A multi-spatial analysis and the balanced requirements of freshwater mussels (Bivalvia: Unionidae) and urban inhabitants in the Cuyahoga River watershed

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Short title: Balancing needs of freshwater mussels in an urban watershed

Abstract

Water quality in the Cuyahoga River, a national heritage river of the United States, has improved greatly since the infamous river fire of 1969, but much of the watershed faces combined demands of a state scenic river valued for nature and the primary water source for surrounding cities. A comparative analysis of mussel abundance was applied to test success between water improvements and mussel assemblages in two similarly sized sub-watersheds, the uper reaches of the Cuyahoga River and an isolated tributary stream, Tinkers Creek, applying multivariate GIS/remote sensing tools and government data resources to contrast variation in lands use, soil types, and potential impacts from impoundments. Mussel populations declined in much of the Upper Cuyahoga River from 1990 to present, while in Tinkers Creek and the West Branch Cuyahoga River, both areas surrounded by residential lands, mussel species changed from a slow water species to species associated with flowing streams. Major structural differences among these stream reaches included regulated flow from reservoirs and consequentially poor soil drainage type in much of the Upper Cuyahoga River, while extensive improvements in Tinkers Creek enhanced flow dynamics and produced well-draining soils. Thus, the mussel assemblages appeared sustained despite a trend towards more human use where water flowed free..

Keywords: anoxic, ArcGIS, drainage, freshwater mussels, land use, remote sensing, stream flow, Unionidae

Introduction

While big rivers can house large assemblages of freshwater mussels (Bivalvia: Unionidae), mussels in the more numerous small rivers provide important ecosystem services [1] across North America [2] and Europe [3-5]. The Cuyahoga River watershed provides such an example as it flows through Akron and Cleveland, Ohio, to Lake Erie, one of the Laurentian Great Lakes. The Cuyahoga River served as a shipping hub of industry during the U.S. Civil War in the 1860s [6], and for a hundred years, its history became one of multiple fires caused by dumping of petroleum and other wastes into the river [7-9]. The last and most infamous fire in June 1969 propelled the creation of both the federal Environmental Protection Agency and the Water Quality Improvement Act of 1970 [10]. Those protections came too late for the mussel fauna of the lower river that once must have composed a diverse array of species not found live since before 1900 (56), as shells continue to erode from banks [11].

Many components of the environment impact freshwater mussels, most notably runoff from urban areas and agricultural [12-14] that impart increased sediment, nutrient loading and potentially toxins to rivers [15,16]. Habitat change may also include alterations in riparian vegetation, substrate permeability, and water velocity [17-19], especially in large rivers [20-22]. Mussels cannot move far from the area they deposit as juveniles, and as long-lived species, sustained habitat quality is essential for survival and reproduction [15,23-24].

Water quality of the Cuyahoga River has steadily improved since the creation of the U.S. EPA [25], particularly in the upper watershed, which has long been considered excellent habitat for freshwater mussels [11,26], and a diverse fish assemblage provides hosts for the mussels present [27]. A 40 km stretch between the confluence of the east and west upper branches downstream to Lake Rockwell, the water supply for Akron, Ohio, is listed as a scenic river. The

Upper Cuyahoga River is also regulated from two additional reservoirs to sustain water levels in Lake Rockwell. Only the West Branch Cuyahoga River flows freely. To assess impacts of land use and water regulation to mussels, we surveyed assemblages of the Upper Cuyahoga River three times over 10 years, and added a study of Tinkers Creek, a large tributary of the Cuyahoga River, in the most recent survey. A comparison of the Upper Cuyahoga River to Tinkers Creek will show two streams that experience similar geologic and climate conditions [28,29] as both flow across the same glacial moraines before descending an escarpment to reach Lake Erie, yet they vary in development.

To compare faunal change across time, our contrast began with land use, which has been implicated repeatedly as relevant to freshwater mussels [2,12,30-32], but rarely using multiple spatial scales [33]. From baseline records in the Upper Cuyahoga River [11], we (1) present surveys from 2012, 2016 and 2021, and contrast our 2021 survey of Tinkers Creek to the first survey there in 2000 [34]; (2) use remote sensing software to relate how land use change in both watersheds across a small 100 m buffer scale and a larger sub-watershed scale may correspond to mussel diversity and abundance; and (3) assess whether soil drainage class and its link with stream flow may impact mussel presence and abundance. The over arching question remained how human use can be made compatible with sustaining or improving mussel habitat.

Methods

Site Locations

All surveys each year were conducted from June to August, the time when river levels generally are at their lowest discharge, and locations for all survey years were limited by stream access points that varied somewhat across time. In 2012 and 2016, 23 survey sites in the Upper Cuyahoga River were selected based on previous surveys of the region, first by Huehner [35] in the West Branch Cuyahoga River followed by Hoggarth [26], who covered a greater spatial area downstream (Fig. 1a). Our surveys in 2012 and 2016 targeted the original sites of Hoggarth, while 2021 surveys sought to overlap more of the region across 28 sites, expanding locations farther downstream where a past report of mussels noted only presence/absence [36]. In 2021, another 35 sites were assessed in the free-flowing Tinkers Creek (Fig. 1b), which possesses headwater regions adjacent to the Upper Cuyahoga River northwest of Lake Rockwell. Past records for Tinkers are limited to a survey in 2000 [34] and a 2014 check on a 350 m reach that had been shifted in 1998 to expand retail parking [37].

The length of all surveys in 2012, 2016 and 2021 was 2-person hours at wadable sites in a search area of approximately 15 linear meters, as personnel moved throughout each designated area, which enabled comparison across time. All live mussels were pulled out of the water for identification, measured for length, and if identification was not obvious, the specimen was photographed. All live mussels were returned to the stream. Shells found were brought to Cleveland State University and catalogued. Species nomenclature followed Williams et al. [38].

GIS Analysis

Map creation and remote sensing analysis applied the latest version of ArcPro (version ArcGIS Pro 2.8.2). Cuyahoga River watershed boundary and elevation data were retrieved from the USGS National Map Viewer (https://apps.nationalmap.gov/viewer/: accessed November 20, 2020). Land Use data from 2001 to 2016 were taken from the Multi-Resolution Land Characteristics Consortium (MRLC) (https://www.mrlc.gov/viewer/: accessed November 20, 2020), and all soil data came from the USDA web soil survey (https://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm: accessed November 20, 2020). Land use, soil, and elevation datasets were clipped to fit the HUC 12 watershed boundaries for the Cuyahoga River watershed. Mussel data collected in summer 2021 were uploaded to ArcGIS as a shapefile and each site was projected as a point with size reflecting the number of live mussels found (Fig. 2).

The hydrology toolset was used to analyze watershed features. Small imperfections in the elevation DEM were corrected using the Fill tool, after which Flow Direction created a raster of water path from each cell to its steepest downslope neighbor. Flow Accumulation characterized the addition of water from land proceeding from headwaters to the river mouth, determined by adding the weight for all cells that flow into each downslope cell. An optional weight factor of 1 was chosen and pour points were snapped closest to each survey site.

The Snap Pour Point and Watershed tools were used for each set of freshwater mussel sites applying maps in time series; 1990 (data from [26]), 2012, 2016 and 2021 for the Upper Cuyahoga River, while Tinkers Creek data composed surveys from 2000 [34] and 2021. Land use in each delineated watershed was obtained with the Tabulate Area tool corresponding to an appropriate and preceding land use raster. The most recently available 2016 maps applied to the 2016 and 2021 mussel datasets, a 2011 land use raster was used with the 2012 dataset, and a 2001 land use raster was assigned for the 2000 and 1990 surveys, as no earlier land use raster was available. The Buffer tool was applied to create a polygon of radius 100 m around each mussel site. The Tabulate Area tool produced areas in square feet, but units were converted to square meters for analysis.

Land use was partitioned into total development area, total forest area, total grassland/herbaceous area, total cropland area, and total wetland area, all calculated from the Tabulate Area table by summing values for land use type and dividing by the total area of land within each sub-watershed. Descriptions of land use classes were defined by the MRLC and can be found on their website (https://www.mrlc.gov/data/legends/national-land-cover-database-class-legend-and-description: accessed December 10, 2020).

Data Analysis

Live mussel abundance was log10 transformed to normalize the variance because a couple high outliers disproportionately affected associations among traits. Changes in mussel abundance across time, as well as correlations between live mussel richness and abundance at both the sub-watershed and buffer scales, were assessed using the Pearson correlation method in Minitab (version 20.4).

Soil drainage categories derived from the USDA soil data were used to produce a shapefile in ArcPro over which survey sites were layered. Soil drainage categories at each site were recorded for both rivers, but ANOVA focused on Tinkers Creek where headwater restoration has been extensive [39] to test potential causes of range shifts between years that occurred only in this stream, targeting three abundant species in Tinkers Creek (*Fusconaia flava*, *Lasmigona costata*, and *Pyganodon grandis*) and the soil drainage class at each site (sub-watershed scale was used). The general linear model ANOVA used mussel abundance by species and soil drainage categories as factors.

Results

Mussel Populations

Within the Upper Cuyahoga River (Table 1), freshwater mussels declined significantly over time ($\log_{10}$ live mussels = 28.6 – 0.014 years, $P = 0.025$). The 122 live mussels and 128 shells in 2021 were fewer than observed in 1990 and 2012, even with surveys broadened to include a stretch of river downstream (Fig. 1a), confirming and extending concerns apparent in the 2016 collections. Furthermore, over half of all live mussels in 2021 came from sites surveyed in the West Branch Cuyahoga River (Fig. 2), and a reduced contrast applying to this one region indicated little if any change in mussel abundance there ($P = 0.58$). and most losses applied to sites downstream.

Of the species found, a common pond species, *Pyganodon grandis* (Giant Floater), remained most abundant, while only a small number of *Lasmigona complanata* (White Heelsplitter) and *Lampsilis siliquoidea* (Fatmucket) were found. Only two *Saggittunio nasutus*, a state endangered species in Ohio, were located.

In Tinkers Creek, 158 live mussels and 609 shells were found in 2021, which was not many more than for the Upper Cuyahoga River, but this stream is slightly smaller and previously possessed fewer in initial surveys two decades earlier (Table 1). Notably, relative abundance shifted extensively from mostly *P. grandis,* at 90 individuals in 2000 to just 1 in 2021, while four times the numbers of *Fusconaia flava* (Wabash Pigtoe) and *Lasmigona costata* (Flutedshell) occurred in 2021 than in 2000. This increase was also reflected in shell abundance. Two new mussel species were found during the 2021 survey that were not observed previously, *Anodontoides ferussacianus* (Cylindrical Papershell) and *Utterbackia imbecillis* (Paper Pondshell).

Watersheds and Land Use

Multiple parks and green spaces border the Upper Cuyahoga River, making much of the surrounding land use largely of forest and cropland (Fig. 3). Yet, across sites, land use showed no significant relationship with mussel abundance either at a large (sub-watershed) or small (buffer) scale (Suppl. Fig. 1), perhaps because most sites in 2021 had few to no mussels even where the proportion of development nearby was low. The area of the West Branch Cuyahoga River from which numerous mussels were found (Fig 2) had a relatively high proportion of developed land (0.11-0.37). Although forested lands (0.29-0.61) predominantly surround the East Branch Cuyahoga River and the upper main stem, which is labeled as the Cuyahoga River proper after these two streams converge, half of all these sites lacked records of mussels in the recent surveys.

A higher proportion of land around Tinkers Creek was assessed as developed (Fig. 3), with forest characterizing the upper reaches. However, many sites from these developed (residential) areas supported mussels, which produced an unexpected positive, although weak, relationship between mussel abundance and proportion developed lands ($r= 0.298$; $p<0.05$), and concurrently, a negative relationship to forest ($r = -0.294$; $P < 0.05$) at both the large (sub-watershed) and small (100 m-buffer) scales. While no mussels were found in surveys below the escarpment (Fig 2), none were previously known from this region.

Concurrently with land use, mussel abundance corresponded with variation in soil drainage type. Few live mussels in either stream occurred in areas identified to have poorly drained (type B/D) soils (Fig. 4), which are indicative of wetland habitats. Soils described as excessively drained (types A & B) also had low mussel numbers compared to moderately well drained soils (type C/D) in the Cuyahoga River (Fig. 4a). In Tinkers Creek, more mussels also were found with good drainage, favoring well-drained (type C) and moderately well drained (C/D) soils in 2001 (Fig. 4b), while most live mussels in the 2021 survey were found in excessively drained (type A) and somewhat excessively drained (type B) soils. Those changes between years in Tinkers Creek corresponded with a large quantitative shift among several mussel species (p=0.006). In 2001, *Fusconaia flava* were found mostly living in moderately well drained (type C/D) soils, but in 2021, this species expanded to inhabit both excessively drained (type A) and some sites with poorly drained (type B/D) soils (Fig. 5). Live *Lasmigona costata* similarly expanded from moderately well drained (type C/D) and poorly drained (type B/D) soils in 2000 to include excessively drained (type A) and somewhat excessively drained (type B) soils in 2021. In 2000, *Pyganodon grandis* occurred in diverse soil types, but this typical slow-water species has all but been replaced.

Discussion

The once derided Cuyahoga River has become a local, state and national symbol of what is possible in making water clean and the river flow free [40]. Yet, all species of freshwater mussels originally found in the Upper Cuyahoga River continue to decline in abundance. In contrast, mussels in the upper reaches of the Cuyahoga River's largest tributary, Tinkers Creek, are sustained and have expressed a shift in their assemblage from predominantly one pond species, *P. grandis*, to two species associated with stream flow, *F. flava* and *L. costata* [41-42]. This response also occurred locally in the West Branch Cuyahoga River and when dams were removed in the Middle Cuyahoga River [19]. Human land use and more impervious surfaces often reduce mussel populations [14,43], but land use failed to provide an explanation here, as the Upper Cuyahoga River remains largely forested with some cropland areas, while Tinkers Creek is surrounded by more residential property.

Soil types relate to drainage [44], but can soil differences among sites be a primary cause of change in mussel presence given that variation will always exist along a stream [45]? Soil variation and sediment relate to stream flow [46,47], and the most obvious difference in the Cuyahoga River watershed between where mussels are common and where they are not relates to where rivers are regulated for flow and where they are not. Cao et al. [48] similarly identified unexpected relationships among habitat traits, where soil permeability contrasted with forested regions, and thus, variation in mussel assemblages. Historically, the Upper Cuyahoga River mainstem was good habitat for mussels [11], but a significant drop in the number of individuals first observed in 2016 was confirmed in 2021.

Large stretches of riparian areas are now wide wetlands where surface flow in the channel is imperceptible. Such structure, where the land remains constantly inundated with water, can create anoxic conditions, and therefore unsuitable habitat [49]. Two large reservoirs are used to regulate flow through all but the West Branch Cuyahoga River, and the released cold, anoxic water, may further exacerbate stress on mussel populations [50,51]. A 1999 biological and water quality study by the OEPA [52] noted that low dissolved oxygen was a concern in the Upper Cuyahoga, with specific mention of areas directly below the East Branch Reservoir, although levels gradually improved downstream towards Lake Rockwell. Even *P. grandis*, the once most abundant live species found in the Upper Cuyahoga River, has all but disappeared from poor soils, as even this pond species requires high oxygen levels and warmer water [2].

Tinkers Creek, like the West Branch Cuyahoga River, faces no flow regulation and appears to paint a promising picture of an improving mussel assemblage, which is supported by shell numbers. Shells are useful predictors where only a small portion of a river is physically surveyed [24]. Despite low richness by site, larger and more continuous populations of *F. flava* and *L. costata* occur today than in at least the recent past, suggesting a shift to a more varied flow pattern in the river ecosystem that can create greater productivity over time [13]. In 1999, water quality was reported to be poor and faunal abundance low in Tinkers Creek [52], demonstrating marked improvement in the last 20 years. Freshwater mussels in Tinkers Creek may have acclimated to local anthropogenic disturbances, or the surrounding residential land uses are not severely degrading the stream. The Portage River, a larger tributary of Lake Erie in NW Ohio similarly supports an abundant number of mussels, if not one also of low and declining richness as it flows through a series of small rural towns that impinge on its riparian zone [53]. But high in the Tinkers Creek watershed, regional parks embarked on significant improvements to flow [39], which eliminated anoxic wetland-type conditions observed in the early survey, and mussels now occur higher in the watershed than before.

Hydraulic conditions constrained by urban needs often account for variation in mussel viability [54-57]. During rains, storm surge down the Upper Cuyahoga River is captured and later released slowly (USGS National Water Dashboard), reducing flood risks downstream and storing water for human use. Rainstorms are important pulsing events that can propel large amounts of water downstream, carrying nutrients, sediments, and organisms [49]. This regulated release limits not just high flow, but also low flow, minimizing deposition of fine sediments and sustaining large expanses of the river as a broad wetland, impacting mussels [22,32]. Consequences of regulated flow are long known:

Charles Lyell ([58], p. 196), in his *Principles of Geology*, said of rivers:

> "it is evident, therefore, that when we are speculating on the excavating force which running water may have exerted in any particular valley, the most important question is not the volume of the existing stream, nor the present level of the river-channel, nor the size of the gravel, but the probability of a succession of floods".

River ecosystems and biodiversity are affected by multiple factors simultaneously [59] and assessing multiple components helps to provide a big picture view [60,61]. After eliminating alternative hypotheses, differences in flow variation remains a predictor of mussel presence. Consequences are not limited to floods, but also to rarity of low water, which can impact reproduction [62]. Visually obvious differences arise between the east and west branches of the Upper Cuyahoga River and between the Upper Cuyahoga River versus Tinkers Creek. Sites in the West Branch Cuyahoga River and Tinkers Creek often had a sand substrate and a mixed flow, a typical riffle, run, pool presentation; and they had more mussels. Wooded riparian banks likely helped but were not required.

That mixed habitat provides a stark contrast to anoxic conditions downstream in the Upper Cuyahoga River where sediments drained poorly, and one could periodically smell the sulfur when the sediment was disturbed. The outcome is that the Upper Cuyahoga River, lacking flood events, has shown no sudden catastrophic loss that could be attributed to a specific cause, but instead, a slow, insidious decline in mussel abundance. Tinkers Creek and the West Branch Cuyahoga River, with their natural hydraulic flow, sustained an assemblage of mussels that has shifted to traditional riverine species, especially after the implementation of land improvement measures that extended beyond water quality.

Applications for Conservation

The prevailing thought within mussel conservation is that if water quality improves and host fish are present, then mussels should return [15,27,63]. The impacts of land use on freshwater mussels are well documented [12,14,64], but. the expectation that simple presence of urbanization and agriculture are the cause of species decline is not always correct, which is an encouraging result, because neither can be removed from a watershed. Future studies of freshwater mussel extirpation should assess relationships between soil types and stream flow conditions both within and above developed areas. Impacts can be unpredictable, with variation in storm surges, floods, droughts, and flow velocity potentially tying into aspects of freshwater mussel viability [65], including a recent discovery of *Pyganodon cataracta* high in the Tinkers Creek watershed [66] in a lentic area largely isolated from mussels downstream. Contrasting mutual human and molluscan requirements for water are too rarely considered concurrently with land use, substrate composition, and water quality [31,67-69].

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Table 1: Number of live mussels (and shells) found in Upper Cuyahoga (UC) and Tinkers Creek (TC) separated by mussel species and survey year. Data by site are available in Andrikanich [69] and Atwell [70].

Species Name	**UC 1990**	**UC 2012**	**UC 2016**	**UC 2021**	**TC 2000**	**TC 2021**
Alasmidonta marginata					(4)	5 (24)
Anodontoides ferussacianus	8 (2)		8			(1)
Fusconia flava					21 (23)	84 (156)
Lampsilis siliquoidea	30 (24)	67 (38)	13 (10)	20 (37)	1 (35)	3 (43)
Lasmigona complanata	88 (11)	135 (105)	39 (34)	13 (15)		
Lasmigona compressa	5 (2)			8 (2)	11 (11)	(10)
Lasmigona costata	4 (7)	30 (5)	8	7 (9)	15 (18)	64 (303)
Saggittunio nasutus	24 (21)	18 (34)	5	2 (1)		
Pyganodon grandis	277 (76)	101 (216)	35 (66)	69 (63)	90 (280)	1 (67)
Strophitus undulatus	22 (7)	20 (6)	3 (4)	(1)	(9)	1 (3)
Toxolasma parvum		9 (1)			(4)	(1)
Utterbackia imbecillis	2 (4)	4 (5)		3		(1)
Total found alive	**460**	**384**	**111**	**122**	**138**	**158**

Figure 1. A comprehensive picture of all historical and recent site locations of freshwater mussel surveys in the (A) Upper Cuyahoga River watershed and in (B) Tinkers Creek, a large tributary flowing to the lower Cuyahoga. Each symbol represents a two-person-hour survey. Maps were produced in ArcPro v10.3.

Figure 2: Map of the entire Cuyahoga River watershed (HUC12) indicating the quantity of the mussel found in the most recent (2021) surveys: Tinkers Creek in purple and the Upper Cuyahoga sites in blue-green. Circle size corresponds to the number of live mussels found, and the smallest dots indicate sites surveyed where no mussels were found.

Figure 3: Total land use area (km^2) of development, forest, and cropland in Tinkers Creek and Upper Cuyahoga watersheds.

Figure 4: The change in live mussels found at different soil drainage types (A) across four surveys in the Upper Cuyahoga River and (B) between two survey years in Tinkers Creek. Soil drainage categories are defined by the USDA, and progress from left to right with A, excessively drained, B, somewhat excessively drained, C, well drained, C/D, moderately well drained, D, somewhat poorly drained, and B/D, poorly drained.

Figure 5: Live *Fusconaia flava*, *Lasmigona costata*, and *Pyganodon grandis* found in Tinkers Creek, separated by soil drainage class denoted as A, excessively drained, B, somewhat excessively drained, C, well drained, C/D, moderately well drained, D, somewhat poorly drained, and B/D, poorly drained.

Supplemental Figure 1: Graphs show the relationship between land use on live mussels across time in the Upper Cuyahoga River for development (a & b) and forested areas (c & d) at the sub-watershed and the buffer scales

Supplemental Figure 2: Correlation between live mussels and land use types in Tinkers Creek at a subwatershed scale (2021, green squares, and 2000, red diamonds): (a) development, (b) forest, and (c) the relationship between development and forest.

Supplemental Figure 3: Correlation between live mussels and land use types in Tinkers Creek at a buffer scale (2021, green squares, and 2000, red diamonds): (a) development, (b) forest, and (c) the relationship between development and forest.

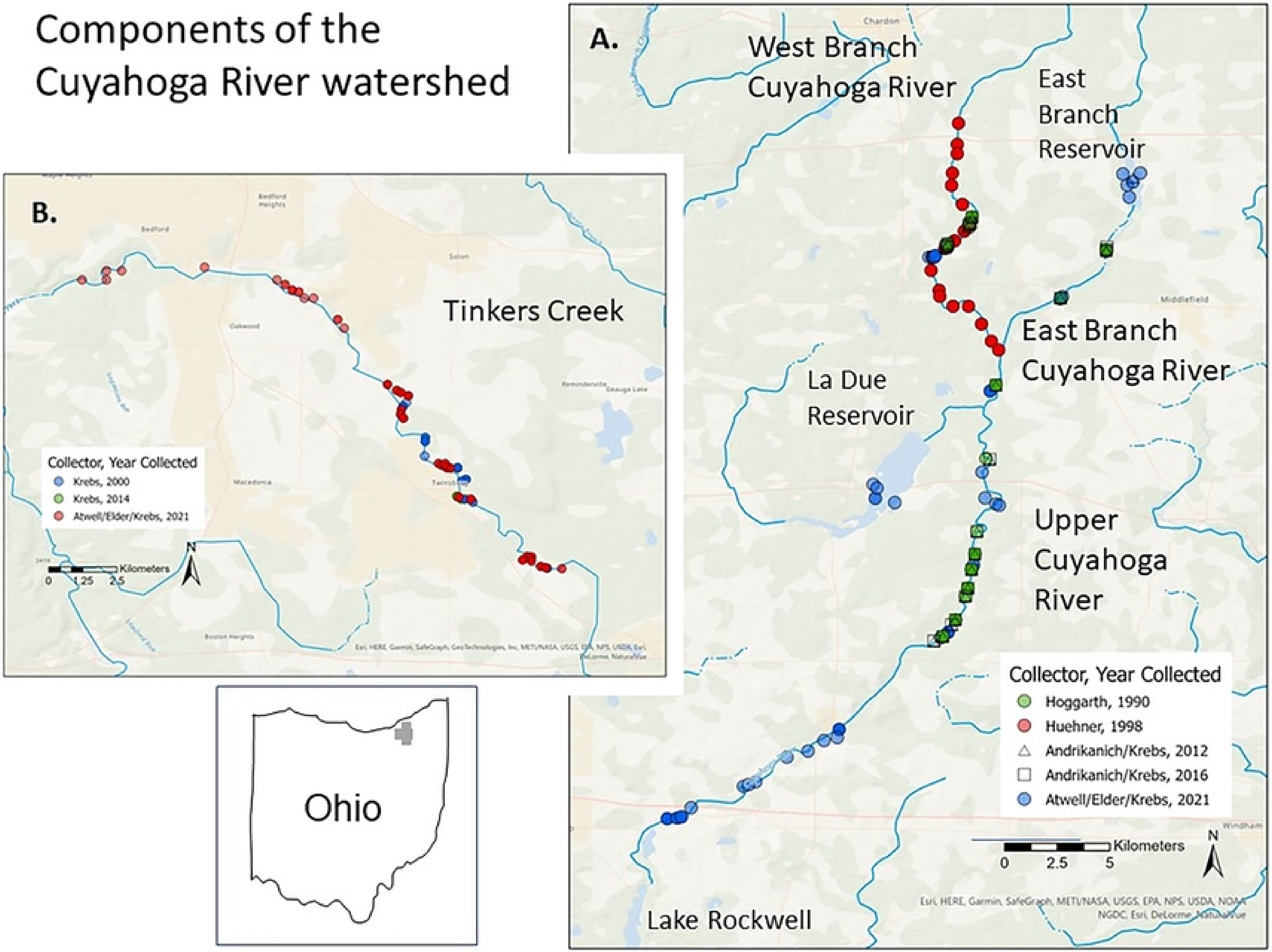

Components of the Cuyahoga River watershed
A.
West Branch Cuyahoga River
East Branch Reservoir
East Branch Cuyahoga River
La Due Reservoir
Upper Cuyahoga River
Lake Rockwell
Collector, Year Collected
Hoggarth, 1990
Huehner, 1998
Andrikanich/Krebs, 2012
Andrikanich/Krebs, 2016
Atwell/Elder/Krebs, 2021
0 2.5 5 Kilometers
N
B.
Tinkers Creek
Collector, Year Collected
Krebs, 2000
Krebs, 2014
Atwell/Elder/Krebs, 2021
0 1.25 2.5 Kilometers
N
Ohio

Figure 1

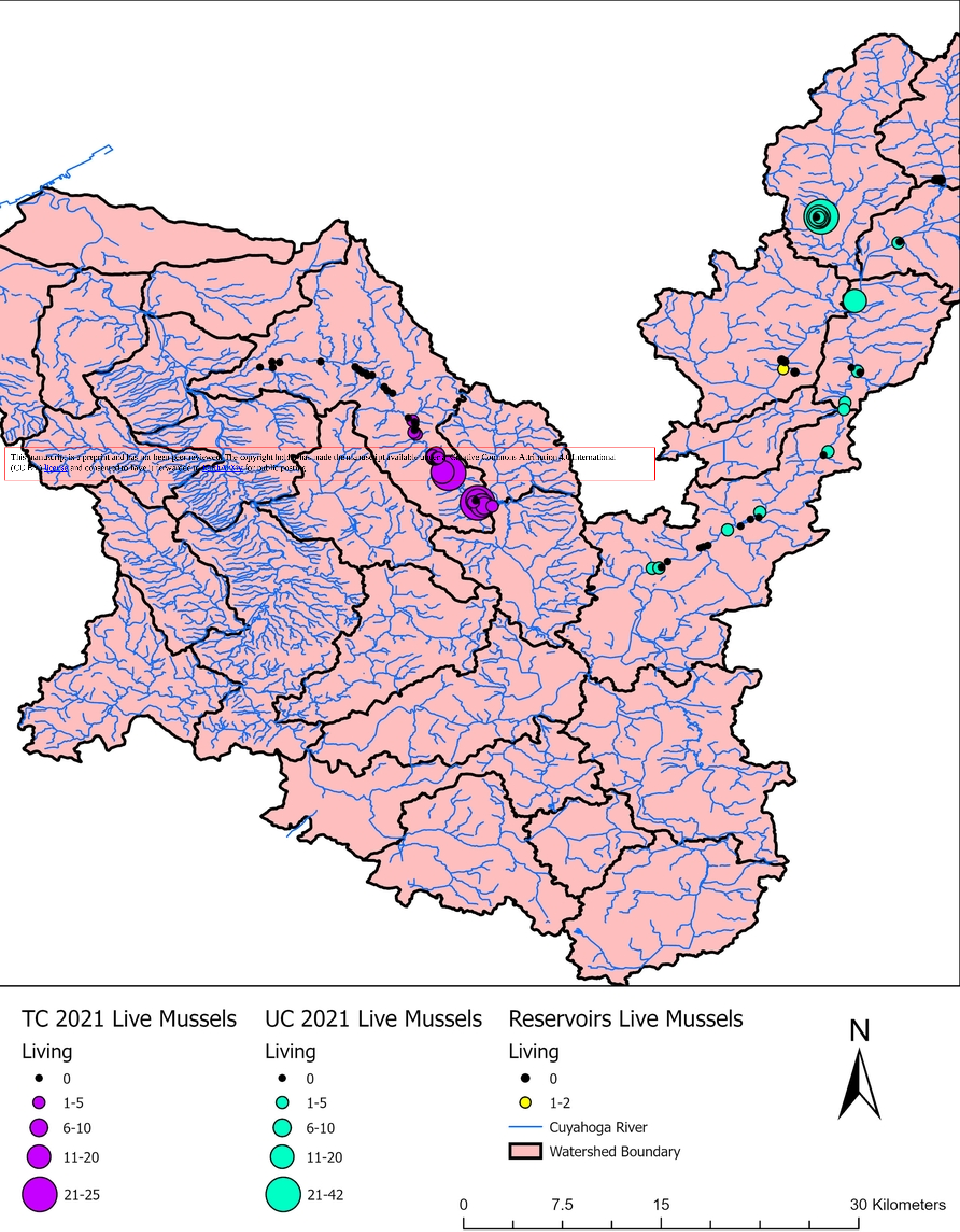

TC 2021 Live Mussels
Living
0
1-5
6-10
11-20
21-25
UC 2021 Live Mussels
Living
0
1-5
6-10
11-20
21-42
Reservoirs Live Mussels
Living
0
1-2
Cuyahoga River
Watershed Boundary
N
0
7.5
15
30 Kilometers

Figure 2

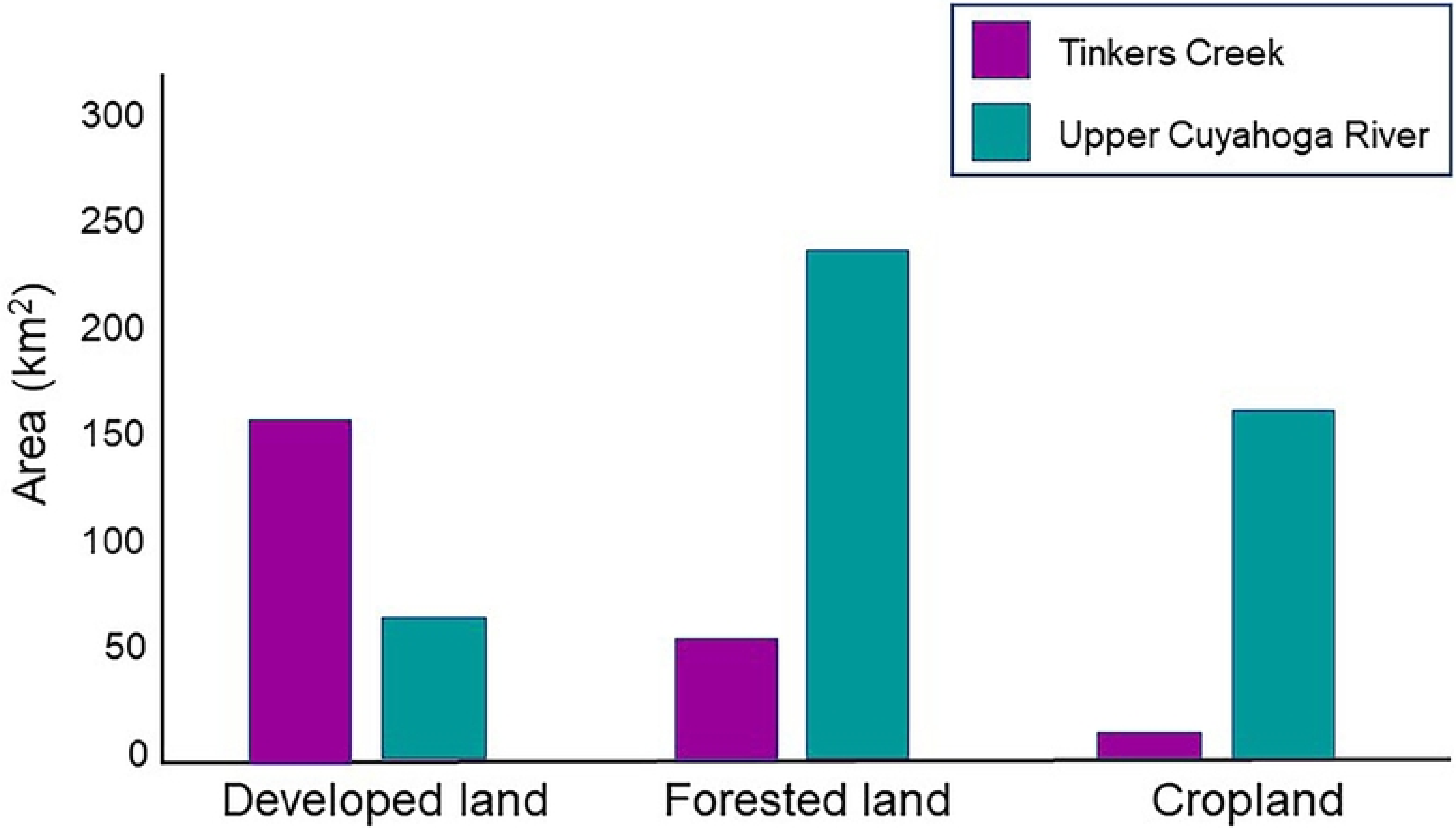

Tinkers Creek
Upper Cuyahoga River
Area (km²)
300
250
200
150
100
50
0
Developed land
Forested land
Cropland

Figure 3

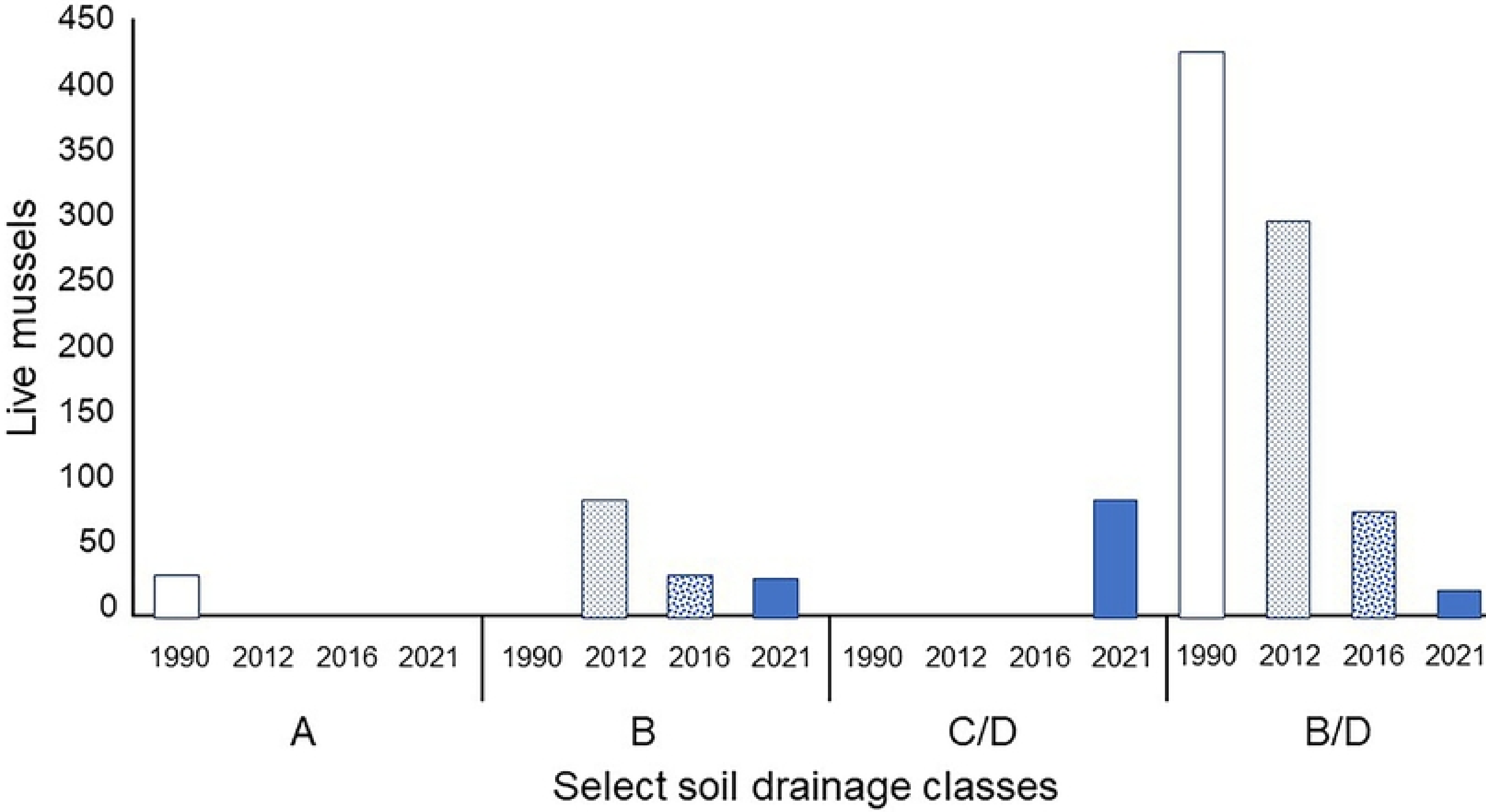
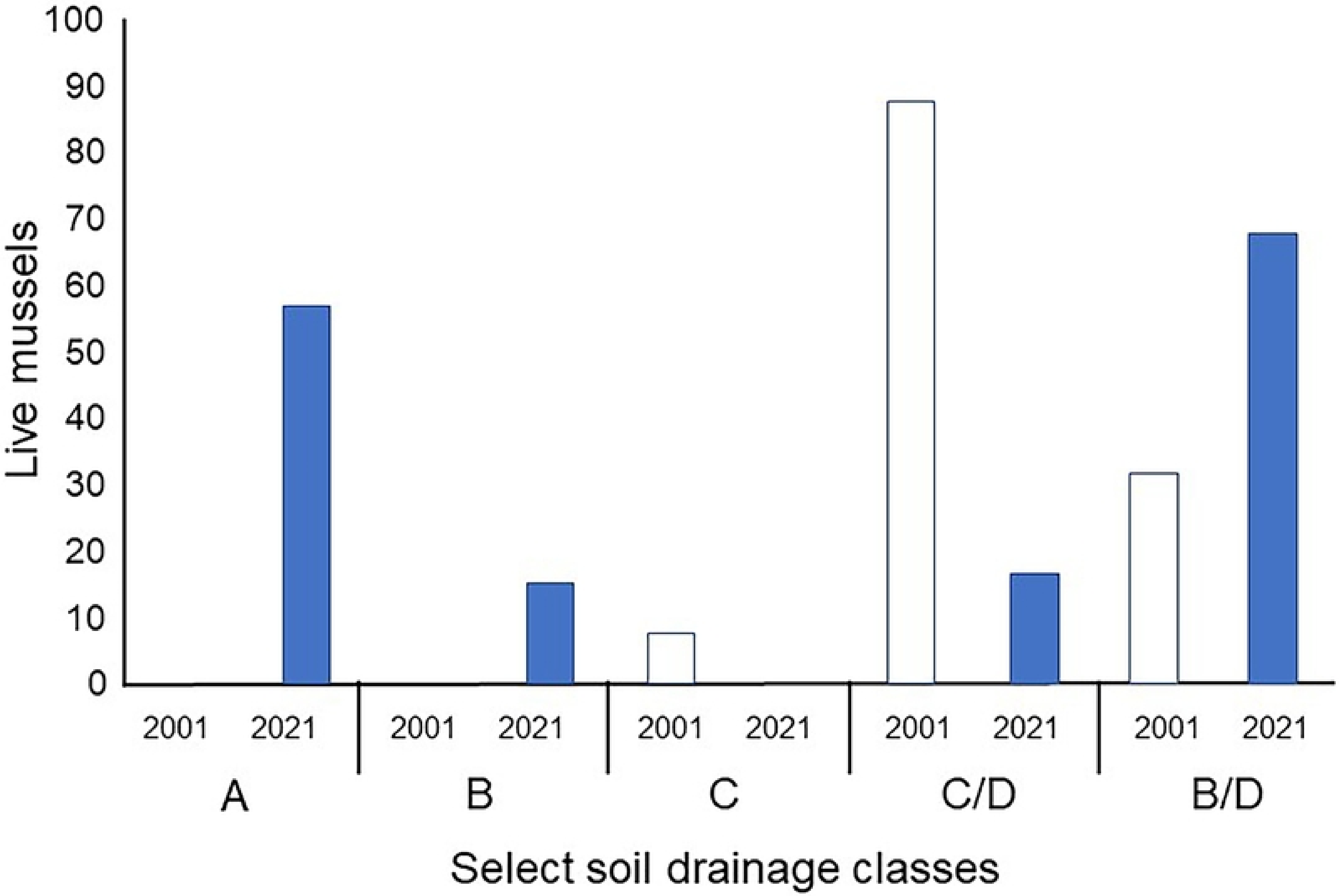
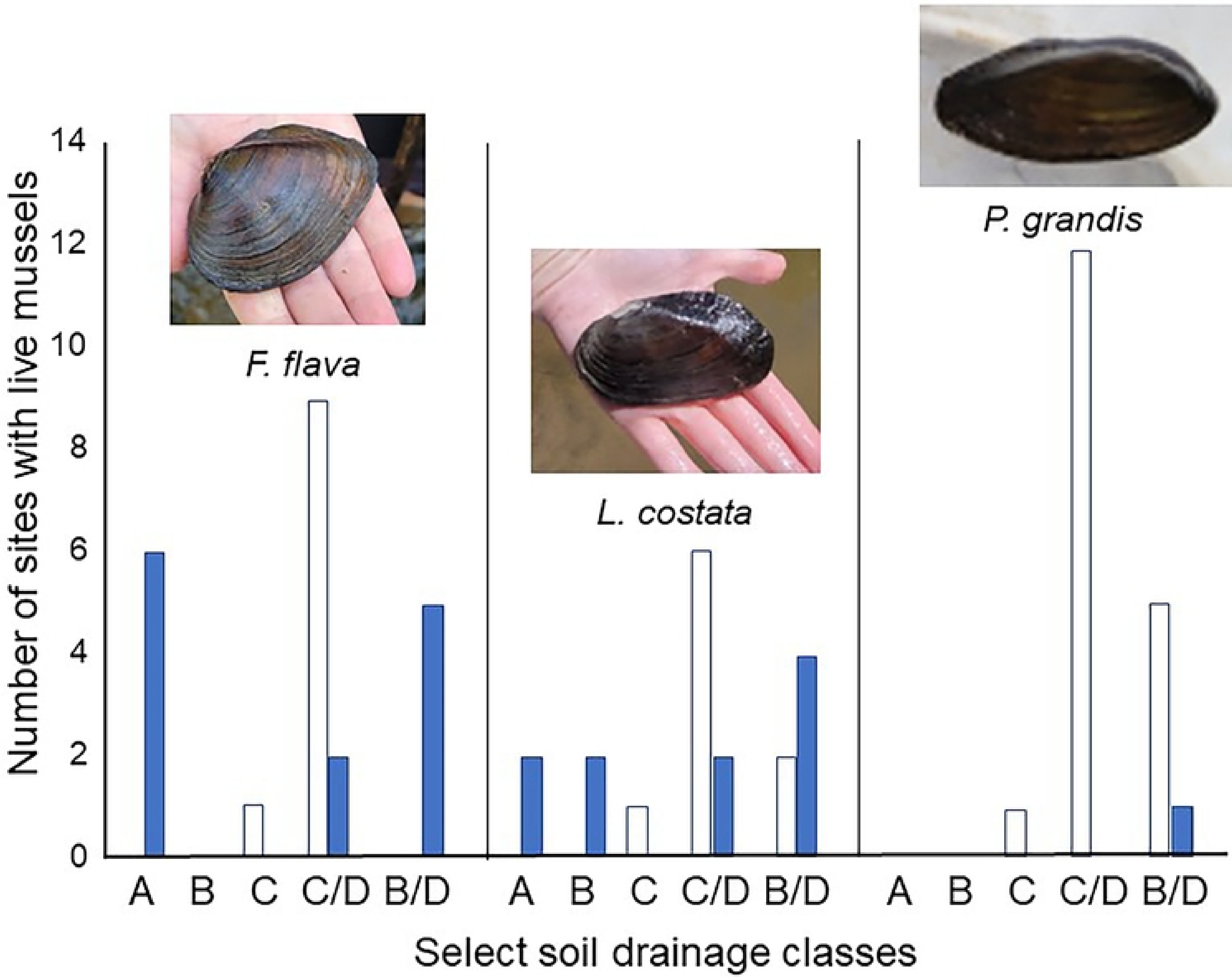

Live mussels
450
400
350
300
250
200
150
100
50
0
1990
2012
2016
2021
1990
2012
2016
2021
1990
2012
2016
2021
1990
2012
2016
2021
A
B
C/D
B/D
Select soil drainage classes

Figure 4a



100
90
80
70
60
50
40
30
20
10
0
Live mussels
2001
2021
2001
2021
2001
2021
2001
2021
2001
2021
A
B
C
C/D
B/D
Select soil drainage classes

Figure 4b



F. flava
L. costata
P. grandis
Number of sites with live mussels
0
2
4
6
8
10
12
14
A B C C/D B/D A B C C/D B/D A B C C/D B/D
Select soil drainage classes

Figure 5