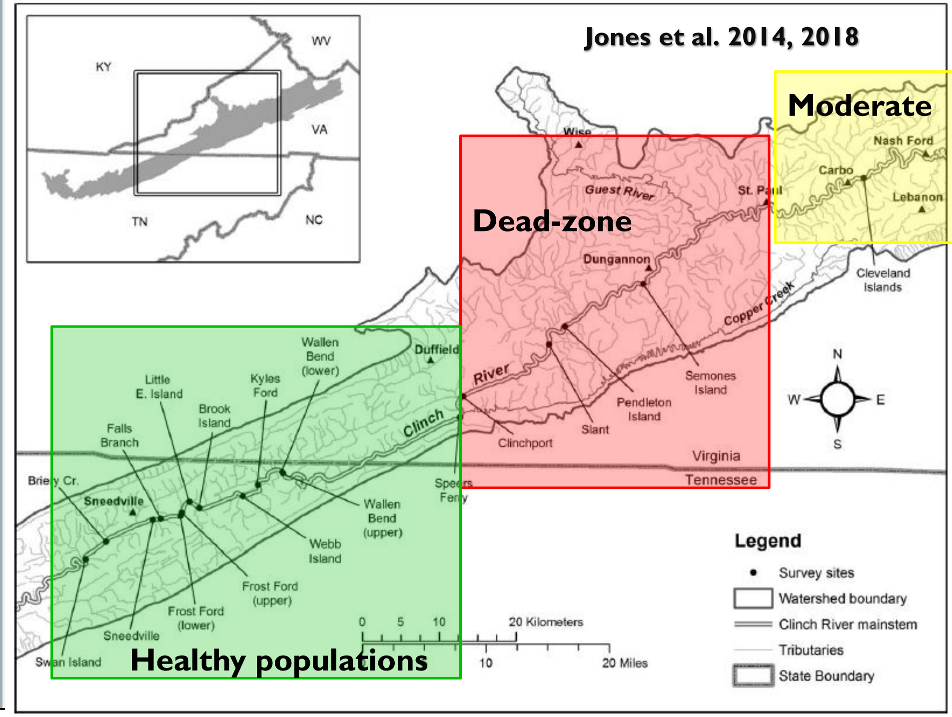


Appendix I. Summary of mussel density in the Clinch River at six sites sampled in TN and VA during quantitative surveys conducted from 1979–2004. NA = data not available or collected.

Ahlstedt et al. 2016

	Swan Island, TN (CRKM 277.1)					Brooks Island, TN (CRKM 295.8)					Kyles Ford, TN (CRKM 305.1)				
Scientific Name	1979	1988	1994	1999	2004	1979	1988	1994	1999	2004	1979	1988	1994	1999	2004
(1) *Actinonaias ligamentina*	5.10	0.60	4.00	1.90	6.50	6.62	5.85	7.54	3.54	5.10	7.41	5.66	7.41	8.68	5.00
(2) *Actinonaias pectorosa*	0.60	-	2.70	1.40	8.30	0.31	0.46	0.92	15.08	0.30	6.05	2.44	9.46	33.76	21.50
(3) *Alasmidonta marginata*	-	-	-	-	0.10	-	-	-	-	-	-	0.10	0.10	-	-
(4) *Amblema plicata*	-	0.10	0.10	-	-	0.15	-	-	0.46	-	0.39	0.29	-	-	-
(5) *Cumberlandia monodonta**	-	-	-	-	-	-	-	-	-	-	0.78	0.10	0.10	0.88	0.10
(6) *Cyclonaias tuberculata*	-	0.10	0.10	0.60	0.10	1.08	1.08	0.62	-	0.90	0.39	0.29	0.39	0.20	0.30
(7) *Cyprogenia stegaria**	-	-	-	0.10	0.10	-	-	0.15	-	0.30	0.10	0.10	0.10	0.39	0.20
(8) *Dromus dromas**	0.10	0.10	0.10	0.80	1.50	-	-	-	0.46	-	-	-	-	0.39	0.20
(9) *Elliptio crassidens*	-	-	-	-	-	-	-	0.15	0.31	-	-	-	-	-	0.50
(10) *Elliptio dilatata*	-	-	-	-	-	-	-	-	0.31	0.20	2.15	0.29	0.49	0.39	1.40

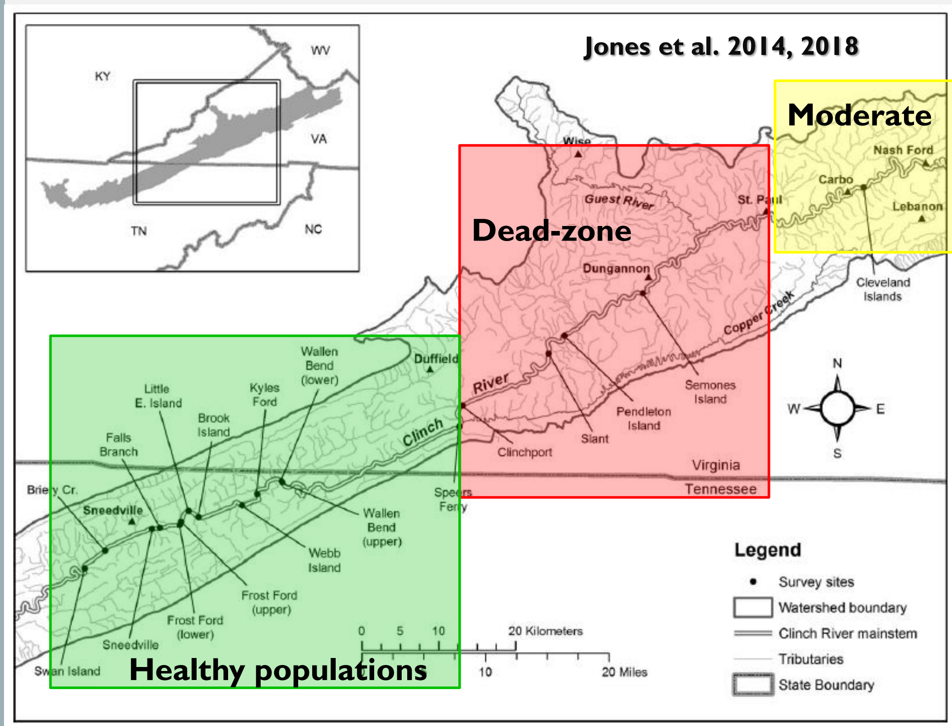
	Speers Ferry, VA (CRKM 339.7)					Pendleton Island, VA (CRKM 364.2)					Semones Island, VA (CRKM 378.4)				
Scientific Name	1979	1988	1994	1999	2004	1979	1988	1994	1999	2004	1983	1988	1994	1999	2004
(1) *Actinonaias ligamentina*	0.80	0.50	0.50	0.90	0.70	3.40	NA	2.60	2.50	0.50	1.90	1.00	1.60	0.70	0.10
(2) *Actinonaias pectorosa*	1.10	0.70	1.20	0.90	0.10	3.60	NA	3.40	4.30	1.80	2.50	1.80	1.90	1.60	0.80
(3) *Alasmidonta marginata*	-	-	-	-	-	-	NA	-	-	-	-	-	-	-	-
(4) *Amblema plicata*	-	0.10	-	-	-	0.80	NA	0.10	0.30	0.40	0.20	0.10	0.20	-	-
(5) *Cumberlandia monodonta**	-	-	-	-	-	-	NA	-	-	-	-	-	-	-	-
(6) *Cyclonaias tuberculata*	0.20	0.10	-	0.40	-	1.10	NA	0.50	0.70	0.60	0.20	0.30	0.50	0.20	-
(7) *Cyprogenia stegaria**	0.10	0.10	-	-	-	-	NA	-	-	-	-	-	-	-	-
(8) *Dromus dromas**	-	-	-	-	-	-	NA	-	-	-	-	-	-	-	-
(9) *Elliptio crassidens*	-	-	-	-	-	-	NA	-	-	-	-	-	-	-	-
(10) *Elliptio dilatata*	0.10	0.10	-	0.20	0.30	6.30	NA	1.40	0.80	0.20	0.10	0.10	0.10	0.10	-

★ Establishing species- and site-level baseline conditions

CASE STUDY:
CLINCH & POWELL RIVER LTM

(Annual) Quantitative Surveys & Methods:

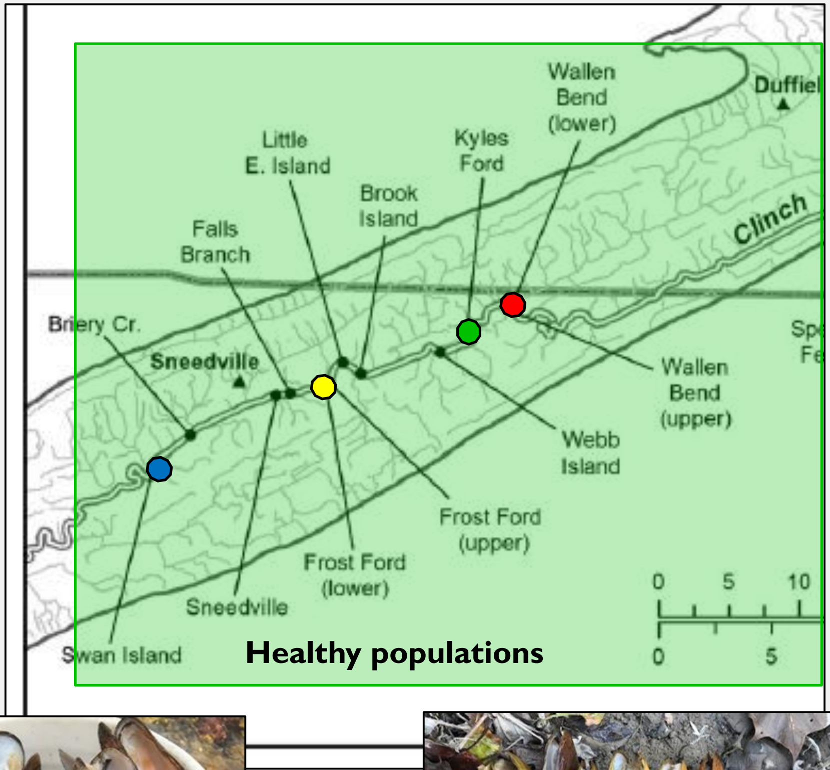
- 2004 – 2014 (11 years) & 2017 – present (5+ years)
- 3 ‘healthy’ lower Clinch River (TN) population sites



CASE STUDY: CLINCH & POWELL RIVER LTM

(Annual) Quantitative Surveys & Methods:

- 2004 – 2014 (11 years) & 2017 – present (5+ years)
- 3 'healthy' lower Clinch River (TN) population sites
  - 🔴 Wallen Bend (27 spp.) ~5,000 m^2
  - 🟡 Frost Ford (30 spp.) ~15,000 m^2
  - 🔵 Swan Island (32 spp.) ~6,000 m^2
- Systematic random sampling (0.25-m^2 quadrat units)
- 60 – 80 quadrats (2004 – 2014)
- 120 – 160 quadrats (2017 – present)
- Quadrat data:
  - Species ID, length, sex
  - ~Sampling unit location within study site
- 🟢 Kyles Ford (2004; 2016 – present)



CASE STUDY: CLINCH & POWELL RIVER LTM

(Annual) Quantitative Survey Data & Population Demographics

- Similar to qualitative & non-annual quantitative LTM…
  - Species lists; diversity (richness, evenness)*
  - Age-class structures*
  - Population size + density*
  - *Snapshots; 3-15+ year intervals between surveys

TABLE 2. Sampling Site, Area Size, and Mussel Density at Sites Sampled from 2004 to 2009 in the Clinch River, Tennessee and Virginia.

Site Location Name	River Kilometer (River Mile)	Total Site Area (m²)	Year(s) Sampled	No. (n) 0.25 m² quadrats yr⁻¹	Mean Density m⁻² (SE)	Lower 95% CI	Upper 95% CI
(2) Briery Creek, Tennessee	280.8 (174.5)	6,600	2006	40	12.0 (1.6)	8.9	15.1
(3) Sneedville, Tennessee	287.6 (178.7)	2,016	2006	40	11.8 (1.6)	8.5	15.0
(4) Falls Branch, Tennessee	288.7 (179.4)	5,334	2006	40	34.9 (4.3)	26.4	43.2
(7) Little E. Island, Tennessee	293.7 (182.5)	11,200	2005	60	19.3 (1.6)	16.2	22.4
(8) Brooks Island, Tennessee	295.3 (183.5)	~6,000	2005	60	21.5 (4.0)	13.6	29.2
(9) Webb Island, Tennessee	301.7 (187.5)	4,576	2006	60	22.8 (2.2)	18.4	27.2
(10) Kyles Ford, Tennessee	305.1 (189.6)	~15,000	2004	146	43.8 (4.1)	35.8	51.8
(13) Speers Ferry, Virginia	339.7 (211.1)	~4,000	2009	80	5.0 (0.7)	3.6	6.4
(14) Clinchport, Virginia	343.1 (213.2)	10,173	2006	220	1.9 (0.2)	1.6	2.2
(15) Slant, Virginia	359.7 (223.5)	9,000	2005	201	3.8 (0.3)	2.6	5.0
(16) Pendleton	364.2 (226.3)	~20,000[1]	2009	360	0.66 (0.1)	0.5	0.9
		)	2009	124	0.61 (0.2)	0.3	0.9
		)	2008	478	6.6 (0.4)	5.9	7.3

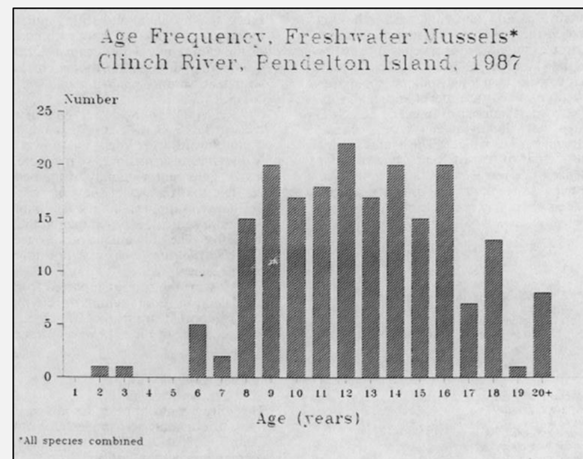
Numbers and Species of Mussels Collected from 22 Quadrat Samples Pendleton Island, Clinch River (Listed in Order of Abundance)

Species	Total	Percent
1. *Actinonaias pectorosa*	47	21.9
2. *Actinonaias carinata*	42	19.5
3. *Elliptio dilatatus*	29	13.5
4. *Fusconaia cuneolus*	25	11.6
5. *Fusconaia barnesiana*	14	6.5
6. *Fusconaia pilaris*	11	5.1
7. *Lasmigona costata*	9	4.2
8. *Cyclonaias tuberculata*	7	3.3
9. *Amblema costata*	4	1.9
10. *Lampsilis fasciola*	3	1.4
11. *Lampsilis ventricosa*	2	0.9
12. *Ptychobranchus fasciolaris*	2	0.9
13. *Quadrula cylindrica*	2	0.9
14. *Villosa nebulosa*	2	0.9
15. *Ptychobranchus subtentum*	1	0.5
16. *Dysnomia triquetra*	1	0.5
17. *Plethobasus cyphyus*	1	0.5
18. *Pleurobema cordatum*	1	0.5
19. *Villosa trabalis*	1	0.5
20. *Ligumia recta latissima*	1	0.5
21. *Conradilla caelata*	1	0.5
Totals:	206	100.0

Ave No./M^2 18.7

Mussel Species collected at Pendleton Island, Clinch River, September, 1987

Species	Live	Dead only
Actinonaias carinata	X	
Actinonaias pectorosa	X	
Amblema costata	X	
Conradilla caelata	X	
Cyclonaias tuberculata	X	
Cyprogenia irrorata	X	
Dysnomia brevidens		X
Dysnomia capsaeformis		X
Dysnomia triquetra	X	
Dysnomia torulosa gubernaculum		X (relic)
Elliptio dilatatus	X	
Fusconaia barnesiana	X	
Fusconaia cuneolus	X	
Fusconaia edgariana	X	



Jones et al. 2014; Dennis 1989

CASE STUDY:
CLINCH & POWELL RIVER LTM

(Annual) Quantitative Survey Data & Population Demographics

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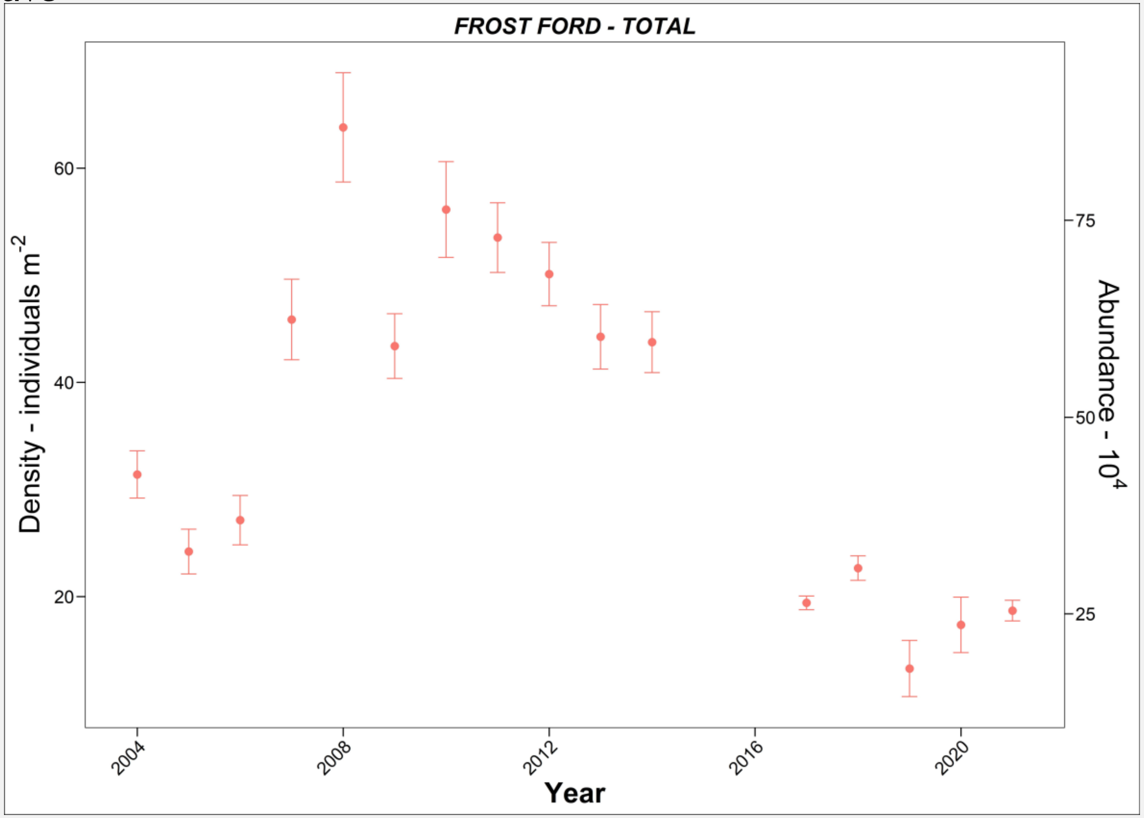
  - Age-class structures*
  - Population size + density*
  - *Snapshots; 3-15+ year intervals between surveys
- + more robust estimates of population demographics with improved precision**
  - Population size + density



Jones et al. 2012; Lane et al. 2021; Carey & Ostby 2018-2021 unpub data

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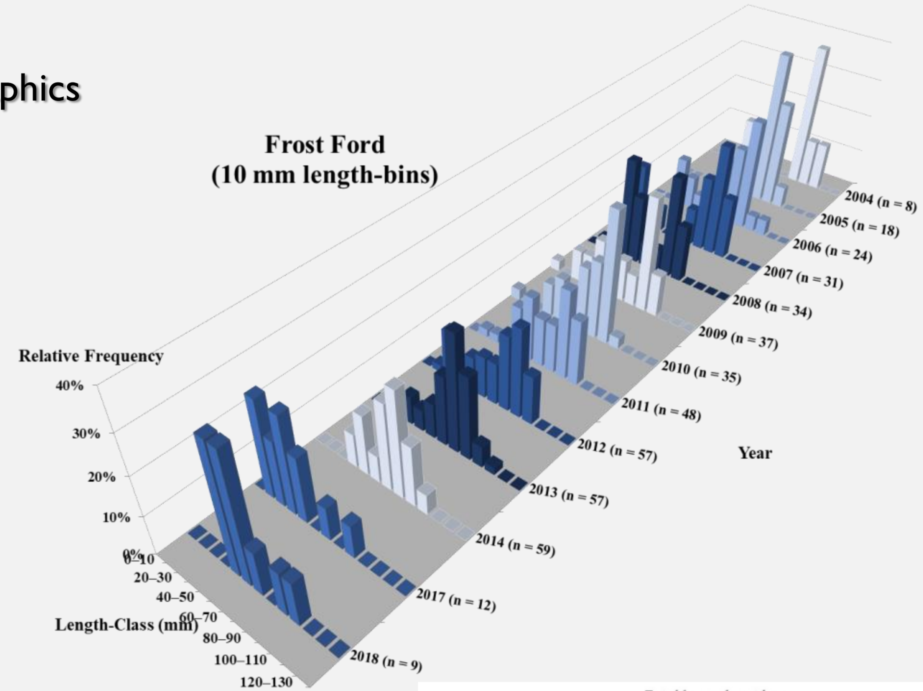

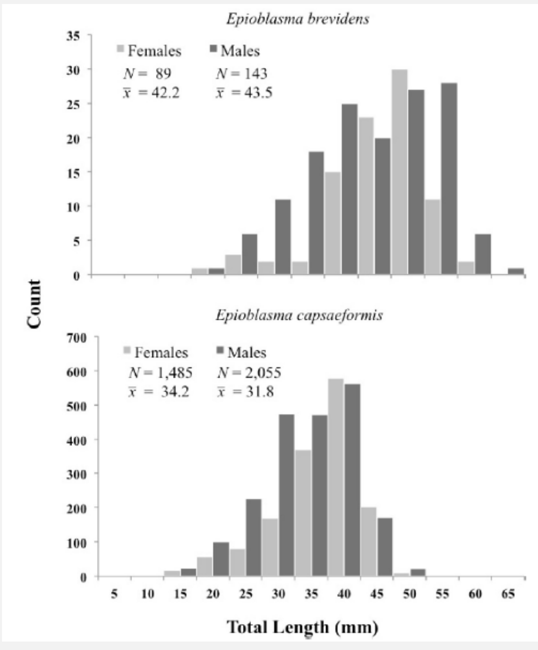

Lane et al. 2021; Carey & Ostby 2018-2021 unpub data

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  - Age-class structures/matrices; sex ratios
  - Survival, mortality, recruitment rates

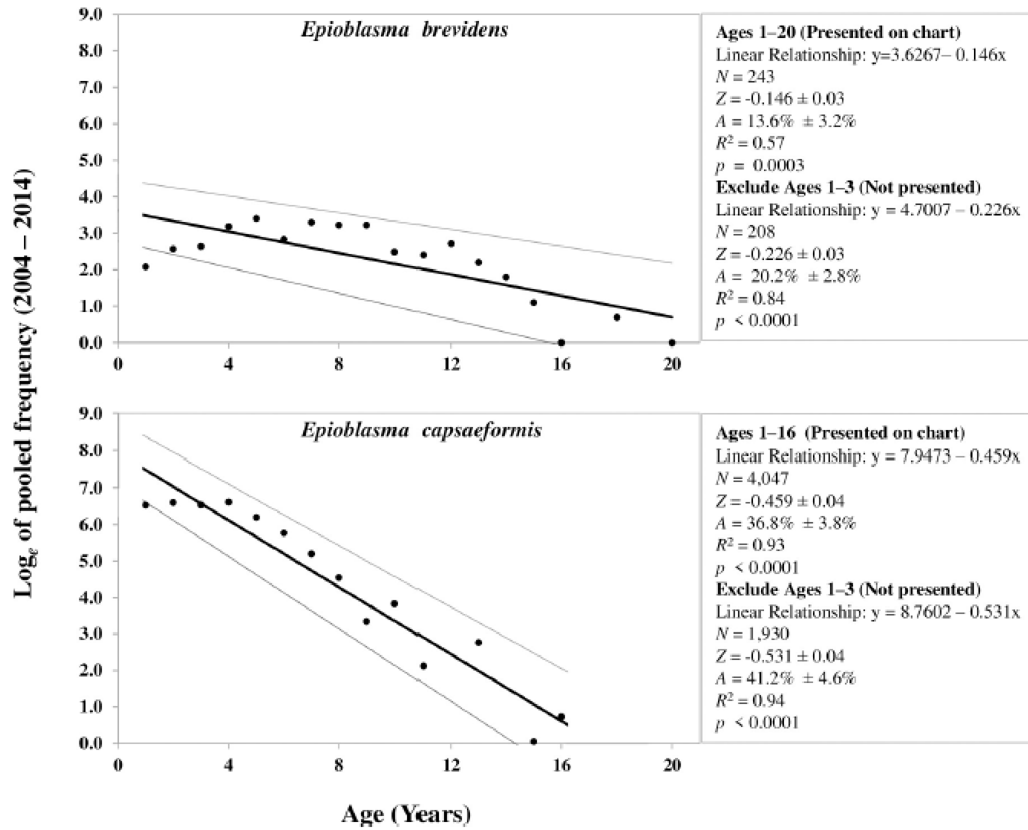

Fig 8. Mortality rates of *Epioblasma brevidens* and *E. capsaeformis* estimated from catch-curve linear regression analyses based on age class frequencies of all individuals sampled at Swan Island, Frost Ford, and Wallen Bend in the Clinch River, Hancock County, TN, from 2004–2014. As shown, Ages 1–3 were included in age-class frequency plots, where thin grey lines are 95% confidence intervals of the mean linear regression line (Bolded). For both species, estimated mortality rates are reported in the respective boxes to the right of the age-class frequency plots, where N = sample size, Z = instantaneous mortality rate, and A = annual mortality; rates were estimated with and without Ages 1–3. Age 0 individuals were not used in the analyses.

Lane et al. 2021

CASE STUDY:
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  - Survival, mortality, recruitment rates
  - Population growth (λ)

TABLE 2
Age-structured Leslie matrices of survival and fecundity values used to simulate population growth and reintroduction of Cumberlandian combshell (*Epioblasma brevidens*) and oyster mussel (*E. capsaeformis*). The three different survival values of juvenile mussels in the first column (0-1*) correspond to stable, low and moderate population growth simulated in the study (see Table 1).

Epioblasma brevidens:

	Immature Age Classes (0-4)					Mature Age Classes (5-15)										
	0-1*	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	15
0-1						0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63
1-2	0.300 0.323 0.363															
2-3		0.95														
3-4			0.95													
4-5				0.95												
5-6					0.95											
6-7						0.95										
7-8							0.95									
8-9								0.95								
9-10									0.95							
10-11										0.85						
11-12											0.80					
12-13												0.75				
13-14													0.70			
14-15														0.65		
15															0.60	0.00

Table 3. Estimated population size per census ($\hat{N}_t$), finite rate of population increase [λ_{t-t+1}] per time step, per capita or instantaneous rate of increase [$\bar{r}$], and cumulative population growth observed in populations of Epioblasma brevidens in the Clinch River, TN at Swan Island, Frost Ford, Wallen Bend, and Total (Sites Pooled) from 2004–2014.

Census (t)	Swan Island				Frost Ford				Wallen Bend				Total (Sites Pooled)			
	All Individuals		Adults Only		All Individuals		Adults Only		All Individuals		Adults Only		All Individuals		Adults Only	
	($\hat{N}_t$)	λ_{t-t+1}	($\hat{N}_t$)	λ_{t-t+1}	($\hat{N}_t$)	λ_{t-t+1}	($\hat{N}_t$)	λ_{t-t+1}	($\hat{N}_t$)	λ_{t-t+1}	($\hat{N}_t$)	λ_{t-t+1}	($\hat{N}_t$)	λ_{t-t+1}	($\hat{N}_t$)	λ_{t-t+1}
2004 (0)	2,304	N/A	2,304	N/A	3,010	N/A	1,003	N/A	636	N/A	212	N/A	5,950	N/A	3,519	N/A
2005 (1)	768	0.33	384	0.17	5,017	1.67	4,014	4.00	636	1.00	636	3.00	6,421	1.08	5,034	1.43
2006 (2)	1,152	1.50	384	1.00	5,017	1.00	3,010	0.75	212	0.33	212	0.33	6,381	0.99	3,606	0.72

Jones et al. 2012; Lane et al. 2021

CASE STUDY: CLINCH & POWELL RIVER LTM

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  - Population size + density
  - Age-class structures/matrices; sex ratios
  - Survival, mortality, recruitment rates
  - Population growth (λ)

**Only 4 – 8 species occur at densities (≥0.3 m^{-2}) adequate to obtain estimates with desired precision (CV ≤ 0.20)

- Pheasantshell (*Actinonaias pectorosa*)
- Oyster mussel (*Epioblasma capsaeformis*)
- Cumberland moccasinshell (*Medionidus conradicus*)
- Fluted kidneyshell (*Ptychobranchus subtentus*)
- Mucket (*Actinonaias ligamentina*)
- Spike (*Eurynia dilatata*)
- Kidneyshell (*Ptychobranchus fasciolaris*)
- Cumberland combshell (*Epioblasma brevidens*)

CASE STUDY:
CLINCH & POWELL RIVER LTM

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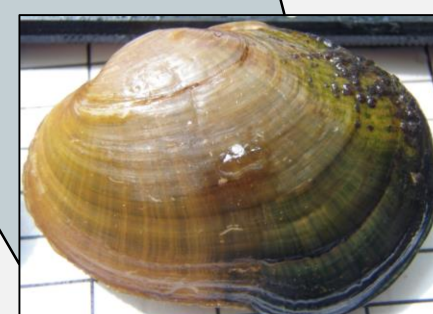
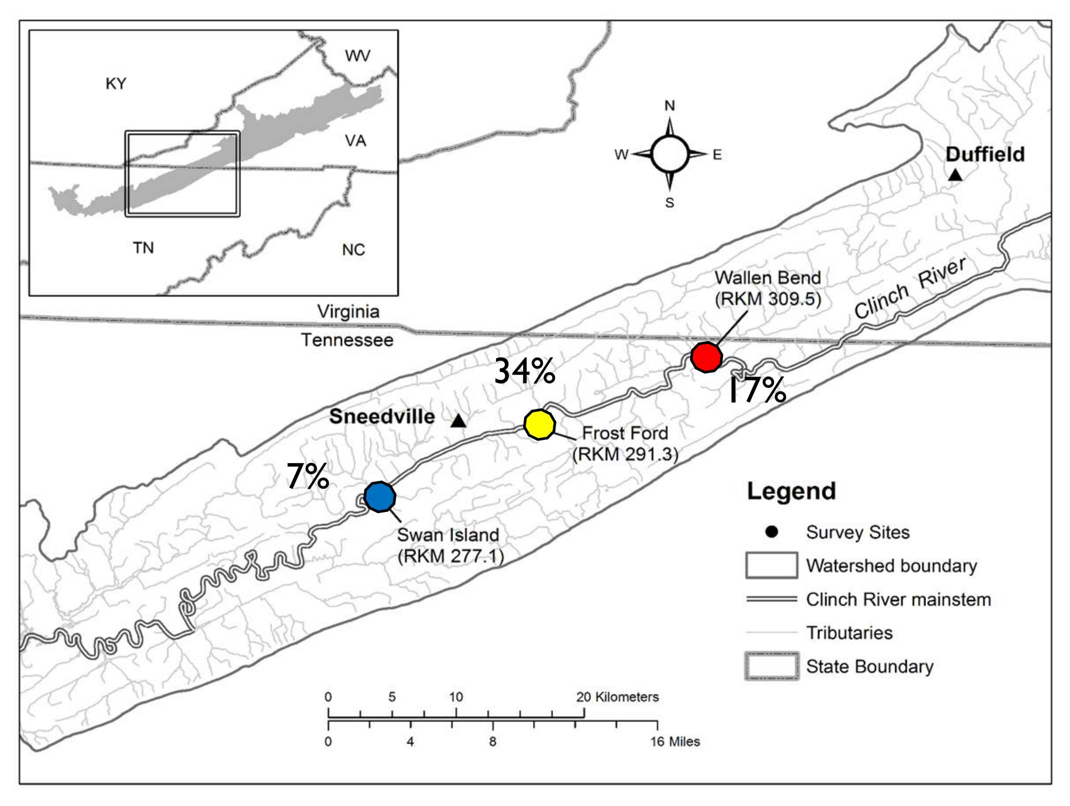
- **Pheasantshell (*Actinonaias pectorosa*)**
- **Oyster mussel (*Epioblasma capsaeformis*)**



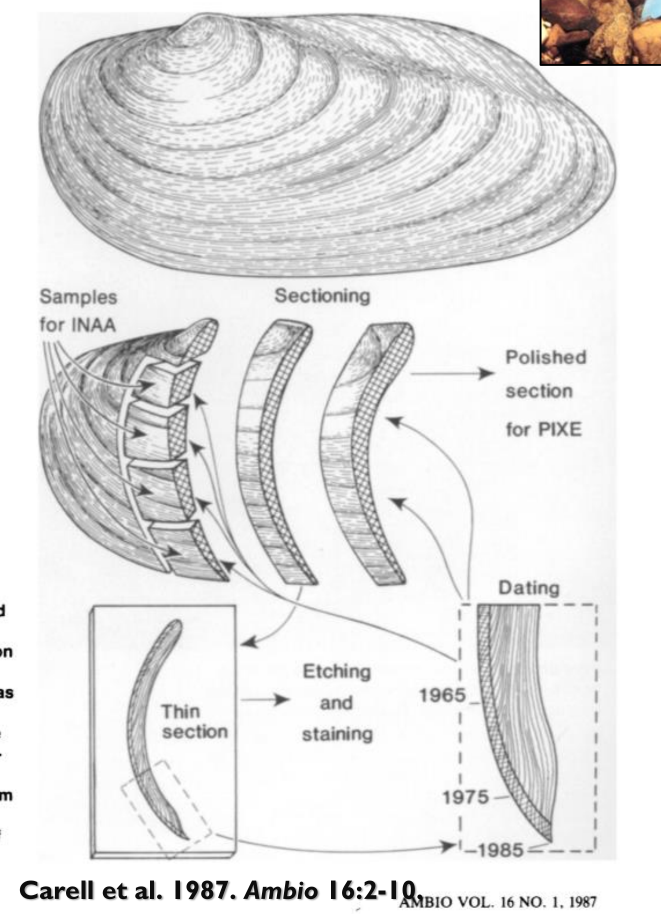
CASE STUDY: CLINCH RIVER LTM – OYSTER MUSSEL

Oyster mussel (*Epioblasma capsaeformis*)

- Federally endangered
- 28 mm (max ~55 mm)
- 9 – 12 years old
- Sexually dimorphic; long-term brooder
- 1 – 59% total site composition (2004 – 2014)



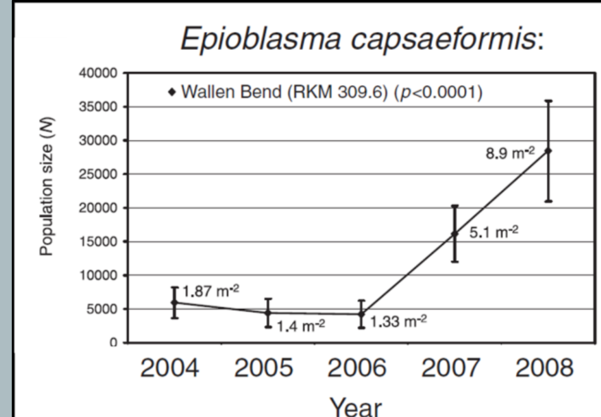
CASE STUDY: CLINCH RIVER LTM – OYSTER MUSSEL **AGE-CLASS STRUCTURE**



Carell et al. 1987. *Ambio* 16:2-10.

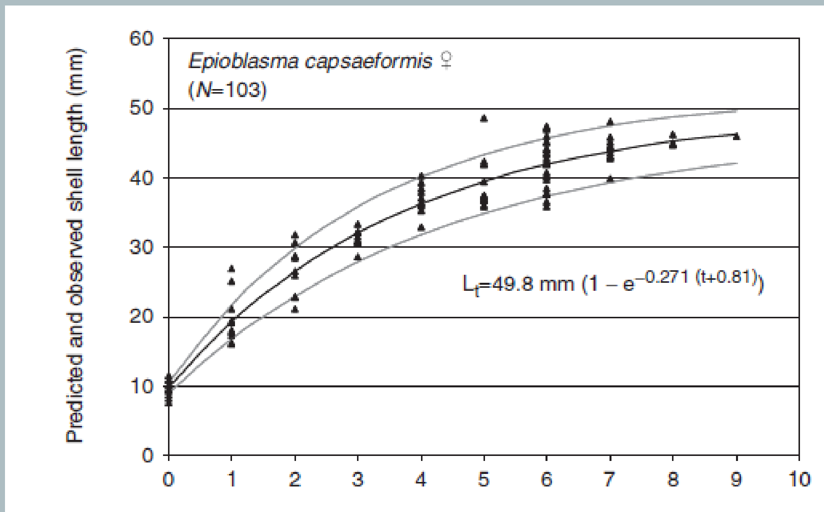
Clinch Annual Quantitative LTM (2004 – 2008)

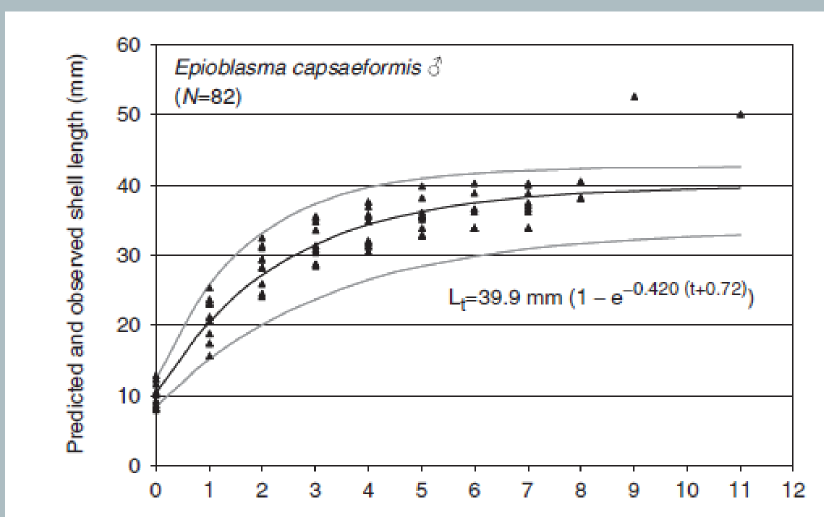
- Shell material
  - Shell thin-sectioning
    - Length @ age data (♀ + ♂)
- Length + sex data (quadrats)
  - Population size/density; growth

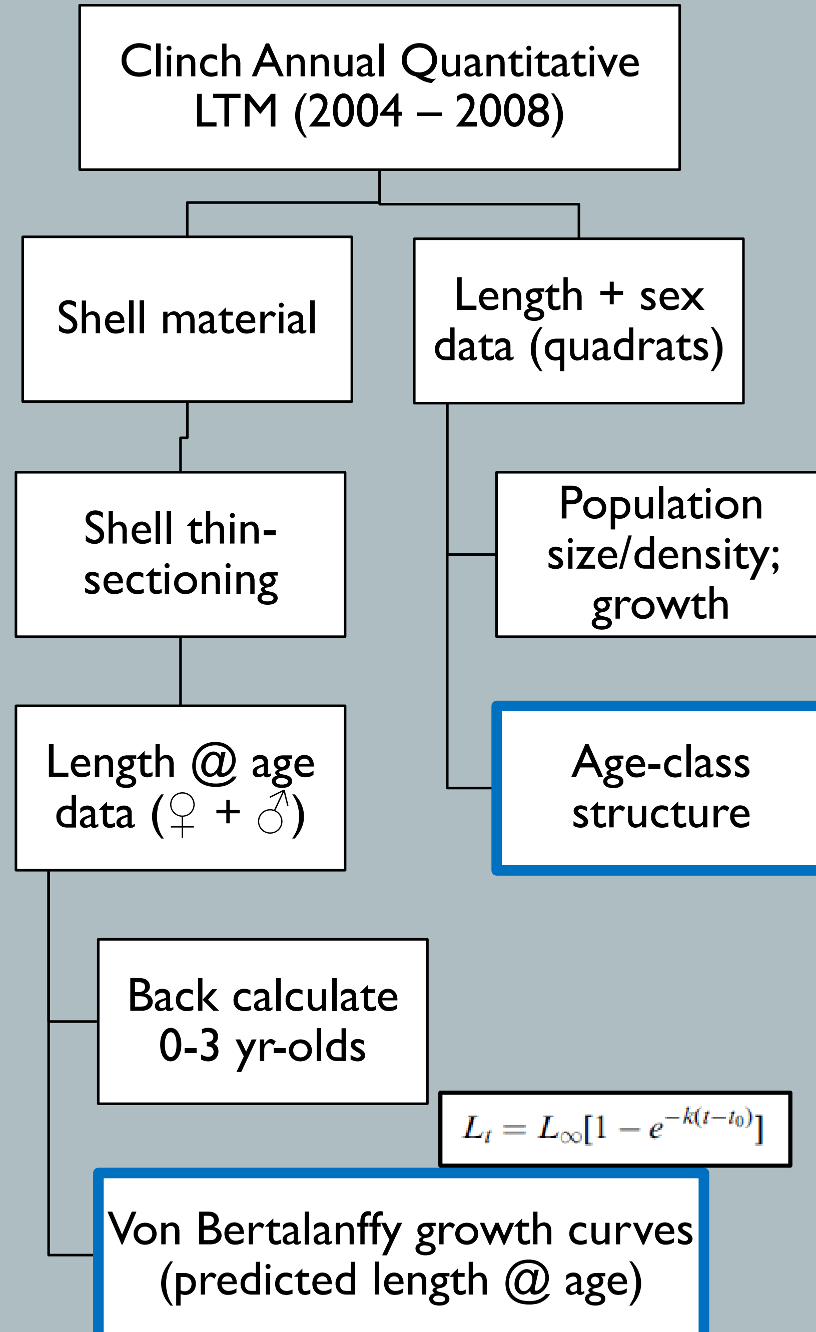


Jones et al. 2011. Influence of life-history variation on demographic responses of three freshwater mussel species (Bivalvia: Unionidae) in the Clinch River, USA. Aquatic Conservation: Marine and Freshwater Ecosystems 21:57-73.

CASE STUDY: CLINCH RIVER LTM – OYSTER MUSSEL







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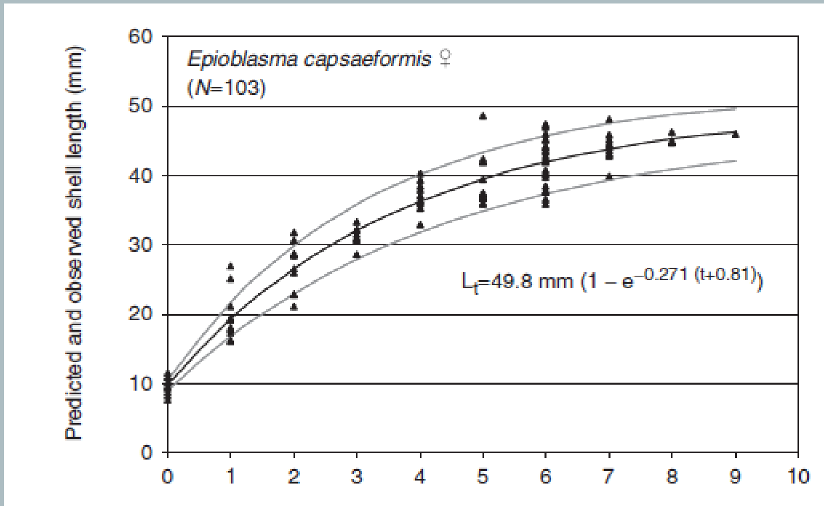

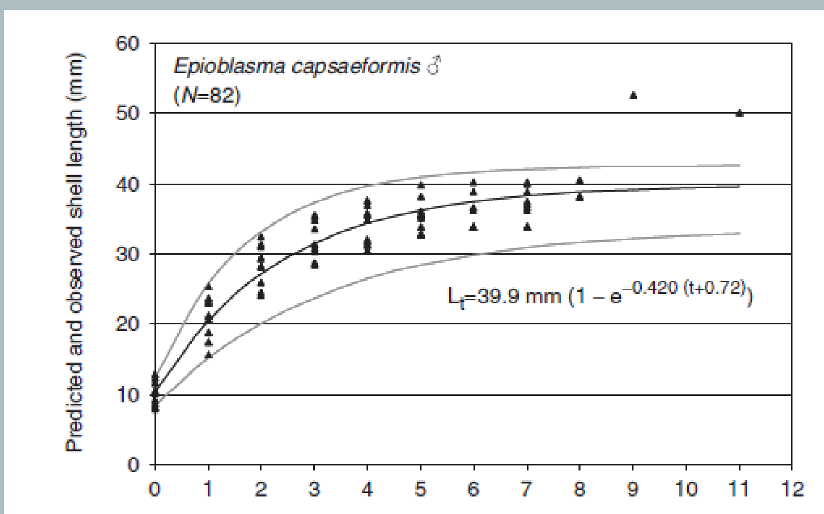

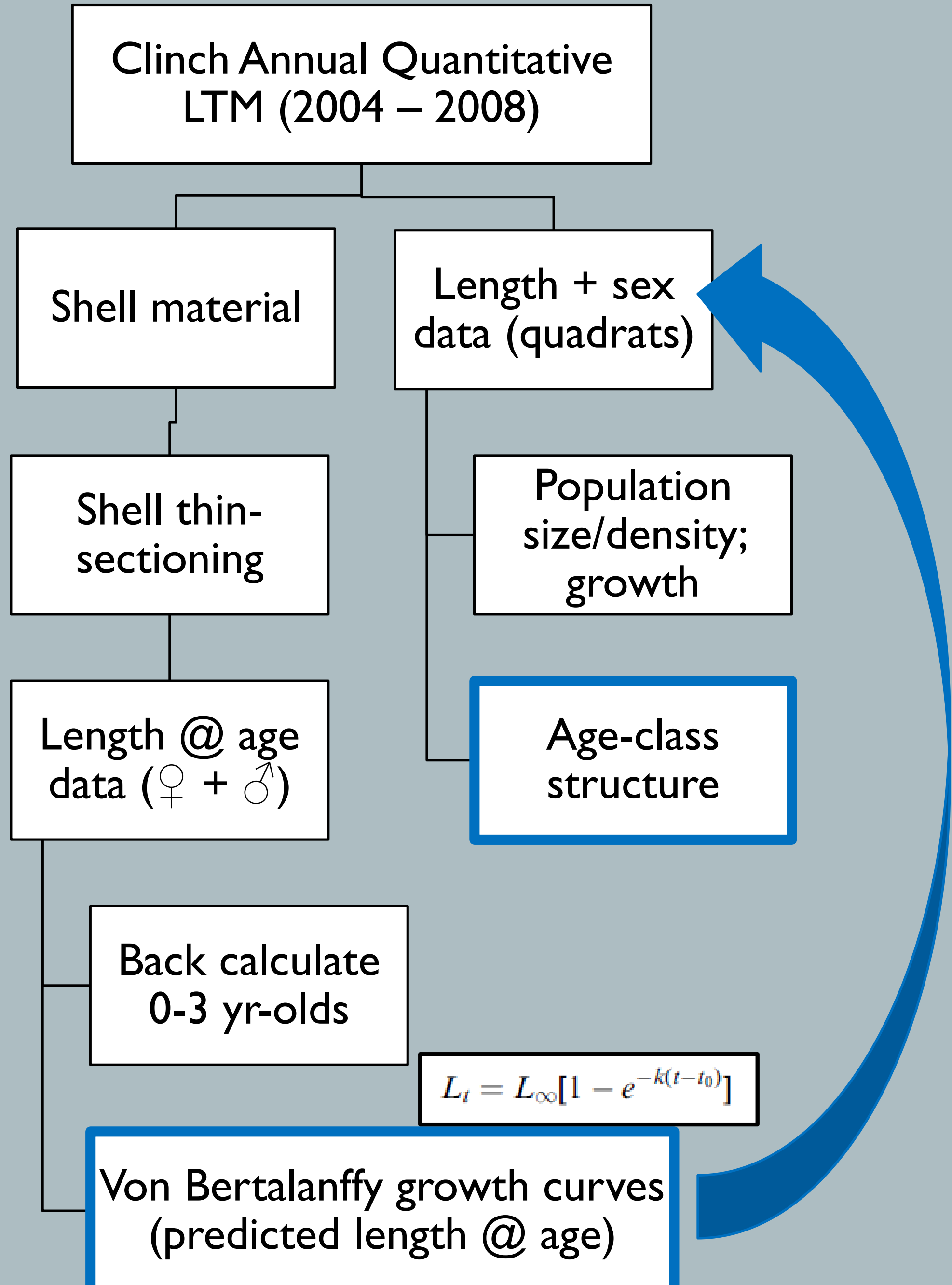

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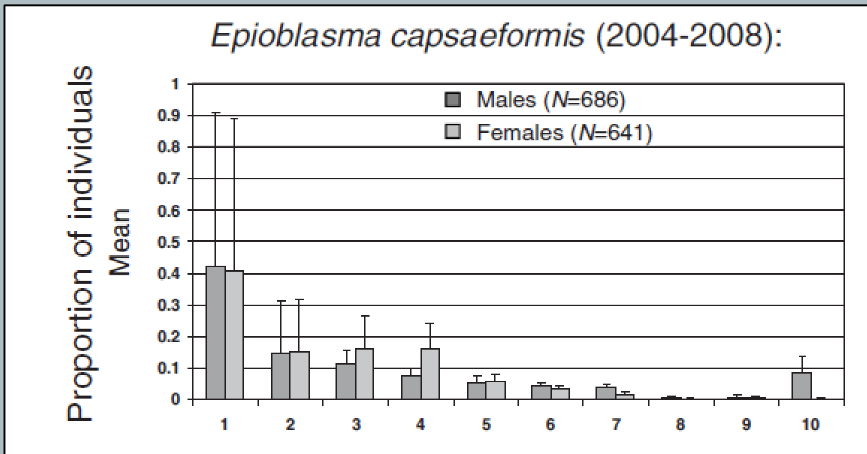

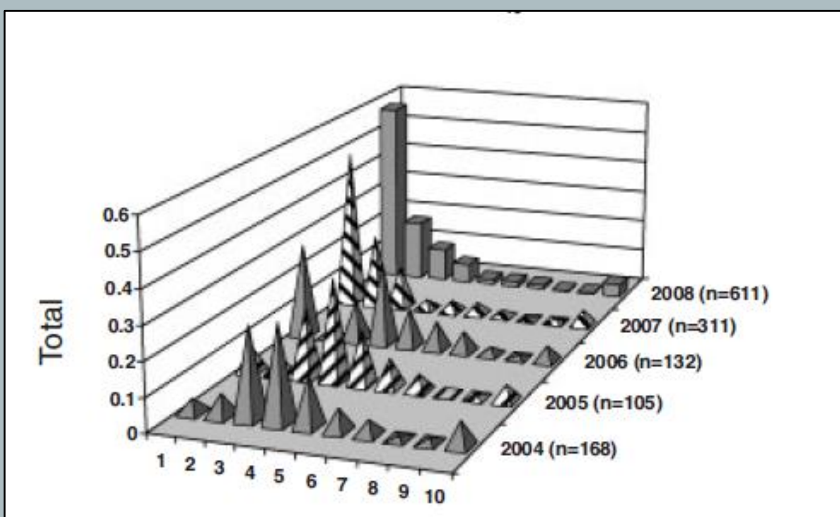

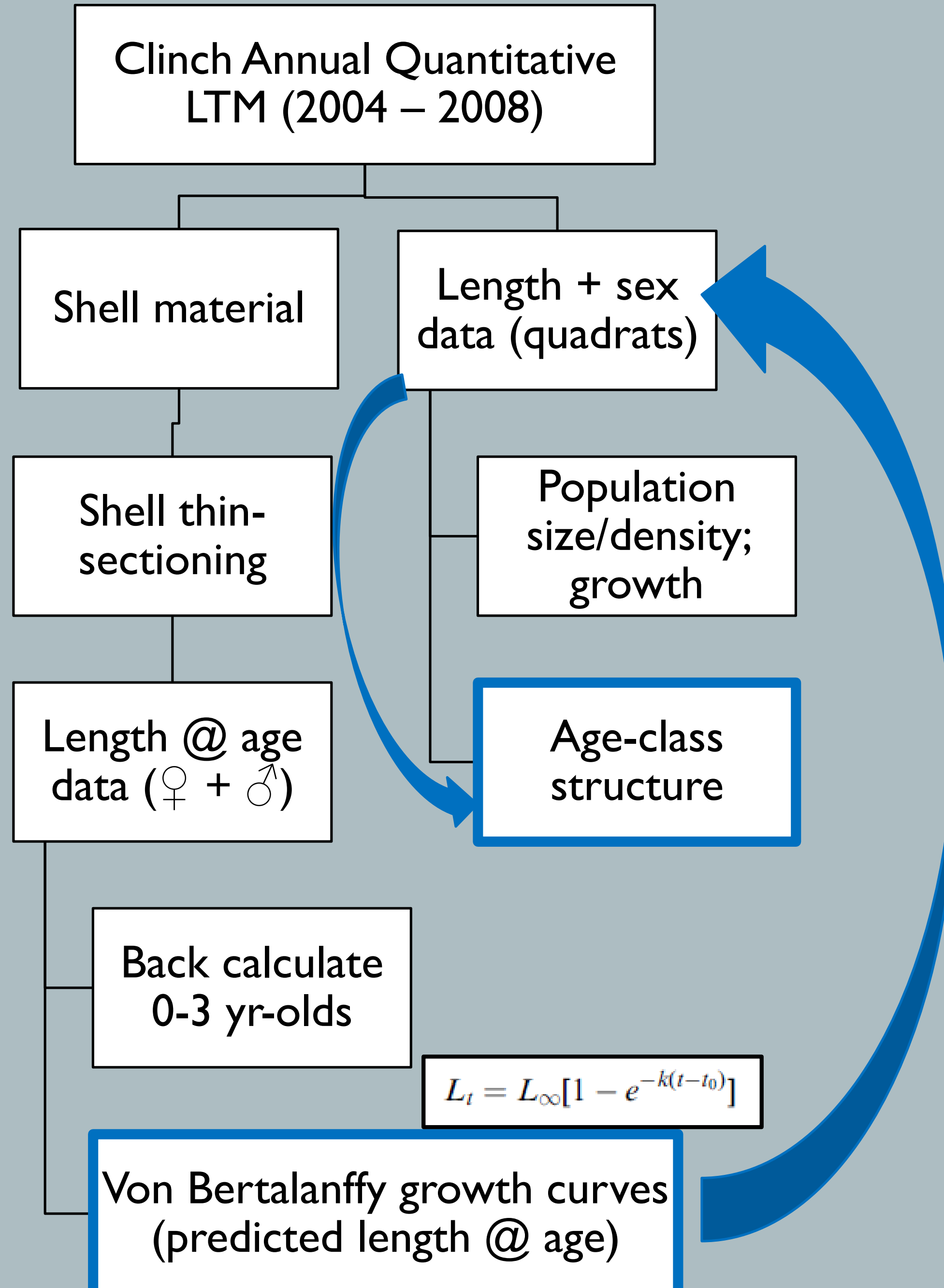

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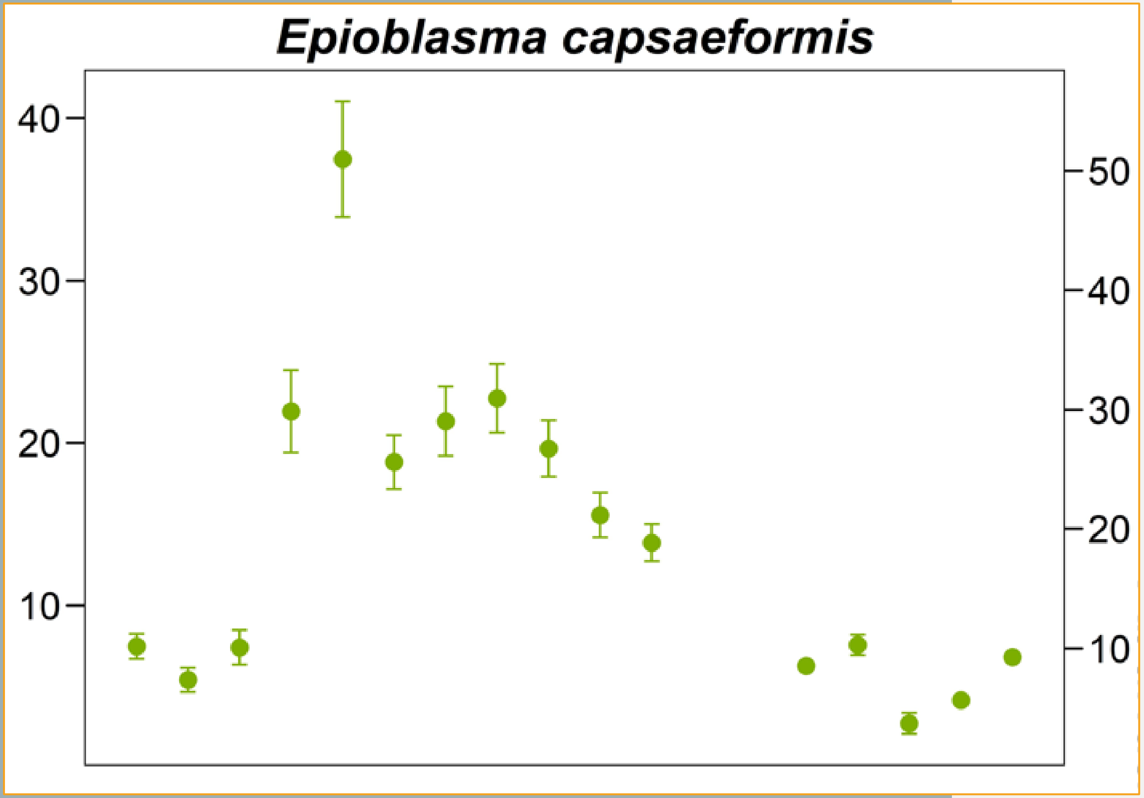
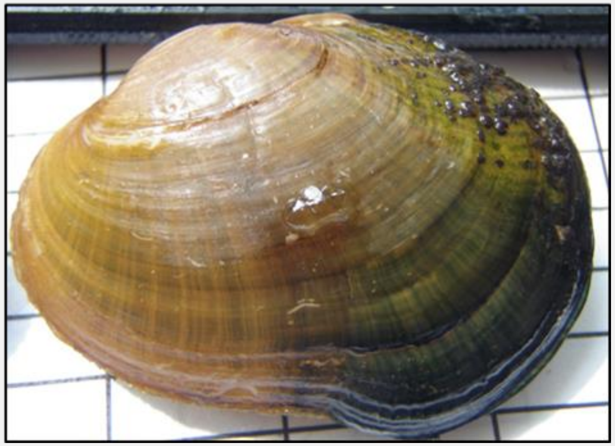
CASE STUDY: CLINCH RIVER LTM – OYSTER MUSSEL

Oyster mussel (*Epioblasma capsaeformis*)

- How environmental conditions influence demographic vital rates
- Has undergone boom and bust cycles, reaching densities as high as 40 individuals per m^2
- Low-flow conditions may contribute to high and variable recruitment rates in following years





CASE STUDY:
CLINCH RIVER LTM –
OYSTER MUSSEL

Oyster Mussel Demography & PVA

Demographic Analyses

1. Max. Age or Longevity
2. Mean age at death
3. Age at Maturity
4. Age structure
5. Density
6. Abundance
7. Population Growth Rate
8. Spatial Distribution

Population Viability Analyses

1. Survival matrix of age classes
2. Fecundity or recruitment
3. Population growth rate (λ)
4. Population ceiling (K)
5. Time horizon
6. Modeling scenarios/outputs:
   - Probability of extinction
   - Restoration/augmentation
   - Declining population
   - Parameter sensitivity

CASE STUDY:
CLINCH RIVER LTM –
OYSTER MUSSEL

Population Viability Analysis (PVA)
Lower Clinch River, TN

Leslie Matrix (Age-structured Models)

- Survival and fecundity rates
- Stable Age Distribution (SAD)
- Population growth (λ)

Population Trajectory

- Model population growth over time
- Simulate reintroduction scenarios

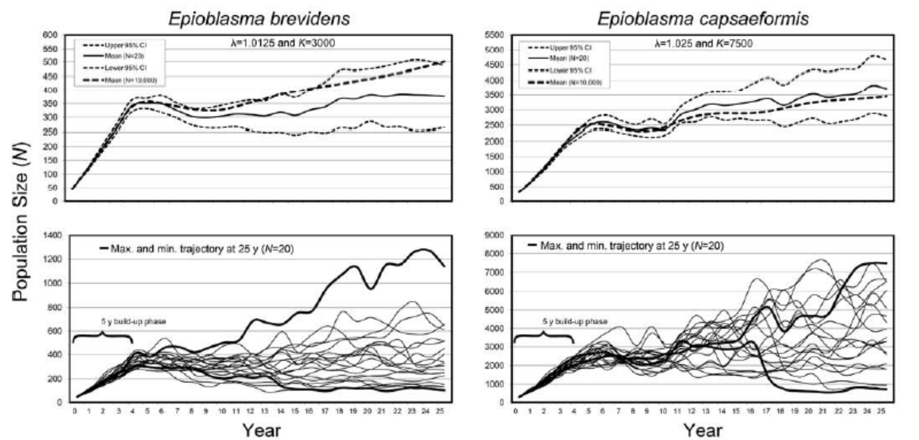


FIGURE 4
The mean of 20 simulated population trajectories (top graph) with 95% confidence intervals (CI), and each corresponding single trajectory (bottom graph) is displayed to show how simulated population size can fluctuate widely over time. Such fluctuations are an inherent outcome of the model and a consequence of the vital rate parameters being treated as stochastic. The figure displays trajectories of reintroductions of either 48 or 300 adults of each species, respectively. The mean trajectories based on 10,000 simulations and modeling scenarios are the same as those given in Fig. 2.

Jones et al. 2012

CASE STUDY: CLINCH RIVER LTM – OYSTER MUSSEL

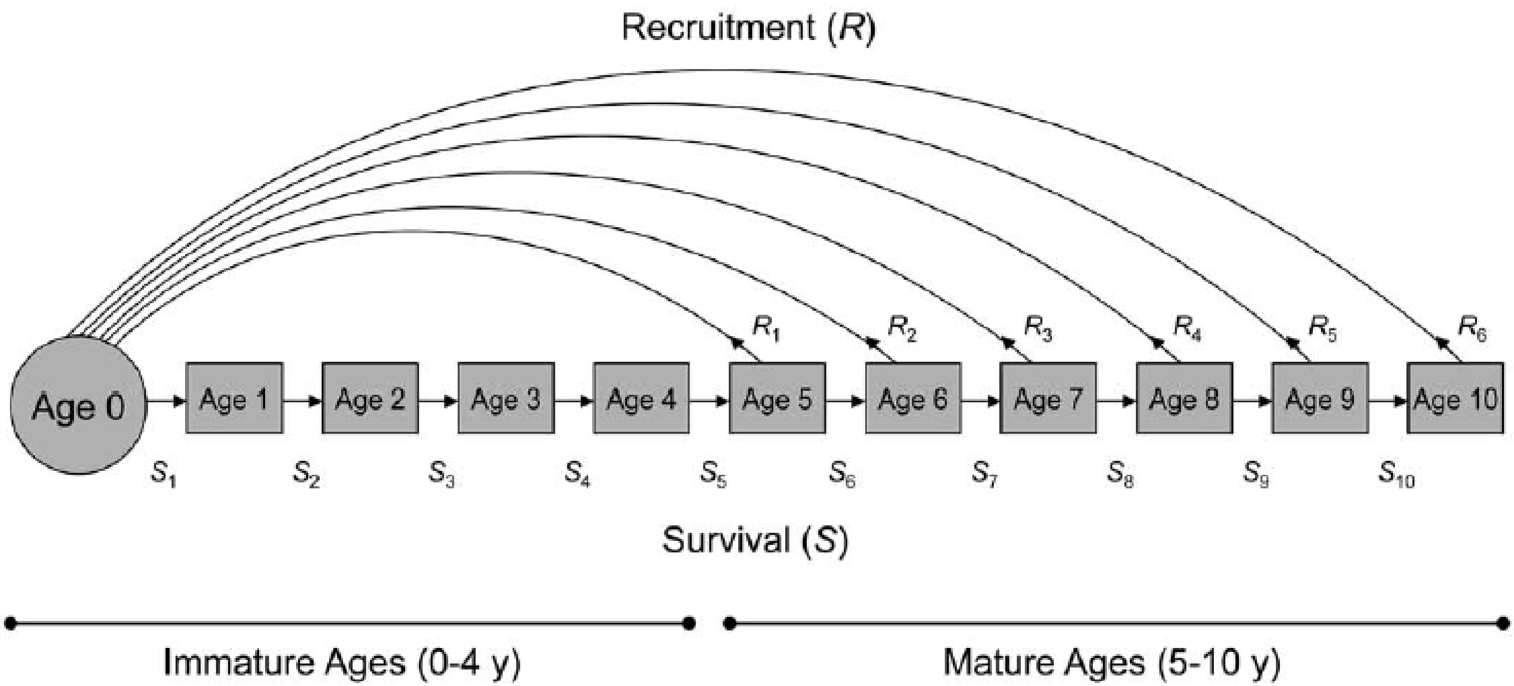


FIGURE 1

A general life-cycle diagram depicting the demography of a freshwater mussel species living to a maximum of 10 y, such as *Epioblasma capsaeformis*. Species living longer can be accommodated in the model by adding age classes, such as five more for *E. brevidens*. Nodes (circle and boxes) represent age-class stages, and arrows between nodes represent transitions (survival) between stages. Recruitment is shown as the number of age-0 individuals produced by adults in mature age classes.

Jones et al. 2012. Population performance criteria to evaluate reintroduction and recovery of two endangered mussel species, *Epioblasma brevidens* and *Epioblasma capsaeformis* (Bivalvia, Unionidae). Walkerana 15:24-44.

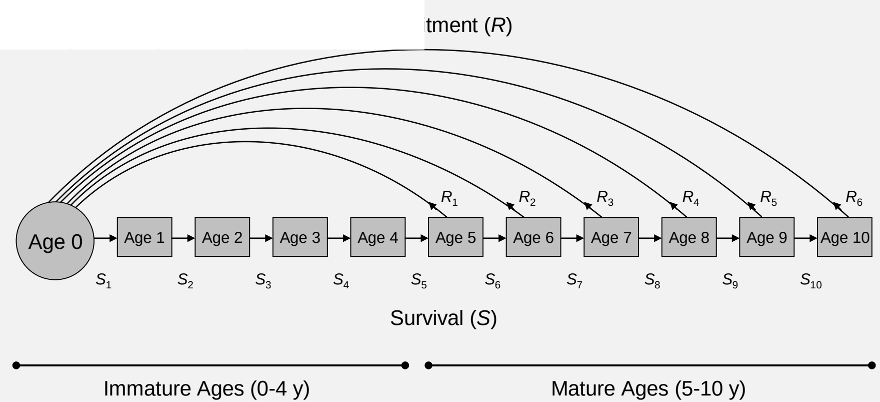
CASE STUDY:
CLINCH RIVER LTM –
OYSTER MUSSEL

Leslie Matrix – Oyster Mussel

	Age Class→	1	2	3	4	5	6*	7*	8*	9*	10*	11*
Age Class↓	↓Age→	0	1	2	3	4	5	6	7	8	9	10
1	0						**1.17**	**1.17**	**1.17**	**1.17**	**1.17**	**1.17**
2	1	**0.30**										
3	2		**0.95**									
4	3			**0.95**								
5	4				**0.95**							
6*	5					**0.95**						
7*	6						**0.85**					
8*	7							**0.8**				
9*	8								**0.75**			
10*	8									**0.70**		
11*	9										**0.65**	

*Mature Age Classes

- Transitional survival probabilities along the sub-diagonal



Jones et al. 2012.

CASE STUDY:
CLINCH RIVER LTM –
OYSTER MUSSEL

Leslie Matrix – Oyster Mussel

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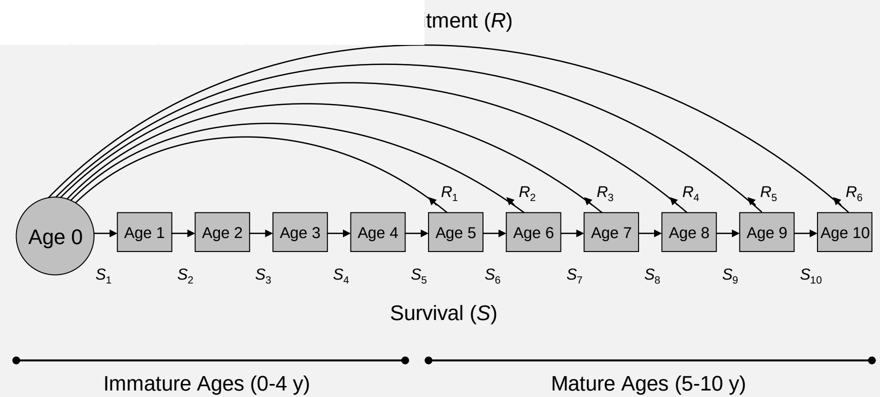
*Mature Age Classes

- Transitional survival probabilities along the sub-diagonal
- 30% survival rate from Age 0 to Age 1



Jones et al. 2012.

CASE STUDY:
CLINCH RIVER LTM –
OYSTER MUSSEL

Leslie Matrix – Oyster Mussel

Age Class↓	Age Class→	1	2	3	4	5	6*	7*	8*	9*	10*	11*
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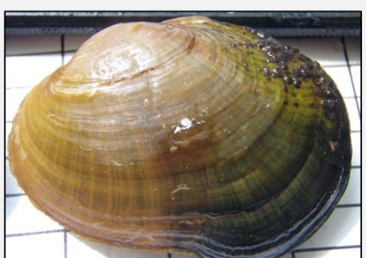
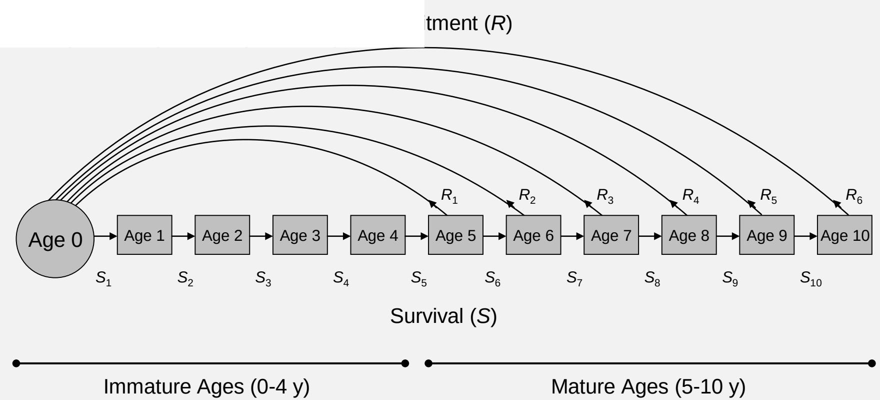
9*	8								**0.75**			
10*	8									**0.70**		
11*	9										**0.65**	

*Mature Age Classes

- Transitional survival probabilities along the sub-diagonal
- 30% survival rate from Age 0 to Age 1
- Fecundity of reproductively mature age classes





Jones et al. 2012.

CASE STUDY:
CLINCH RIVER LTM –
OYSTER MUSSEL

Leslie Matrix – Oyster Mussel

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8*	7							0.8				
9*	8								0.75			
10*	8									0.70		
11*	9										0.65	

*Mature Age Classes

x

2010 Population at time *t*		2011 Population at time *t+1*
$N_0(t)$		$N_0(t+1)$
$N_1(t)$		$N_1(t+1)$
$N_2(t)$		$N_2(t+1)$
$N_3(t)$		$N_3(t+1)$
$N_4(t)$		$N_4(t+1)$
$N_5(t)$	=	$N_5(t+1)$
$N_6(t)$		$N_6(t+1)$
$N_7(t)$		$N_7(t+1)$
$N_8(t)$		$N_8(t+1)$
$N_9(t)$		$N_9(t+1)$
$N_{10}(t)$		$N_{10}(t+1)$

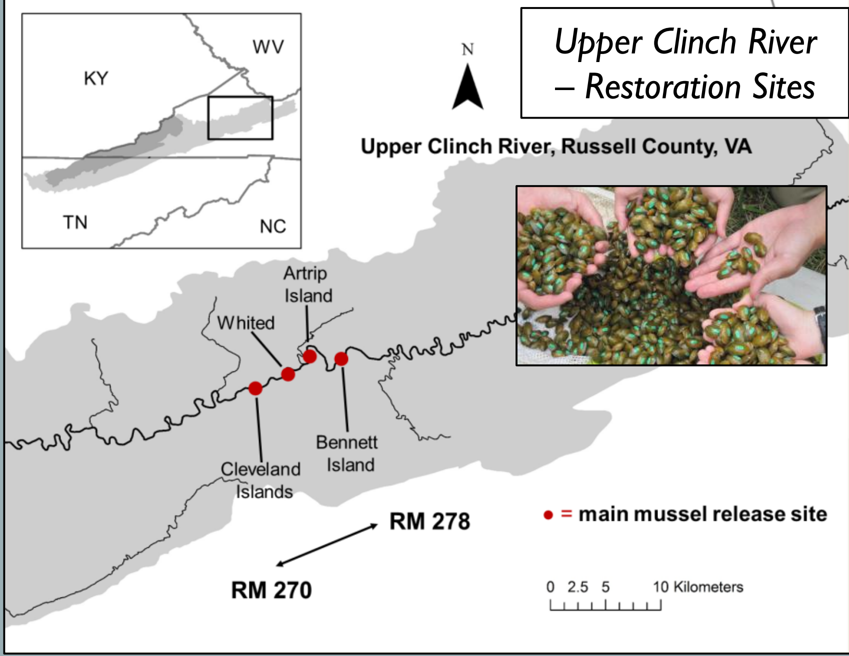
$N_6(t) = N_6(2010) =$ # of Age 6 individuals in the population in 2010

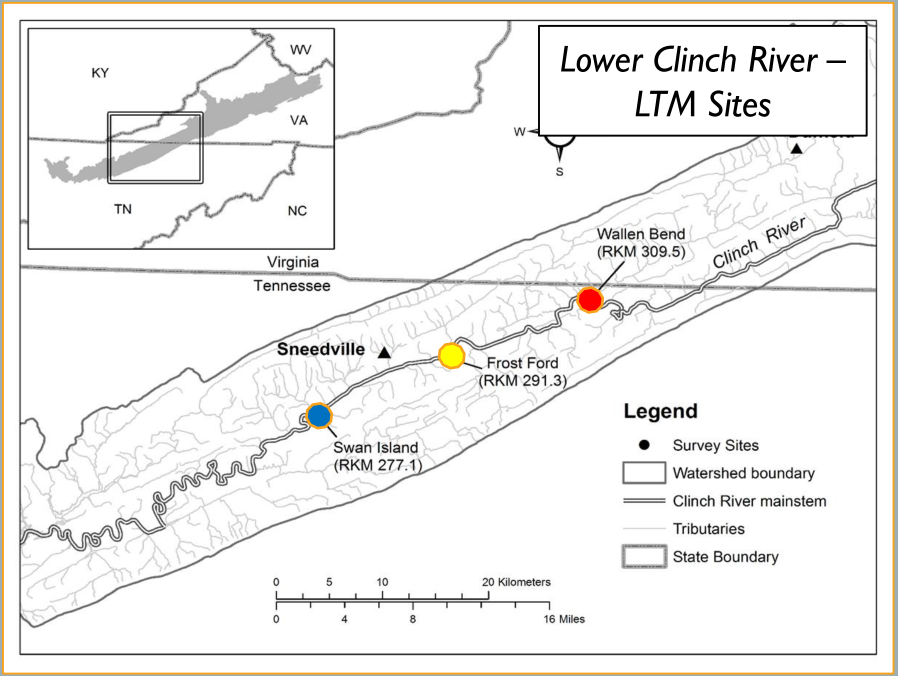
Population growth (from 2010 to 2011) =

$$\lambda = \frac{N(t+1)}{N(t)} = \frac{total\ pop\ size\ 2011}{total\ pop\ size\ 2010}$$

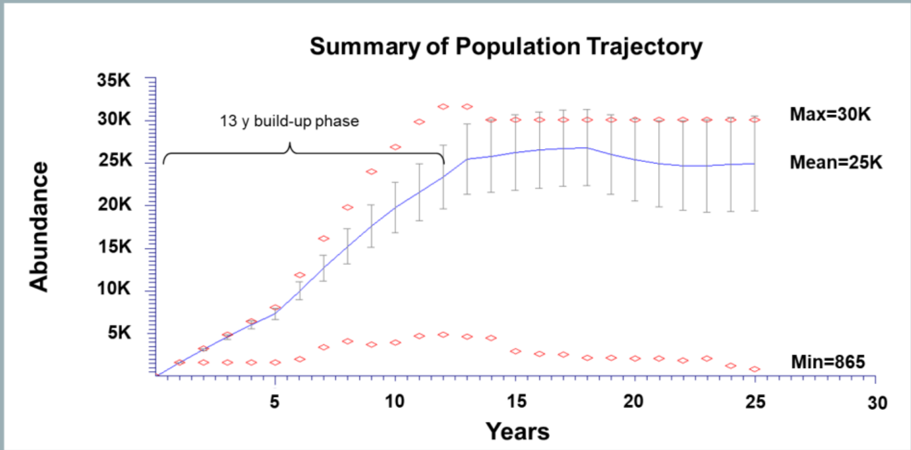
CASE STUDY: CLINCH RIVER LTM – OYSTER MUSSEL

LTM data from the lower Clinch River used to estimate survival, recruitment, and population growth rates---parameters that inform (and can improve) reintroduction/augmentation efforts in Upper Clinch River





Simulating reintroduction scenarios in RAMAS Metapop using Leslie-matrix transition probabilities



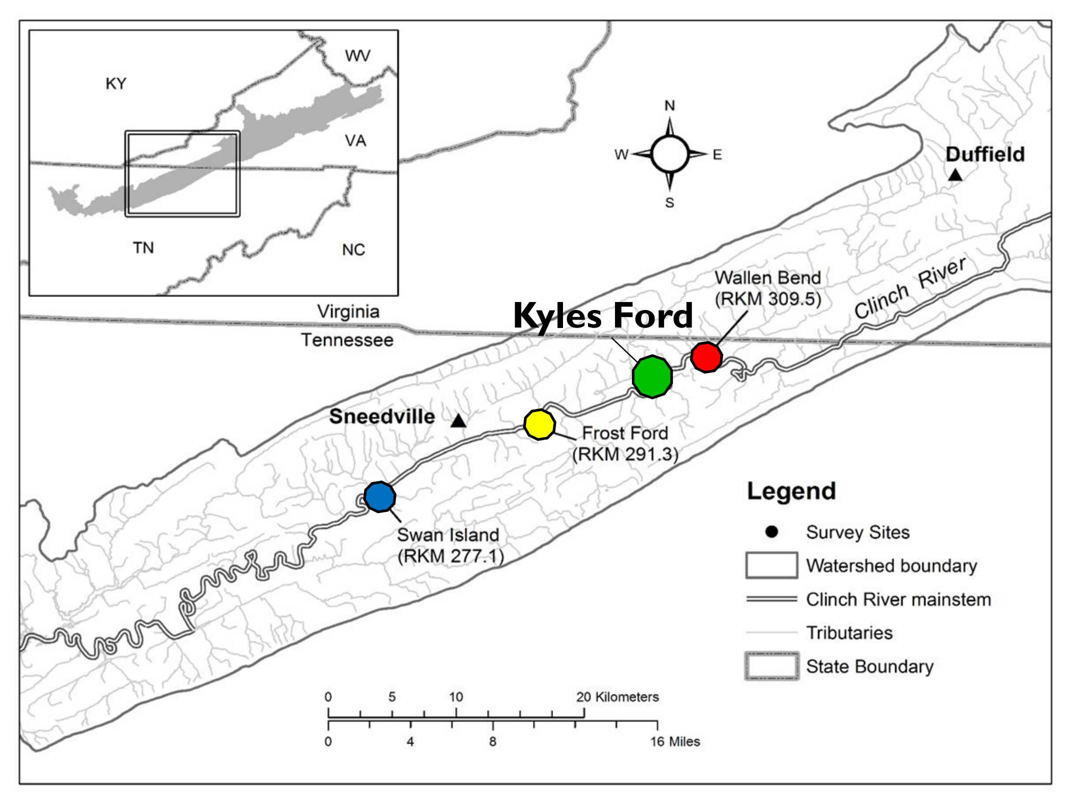
Model Input Parameters:

1. Stable growth rate λ = 1.004
2. Stock 1,622 mussels per yr. for 13 yrs.
3. Run 10,000 simulations
4. Project to 25 years
5. Carrying capacity (K) = 30K

CASE STUDY: CLINCH RIVER LTM – PHEASANTSHELL

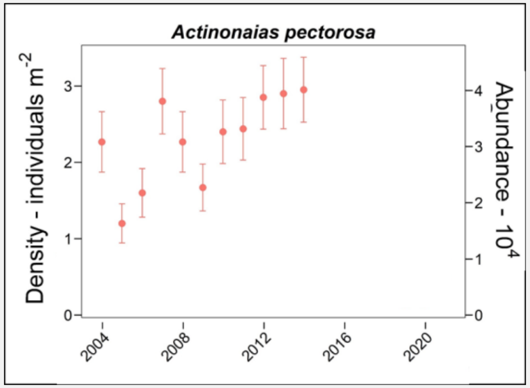
Pheasantshell (*Actinonaias pectorosa*)

- 75 mm (~130 mm max)
- Long-lived species (>30 – 40+ years)
- Non-listed
- 3 – 47% total site composition (2004 – 2014)



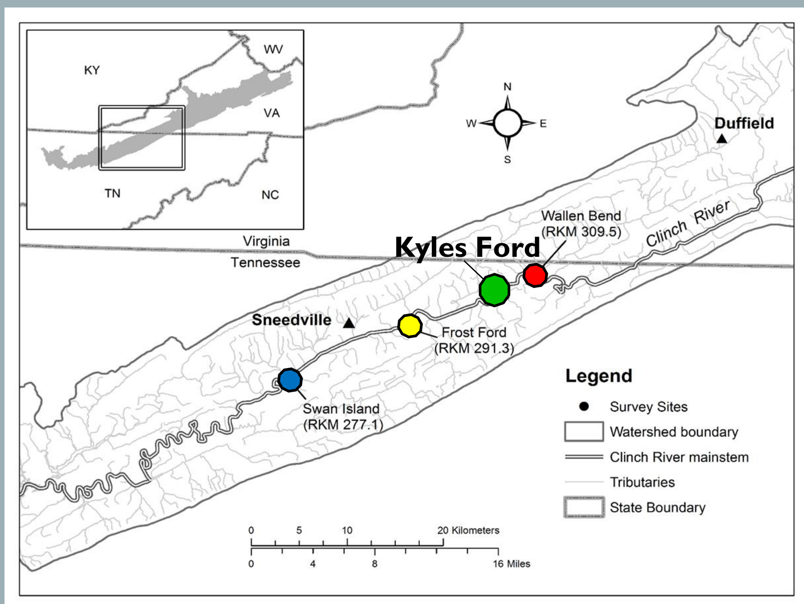
Quantitative Datasets on Pheasantshell in the Clinch River:

- 11 consecutive years (2004 – 2014) @ 3 sites
- ~15 other sites with 1 – 2 intermittent (‘population snapshot’) datasets



CASE STUDY: CLINCH RIVER LTM – PHEASANTSHELL

Pheasantshell (*Actinonaias pectorosa*)

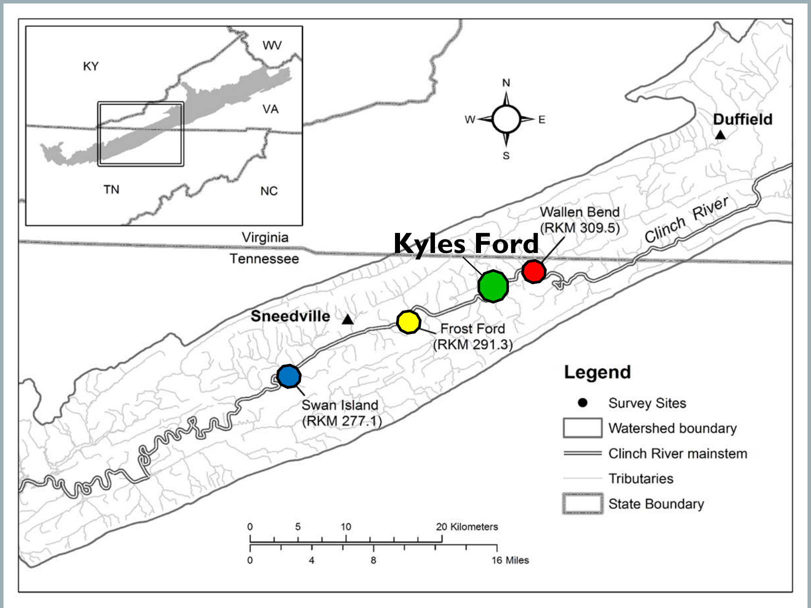


Suspected Mass Die-off Event 2016

- Quantitative survey conducted @ Kyles Ford
- Surveyors observed large numbers of gaping/dying Pheasantshell + fresh dead material
- Not localized to Kyles Ford – independent reports of high mortality and stress in Pheasantshell (*Actinonaias pectorosa*) observed across sites below VA-TN border

CASE STUDY: CLINCH RIVER LTM – PHEASANTSHELL

Pheasantshell (*Actinonaias pectorosa*)



Quantifying Magnitude of Decline

- Only 2 years of quantitative data available for Kyles Ford (2004 & 2016); population trends could not be reliably assessed
- Uncertainty surrounding significance of "observed" die-off; no smoking gun
- Need for further investigation
- Annual quantitative surveys reinitiated at the 3 LTM sites in 2017; Kyles Ford added to LTM project sites

CASE STUDY: CLINCH RIVER LTM – PHEASANTSHELL

RESEARCH QUESTIONS

- Have populations experienced significant declines?
- Specific age/size classes?
- What is the spatial extent of the event?
- What species are being impacted?
- Natural or unnatural mortality?
- What caused mortality?

CASE STUDY:
CLINCH RIVER LTM – PHEASANTSHELL

RESEARCH QUESTIONS

- Have populations experienced significant declines?
- Specific age/size classes?
- What is the spatial extent of the event?
- What species are being impacted?

Quantitative LTM data to answer these

- 2004-2014
- 2016-2021 (+ongoing)

- Natural or unnatural mortality?
- What caused mortality?

CASE STUDY:
CLINCH RIVER LTM –
PHEASANTSHELL

OBJECTIVES

- Conduct quantitative sampling to estimate population densities
- Compare species-specific densities to historical, baseline levels (direction + magnitude of change)
- Examine trends in age(size)-class structures
- Conduct qualitative monitoring at sites periodically throughout the year

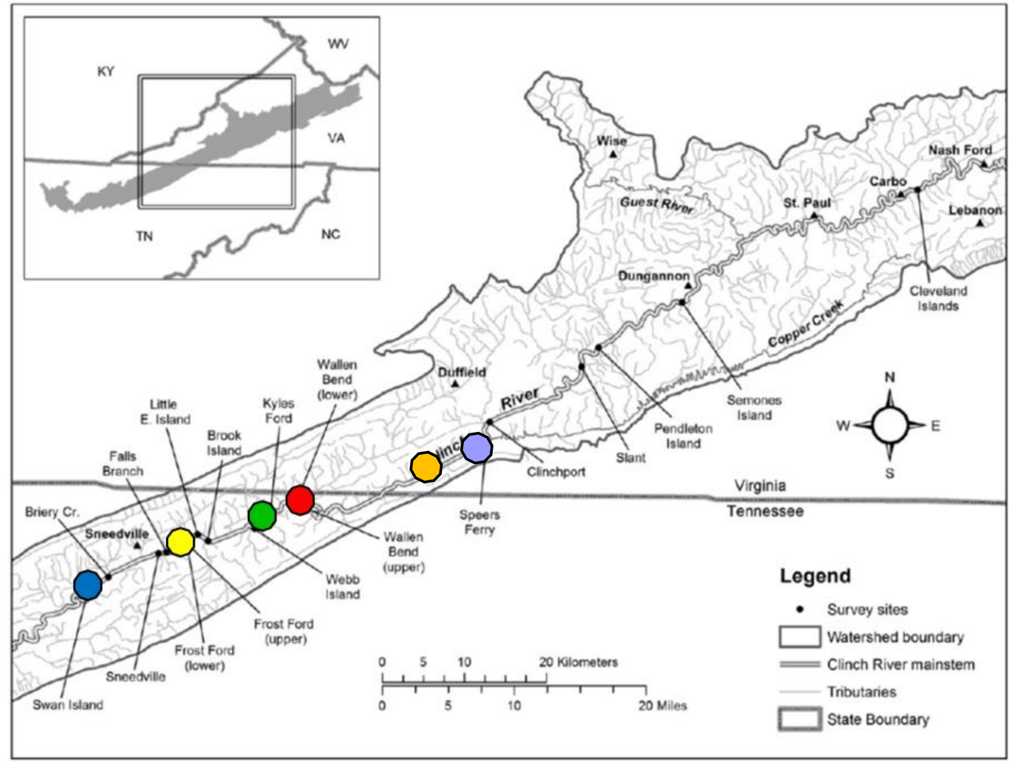


FIGURE 1. The 18 Sites Sampled from 2004 to 2009 in the Clinch River, Tennessee and Virginia, Upstream of Norris Reservoir. Swan Island, upper Frost Ford, and upper Wallens Bend were sampled annually, while the remaining sites were sampled once during the study period.

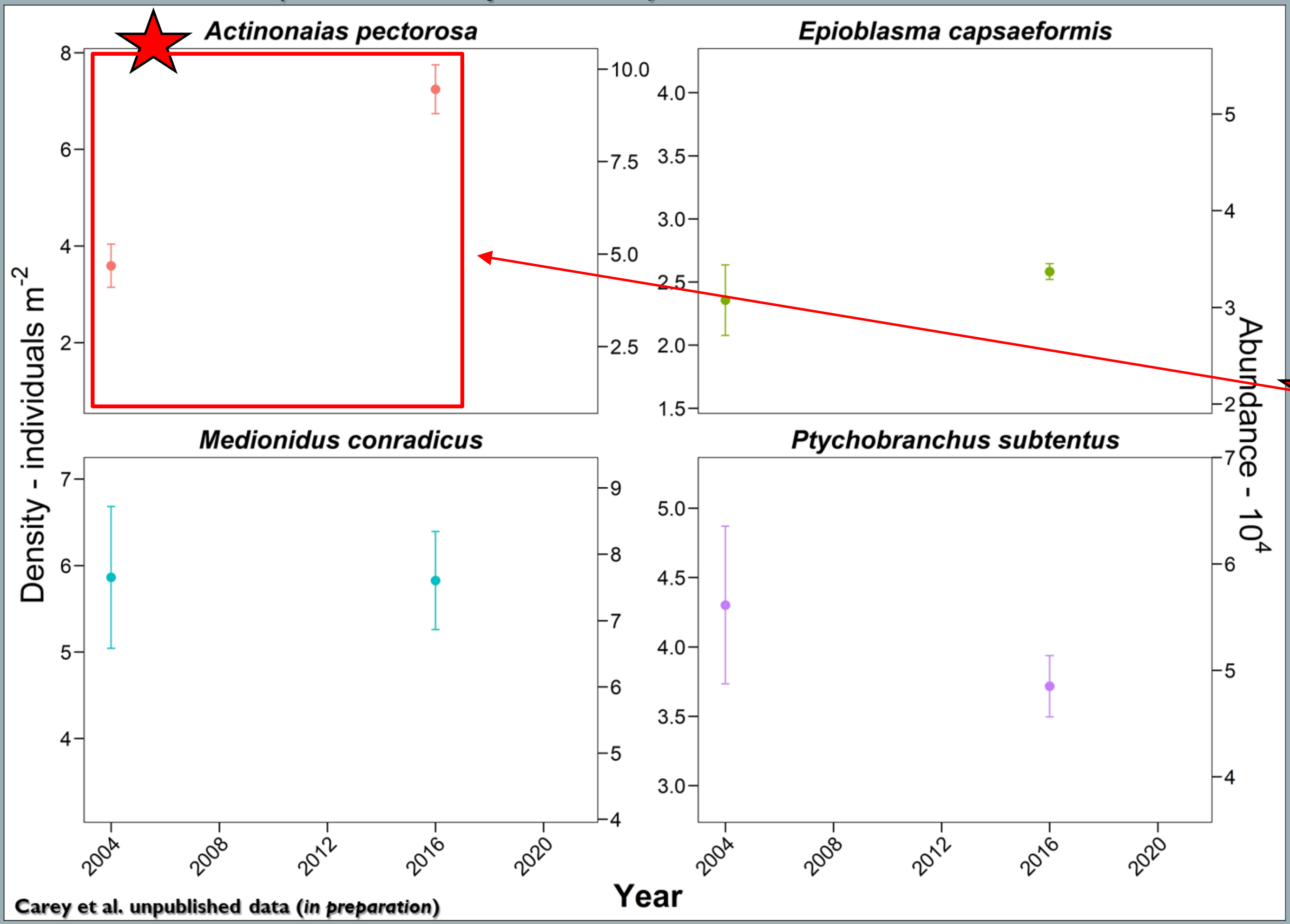
Speers Ferry + Sycamore Island (VDWR Musselrama)

Wallen Bend
Kyles Ford
Frost Ford
Swan Island

INTERPRETING LTM DATA

KYLES FORD – TWO DATA POINTS

Pheasantshell (*Actinonaias pectorosa*)



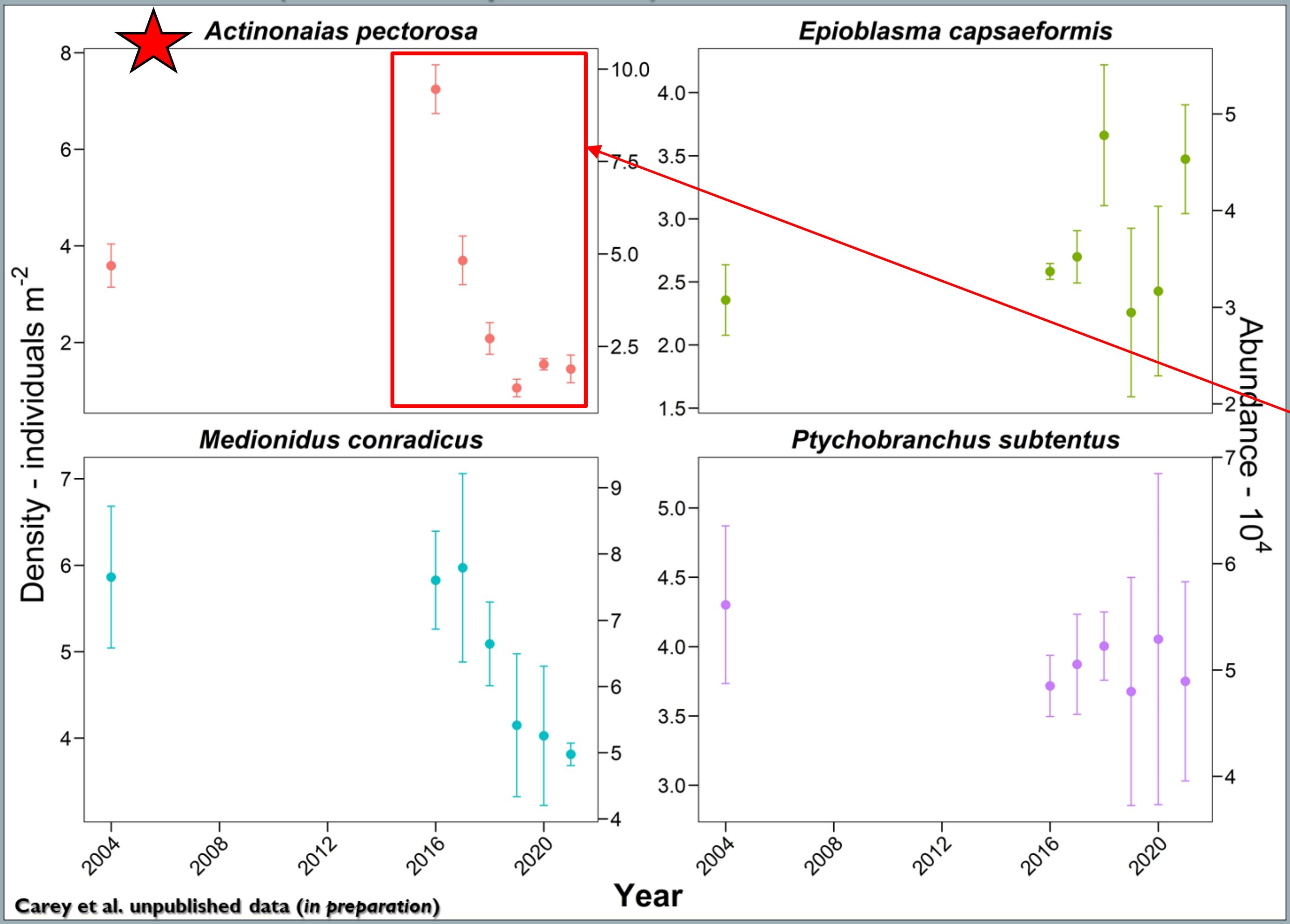
- Recall that we only had 2 years of quantitative data available for Kyles Ford (2004 & 2016)

While a mass die-off was suspected in 2016, quantitative data indicated Pheasantshell numbers had actually increased from 2004 to 2016 at Kyles Ford

*Error bars presented in all graphs represent standard error estimates

KYLES FORD – LTM DATA

Pheasantshell (*Actinonaias pectorosa*)

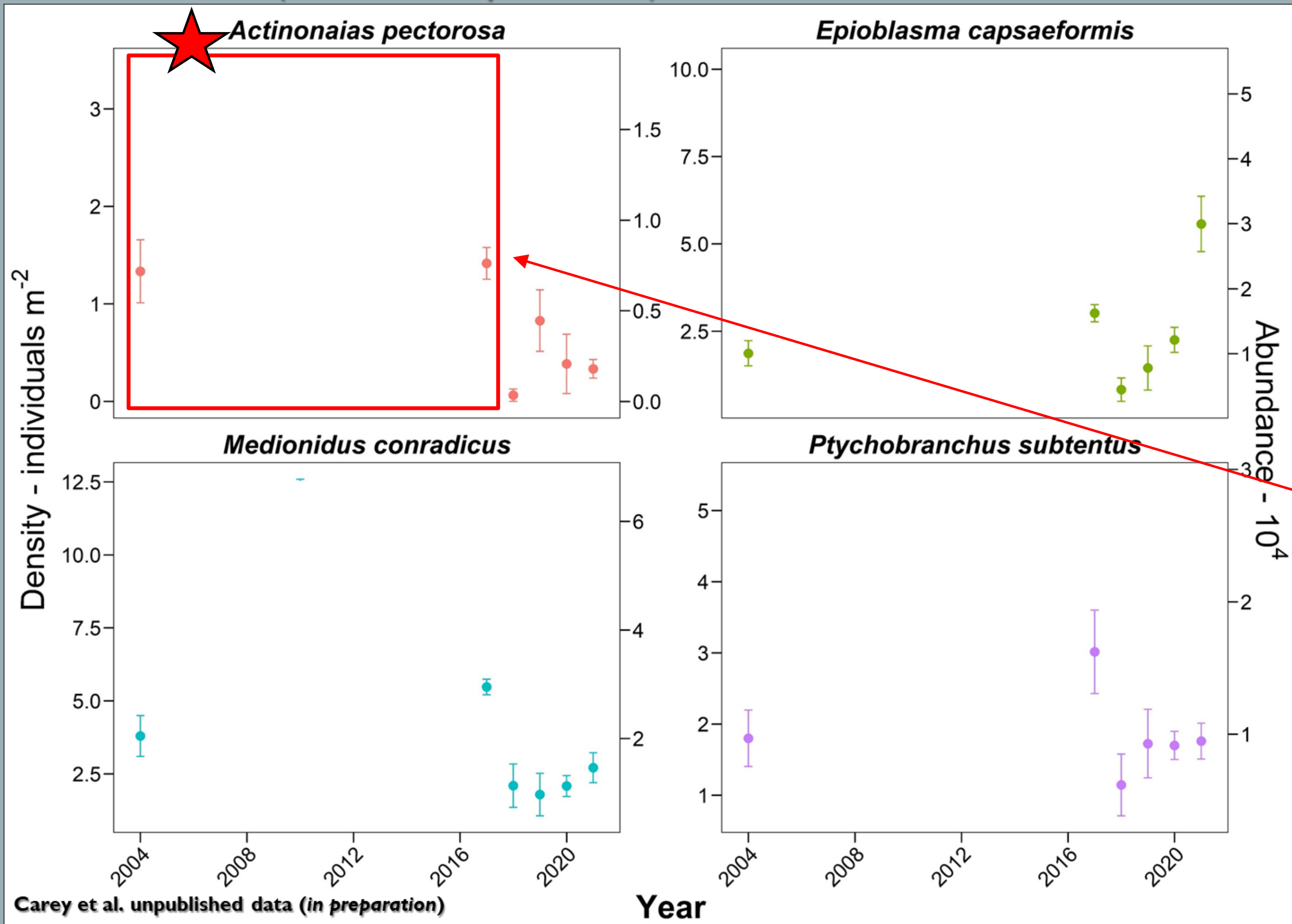


- With only 2 data points, there was not enough quantitative data to support suspicions that a mass die-off had/was occurring
- In contrast, inferences drawn from examining LTM data (2016-2021) at Kyles Ford revealed a significant decline in the Pheasantshell population had occurred over the 6-year period

*Error bars presented in all graphs represent standard error estimates

WALLEN BEND – LTM DATA

Pheasantshell (*Actinonaias pectorosa*)

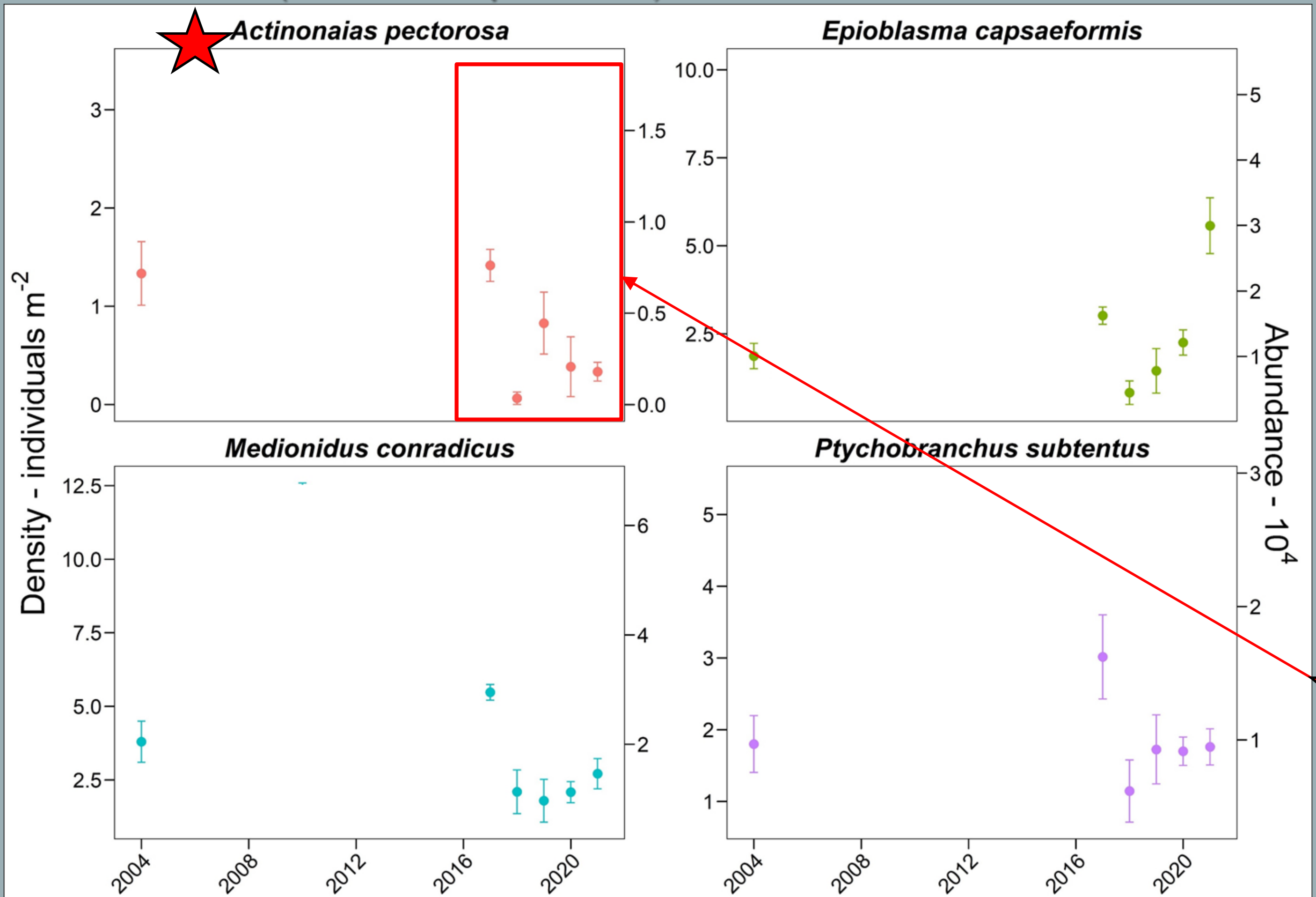


If LTM data were only available for 2004 and 2017-2021 at Wallen Bend, what conclusions would we draw from these population estimates?

Pheasantshell population appears stable (2004 to 2017)?

WALLEN BEND – LTM DATA

Pheasantshell (*Actinonaias pectorosa*)



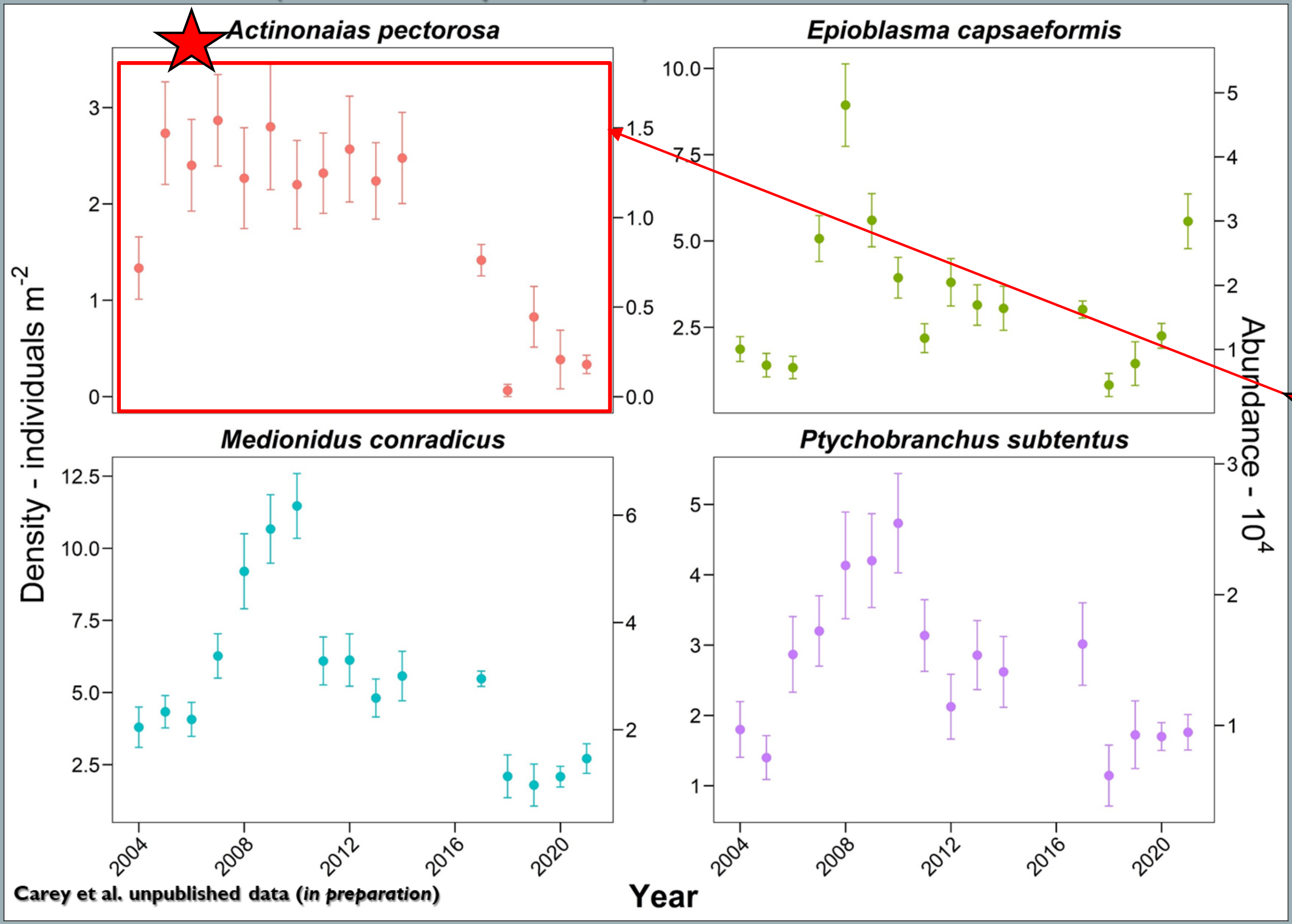
Carey et al. unpublished data (*in preparation*)

If LTM data were only available for 2004 and 2017-2021 at Wallen Bend, what conclusions would we draw from these population estimates?

- Pheasantshell population appears stable (2004 to 2017)?
- A general declining trend from 2017 to 2021?

WALLEN BEND – LTM DATA

Pheasantshell (*Actinonaias pectorosa*)

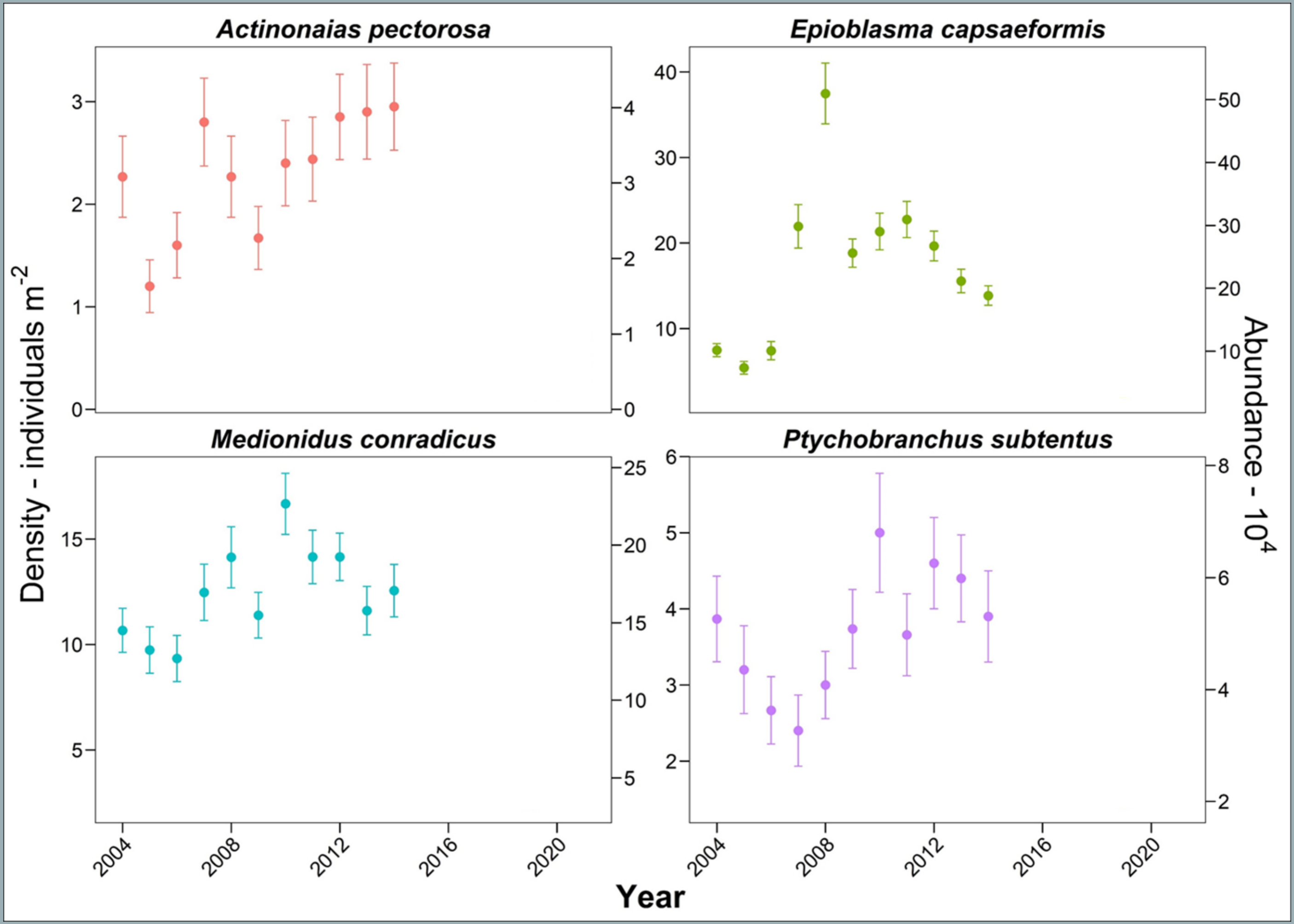


Continuous LTM data are available from 2004-2014 + 2017-2021 at Wallen Bend; now what conclusions would we draw from these population estimates?

- Additional support for decline in Pheasantshell population over 18 year period?
- Missing population estimates for 2015+2016; cannot establish when Pheasantshell die-off began

FROST FORD– LTM DATA

Pheasantshell (*Actinonaias pectorosa*)

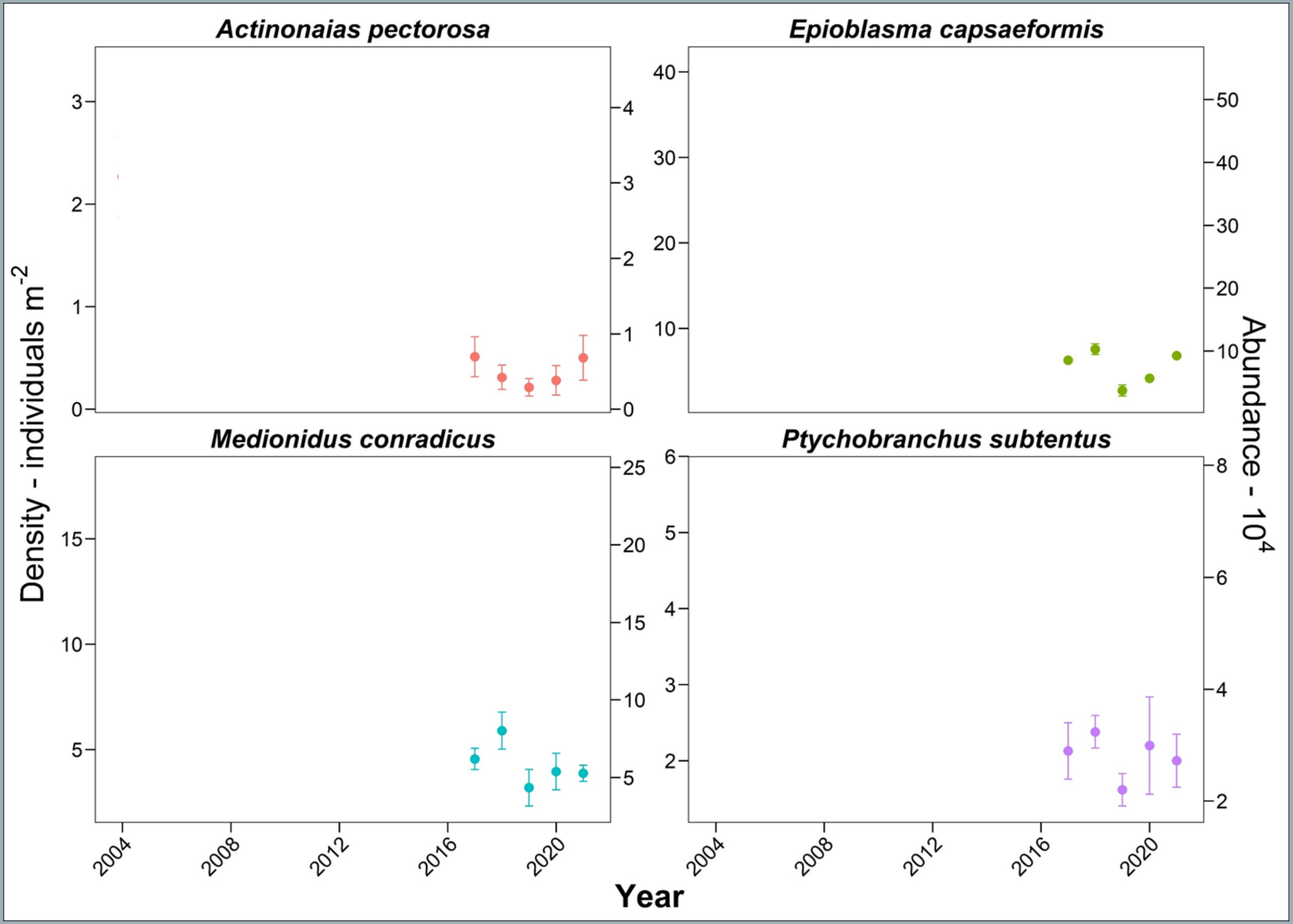


How might the duration of a continuous LTM dataset, or the point in time LTM occurs, influence our interpretation of population trends and health over time?

Continuous LTM dataset from 2004 to 2014

FROST FORD– LTM DATA

Pheasantshell (*Actinonaias pectorosa*)

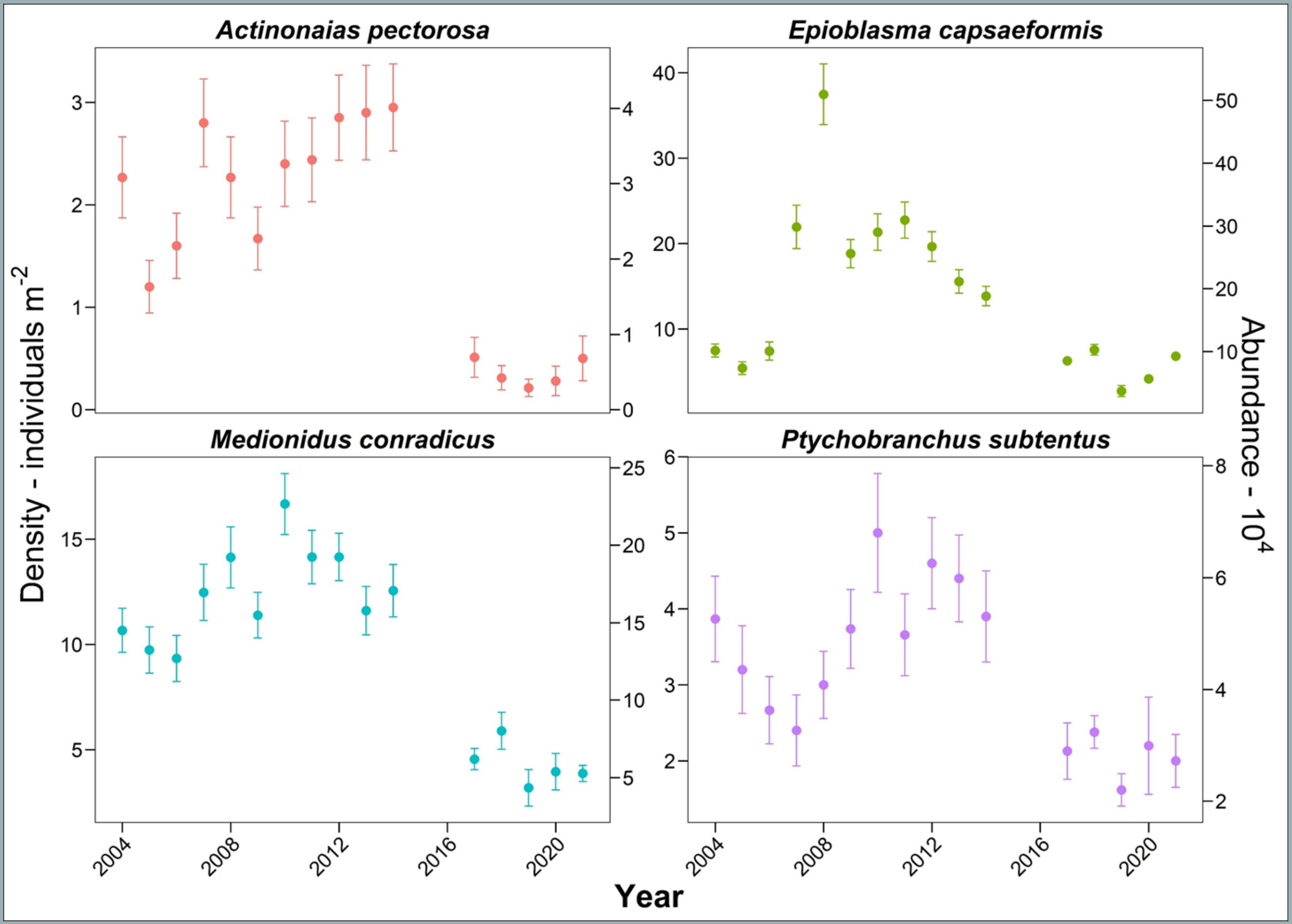


How might the duration of a continuous LTM dataset, or the point in time LTM occurs, influence our interpretation of population trends and health over time?

Continuous LTM dataset from 2017 to 2021

FROST FORD– LTM DATA

Pheasantshell (*Actinonaias pectorosa*)



How might the duration of a continuous LTM dataset, or the point in time LTM occurs, influence our interpretation of population trends and health over time?

Continuous LTM dataset from 2004 to 2014

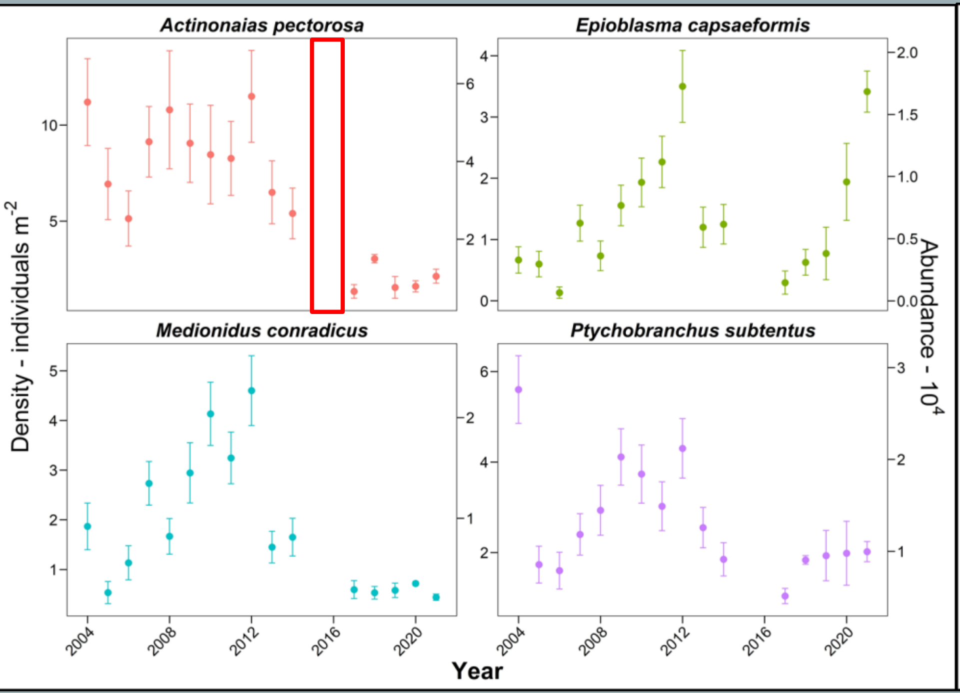
Versus

Continuous LTM dataset from 2017 to 2021

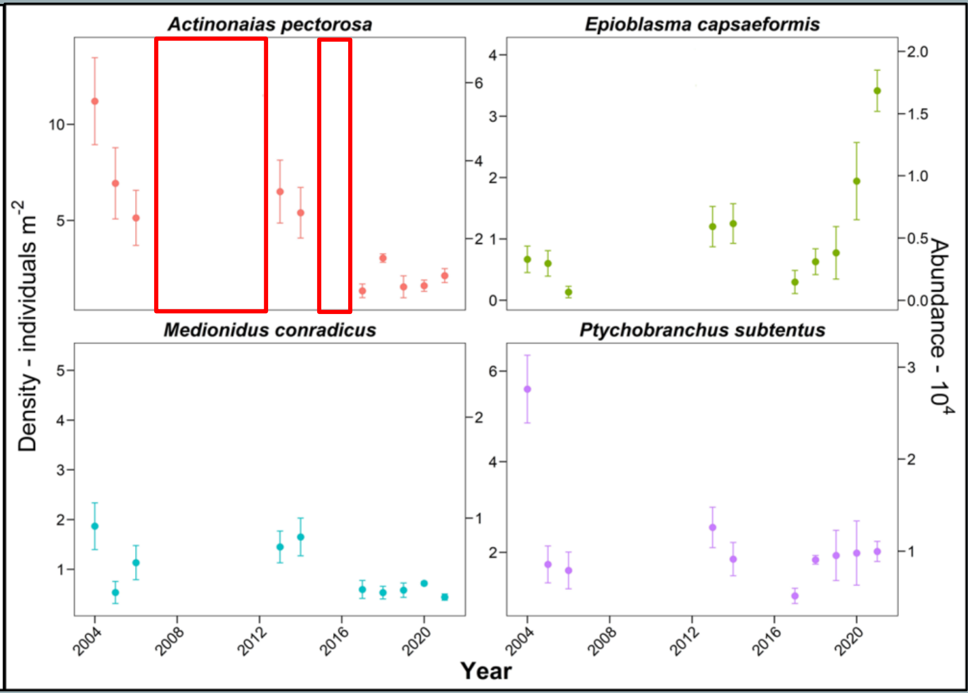
SWAN ISLAND – LTM DATA

How might gaps in LTM data influence our interpretation of population trends and health over the past 18 years?

Missing 2015 - 2016

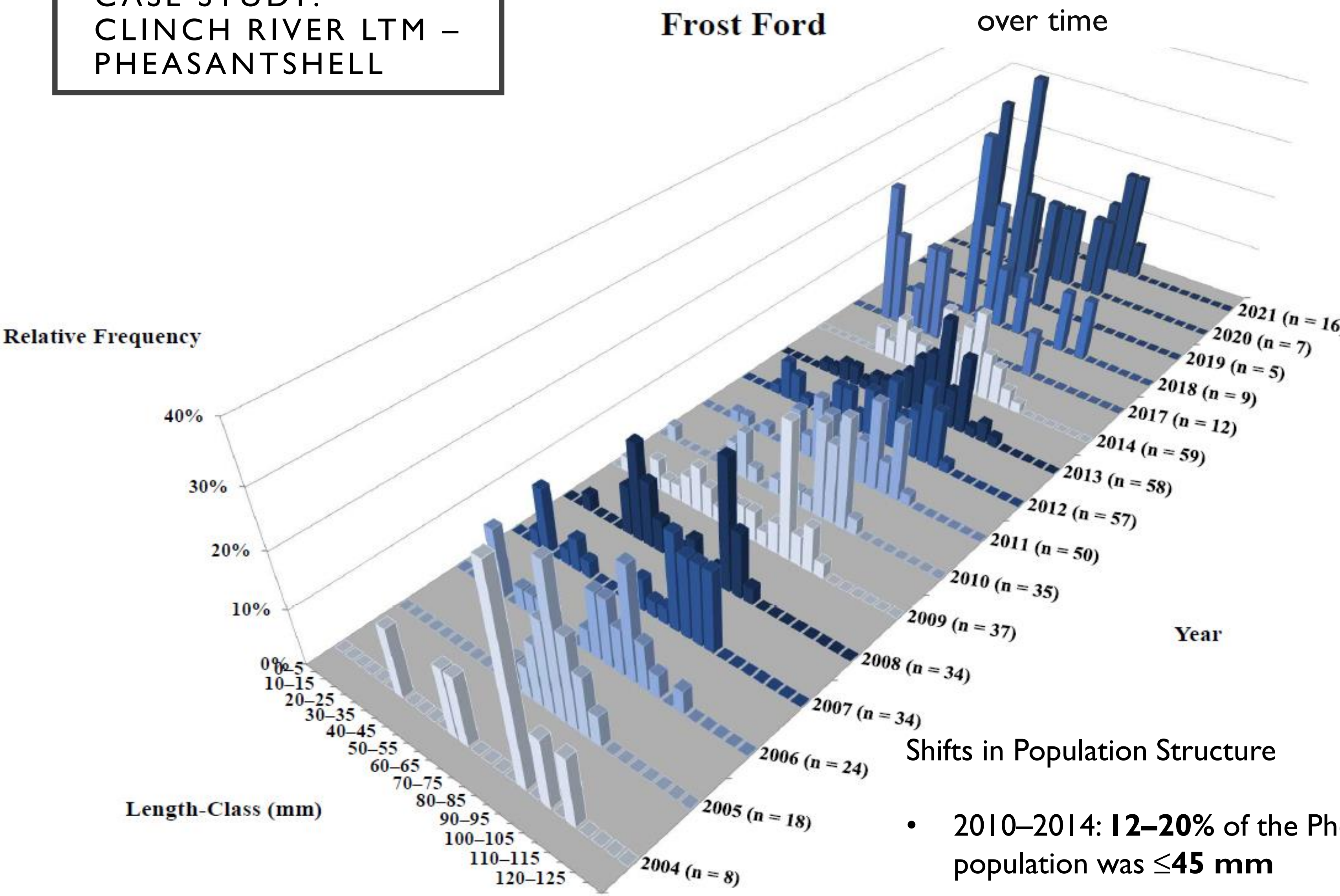


Missing 2007- 2013 & 2015-2016



CASE STUDY: CLINCH RIVER LTM – PHEASANTSHELL

LTM data to examine trends in Pheasantshell population structure over time



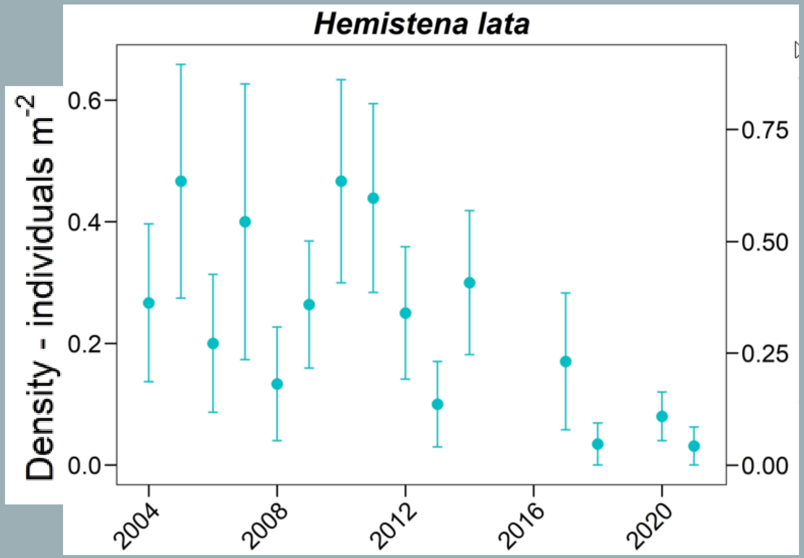
Shifts in Population Structure

- 2010–2014: **12–20%** of the Pheasantshell population was ≤**45 mm**
- 2017: **83.3%** of the population represented by individuals ≤**45 mm**

CASE STUDY:
CLINCH RIVER LTM

IMPORTANCE OF QUALITATIVE DATA

- Periodic + qualitative site checks
- Seasonal trends in observed high mortality events
  - Peaking in September - November
- Cracking pearlymussel (*Hemistena lata*)
  - Occurs at low densities; fresh dead material not commonly encountered
  - Densities (or detectability) too low to obtain reliable estimates for comparisons
  - Over 300 fresh dead shells collected 2017-2018



- Fluted kidneyshell & Cumberland moccasinshell
  - Anecdotally observing unnatural high mortality (shell material) for fluted kidneyshell; however, quantitative data don't indicate significant overall declines
  - Conversely, while unnatural high mortality has not been qualitatively observed for Cumberland moccasinshell, quantitative data indicate declining trends

CASE STUDY:
CLINCH RIVER LTM

SPATIAL TRENDS -QUALITATIVE DATA

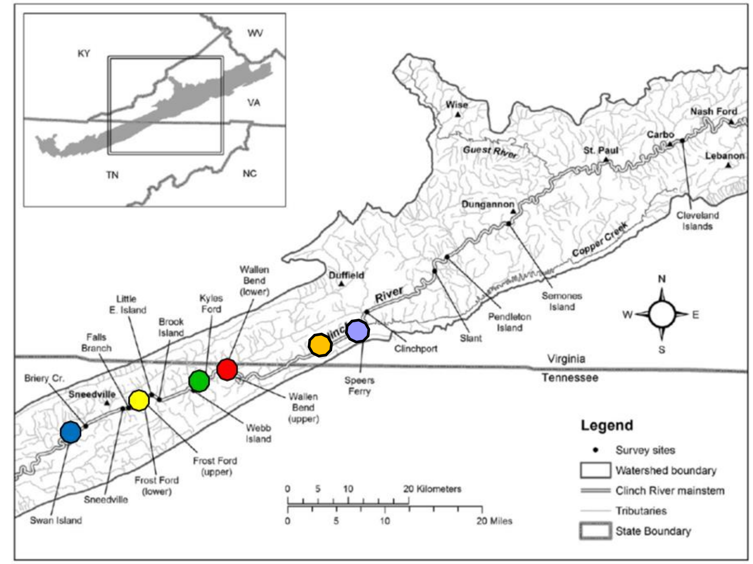


FIGURE 1. The 18 Sites Sampled from 2004 to 2009 in the Clinch River, Tennessee and Virginia, Upstream of Norris Reservoir. Swan Island, upper Frost Ford, and upper Wallens Bend were sampled annually, while the remaining sites were sampled once during the study period.

Sycamore Island, Virginia

- Qualitative site checks (2016 - 2021) and quantitative surveys (2017, 2019, 2021)
- Mass mortality in Pheasantshell qualitatively observed in 2018
- Significant decline not quantitively detected until 2021
- Qualitative site checks provided evidence and insight 3 years before quantitative surveys (time lag effect)

CASE STUDY:
CLINCH RIVER LTM –
PHEASANTSHELL

SUMMARY FINDINGS

- Have populations experienced significant declines?
  - ~80% decline in Pheasantshell density across each Tennessee Clinch River LTM sites
- Specific age/size classes?
- Older *A. pectorosa* may have been more heavily impacted by the die-off relative to smaller individuals
- What is the spatial extent of the event?
  - Observed + quantified declines in Pheasantshell across Tennessee sites
  - Virginia (-closest to TN border): First observations of high mortality in 2018
- Are other species being impacted?
  - Quantitative evidence: Cumberland moccassinshell, potentially fluted kidneyshell
  - Qualitative evidence: Crackling pearlymussel; *significantly* larger amount of FD material observed
  - Shifts in community structure over time

TAKE AWAYS FROM LTM IN CLINCH RIVER

- Management and restoration of native mussels will require a thorough understanding of species population dynamics and baseline conditions
- Qualitative & quantitative data have their strengths + limitations
- Having clearly defined and quantifiable objectives is essential to developing effective, efficient, and feasible monitoring programs
- Project goals and objectives, study area size, habitat characteristics, and availability of resources (funding limitations) are a few important factors to carefully consider when designing a monitoring study (one-size ≠ ≠ fit all!)
- Intensive quantitative quadrat surveys may not be optimal for low density species (objective dependent) or logistically feasible; CMR approaches good alternative for estimating demographic vital rates
- Clearly define and document your effective sampling study area boundaries
- Interpret datasets/trends carefully
- Establishing species- and site-level baseline conditions; data which serve as the foundation for developing effective restoration plans, evaluating population performance post-restoration, informing SSAs/5-year reviews, eDNA protocol development studies

ACKNOWLEDGEMENTS

Implementation and success of LTM requires multi-stakeholder participation across state and federal agencies, academia, non-governmental organizations, and volunteers. We thank the many people, agencies, and working groups who have volunteered their time and resources and/or provided technical guidance and historical collection data in support of LTM in the UTNRB

VDWR
TWRA
Daguna Consulting
OSM
USGS
USFWS
TNC
Virginia Tech
UTNRB Mussel Recovery Group + Tennessee Endangered Mollusk Conservation group members + many additional volunteers

Clinch + Powell Mussel Survey Literature (not all-encompassing)

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