Mapping the landscape of live baitfish regulations for aquatic invasive species prevention in the United States

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Abstract

Aquatic invasive species (AIS) pose a significant risk to global ecosystems, economies, and societies. In the United States, the live baitfish trade is a major pathway for their spread. While the presence of invasive species and pathogens in this trade has been documented, a comprehensive, nationwide analysis of the regulations governing live baitfish has been lacking. This study fills that gap by systematically mapping state-level and federal regulations across the U.S. Our analysis reveals significant variations in regulatory strength. States in the western and northern regions generally have more robust regulations, with some imposing complete bans on live baitfish use. Conversely, many southern and eastern states have weaker regulations, leaving gaps that could facilitate the spread of AIS. These findings provide a crucial resource for policymakers and researchers to evaluate existing policies, identify weaknesses, and develop more effective strategies to address risks posed by aquatic invasive species.

Keywords: Arkansas; case law; exotic; fathead minnow; golden shiner; statutes

Introduction

Aquatic invasive species (AIS) present a multifaceted threat to global ecosystems, economies, and human societies. Ecologically, AIS can drastically alter habitats, disrupt food webs, and outcompete native species, leading to biodiversity loss [1,2]. The economic costs associated with these invasions are substantial, encompassing direct damages to industries like fisheries, tourism, and power generation, as well as the significant expenses of control and eradication efforts [3,4]. Socially, AIS can hinder recreational activities, threaten cultural heritage tied to native species, and pose risks to human health through the introduction of pathogens or parasites [5,6]. These interconnected damages underscore the urgent need for comprehensive management strategies to address the increasing impacts of aquatic invasions.

In the United States, a key pathway for AIS is the live baitfish trade [7]. While a number of countries have a trade in live baitfish, the US is somewhat unique in having an industry where live baitfish are farmed, harvested from the wild, and transported across state borders at an industrial scale [8]. The United States Department of Agriculture reported that, in 2023, there were 205 farms that produced over one billion baitfish in the country [9]. These baitfish are produced by large-scale aquaculture operations and shipped to bait shops and anglers across the country [10–12].

According to the Nonindigenous Aquatic Species database maintained by the U.S. Geological Survey, the bait trade has caused the introduction of aquatic invasive species in every US state [13]. A number of publications have also reported on the presence of invasive aquatic species, unadvertised or illegal species, parasites, and/or viral and bacterial pathogens in the US baitfish trade [12,14–23]. Studies varied in purpose, methodology, date, and region, resulting in differences in the specific organisms identified. Notably, every such study documented the presence of invasive species or pathogens. Invasive species have also been documented in baitfish transported across state borders and sold to anglers in a different state [11].

In the United States, baitfish are generally regulated by state governments. However, despite the importance of the baitfish pathway for AIS prevention, there has been no systematic treatment of baitfish

regulations across the United States. Such a treatment is challenging because each state treats baitfish differently and baitfish regulations are often spread widely in state laws (e.g. in the fishing regulations, wildlife regulations, biosecurity regulations, and so on). Kerr [24] listed baitfish regulations by state, but this analysis was limited in detail and occasionally inaccurate. Gunderson [7] summarised the baitfish regulations in the Mississippi River Basin. However, due to Gunderson's spatial focus, the analysis only covered some states. Most recently, Mulligan *et al.* [10] mapped baitfish regulations across the US as part of a larger project on regulations, education, and inspections. However, the analysis was limited to the level of the region rather than the level of the state. Since baitfish regulations are primarily implemented at the state level, a systematic examination of state-level baitfish regulations in the US remains an important knowledge gap.

In this study, we fill this gap by mapping the baitfish regulations across the US. We systematically collect and analyse all regulations relating to baitfish across the US to derive detailed maps of the regulation landscape, covering the state level and the Federal level. This analysis enables policymakers, researchers, and other stakeholders to readily grasp the strengths and limitations of each state's baitfish regulations and to identify gaps in regulations, which will help these stakeholders craft policies to help mitigate the further spread of AIS.

Methods

In this study, we aimed to map the regulatory framework for freshwater finfish used as live bait in the United States. We excluded from our analysis regulations relating to saltwater fish—marine ecosystems, while worthy of attention, face different challenges from human activity from freshwater systems. We also excluded regulations relating to invertebrates, such as worms and crustaceans, and regulations relating to dead fish or cut bait. Most notably, we made no attempt to capture regulations governing aquaculture *per se*. While baitfish are farmed in large quantities in the United States, it would only be possible to capture the regulations governing baitfish aquaculture if we also mapped the entire system of aquaculture regulations in the country. This is a larger endeavor than we could attempt here. Moreover, American aquaculture regulations have already been examined in a number of studies [25,26].

Compilation of statutes, regulations, and case law

We performed a web scrape to obtain all US state-level statues and regulations relevant to invasive fish management. We scraped the website Justia (https://justia.com/), which maintains full and up-to-date copies of the codified statutes and regulations of each US state. For each state's legal code, we selected those titles, chapters, or high-level sections that relate to fish, fisheries, natural resources, environmental conservation, and water. Using R, we downloaded and stored the full texts of all documents contained within those titles, chapters, or sections. This resulted in 414,011 documents, each of which was a chapter, section, subsection, or paragraph of a statute or a regulation, depending on the state.

From that collection of 414,011 documents, we extracted all documents that contain the following search terms related to baitfish: bait, live fish, live finfish, live aquatic, fish live, minnow, nongame, non-game, non game, baitfish. This resulted in 4,587 documents (1.1 %) that each contained at least one of the search terms. We arranged the full text of those documents, plus metadata describing the documents (e.g. state, statute or regulation, full legal citation) into a spreadsheet.

Turning to case law, we used the API from the website Court Listener (https://www.courtlistener.com) to search for any federal or state court opinions that contained both the

term "bait" and the term "fish". Since many court opinions used these terms just one or two times but in contexts unrelated to baitfish, we restricted the results to those opinions where each term appears at least three times. This resulted in 309 court opinions. We arranged the full text of those court opinions, plus metadata describing the relevant court case (e.g. state, court, full legal citation) into the spreadsheet.

Together, the 4,587 documents containing statutes or regulations and the 309 court opinions formed the core dataset that we used for mapping the landscape of baitfish regulations in the US. Going state-by-state, we manually read all of these documents and court opinions and derived a qualitative description of all regulations relating to the baitfish supply chain and baitfish use in the United States. In several cases, we enhanced this qualitative description with information from existing publications on US baitfish regulations, including both peer-reviewed literature and state government-issued angler guides.

Measure 1: Use of regulatory mechanisms

First, we sought to describe each state government's use of different regulatory mechanisms to the range of activities involving baitfish.

We based our framework on that published by Peters and Lodge [27] for mapping the regulations relating to invasive crayfish management in the Great Lakes region. Peters and Lodge described a range of regulatory mechanisms, ranging from complete prohibition of crayfish use to no regulations, for each state and Canadian province in the Great Lakes region. Their framework also allowed the regulatory mechanisms used to vary by activity (e.g. angling, bait dealing).

Likewise, we considered three key activities across the bait supply chain: importation of baitfish from other states, use of baitfish, and wild harvesting of baitfish. For each of these three activities, we considered the following regulatory mechanisms: regulating species used (e.g. ban list, approved list), regulating methods of the activity (e.g. gear type, farm practices, other miscellaneous requirements placed on anglers), regulating movement of bait (e.g. bans on movement from one lake to another, or bans on movement across specified geographic units), regulating spatial areas (e.g. prohibition on some activity in one lake but no such prohibition in another lake), regulating numbers of bait (e.g. limit to the number of

fish used per fishing trip), license or reporting requirement, and biological monitoring and testing (e.g. monitoring for particular sets of invasive species or diseases).

Regulatory mechanisms were orthogonal with the three activities. For example, a state might regulate the species that are permitted to be wild-harvested separately from the species that can be used as bait. However, not every mechanism is relevant for every activity. For example, a requirement to test for pathogens has no meaning for baitfish users, only baitfish wild-harvesters and baitfish importers.

Drawing on our qualitative synthesis of the state's regulations and case law, we assigned a "yes" or "no" score to each pair of regulatory mechanism and activity for that state. If the state's regulations and case law demonstrated that a given regulatory mechanism was used to govern or restrict a particular activity in that state, we scored that state as "yes" for that pair of regulatory mechanism and activity for that state. Otherwise, we scored that state as "no" for that pair.

This resulted in, for each state, a table illustrating which regulatory mechanisms are applied to each activity involving baitfish in that state. For the purpose of rapid comparison between states, we also assigned each state a numerical score for each of the three activities. This score was simply equal to the number of regulatory mechanisms used to govern that activity in the state. In cases where a particular activity was completely prohibited (e.g., importing baitfish in many states), we assigned that state a numerical score equal to one plus the number of possible regulatory mechanisms that could apply to that activity—this captured the intuitive conclusion that a complete prohibition on an activity should be perceived as more stringent than a state's utilization of all possible regulatory mechanisms other than a complete prohibition for that activity.

Measure 2: Water area covered by baitfish prohibitions

Considering each state's use of regulatory mechanisms, while highly informative as a way to describe a state government's approach to regulation, does not in itself capture the intensity of a particular regulatory mechanism. For example, it is possible to have two states that both regulate the spatial area where baitfish can be used, but for one state to have many baitfish-prohibited waterbodies while the other state has few. Our summary of regulatory mechanisms was unable to capture these cases.

As such, we estimated the water area covered by baitfish prohibitions within each state. Using our qualitative synthesis of each state's regulations, we compiled a list of all waterbodies, parks, counties, or other areas within that state where the use of baitfish is prohibited or permitted.

We downloaded country-wide spatial datasets containing information about the rivers (linear waterbodies), lakes (waterbodies that are not linear), and parks of the US [28–30]. We also obtained political boundaries (county and state boundaries) from the R package *usmap* [31].

The regulatory frameworks of each state made it apparent that a number of states (Alaska, Idaho, Oregon, Utah, and Washington) completely prohibit the use of baitfish. We flagged all waterbodies in these states as "baitfish prohibited". Other states (Alabama, Arkansas, Florida, Illinois, Louisiana, Oklahoma, Mississippi) permitted the use of baitfish in all waterbodies. We flagged all waterbodies in these states as "baitfish permitted".

For the remaining states, we systematically matched the names of all waterbodies where baitfish are prohibited with the names of waterbodies in the rivers and lakes spatial data, flagging all such waterbodies as "baitfish prohibited". Some regulations specify that baitfish are prohibited in only a segment of a river. There was no easy way to capture this in the spatial data, so we simply flagged the full river. Likewise, a handful of states prohibit baitfish in particular rivers and all of those rivers' tributaries. This cannot be readily captured in spatial data, as this requires on-the-ground knowledge of river flow and aquatic connectedness. The majority of waterbody names successfully matched with the data (see Supplemental Information).

We performed similar matching for parks and counties, flagging all waterbodies within matching parks and counties as "baitfish prohibited". Some states utilized region-wide prohibitions in ways that were not easily captured in the spatial datasets; in these cases, we performed manual data analysis to flag as "baitfish prohibited" all waterbodies covered by such regulations. Lastly, we noted any waterbodies, parks, or other entities where states had exceptions to baitfish prohibitions, and flagged these waterbodies as "baitfish permitted". We flagged all waterbodies not covered by a baitfish prohibition as "baitfish permitted".

Lastly, for each state, we calculated the total length of rivers that are a) covered by baitfish prohibitions, and b) not covered by such prohibitions. We performed the same calculation for the surface area of lakes.

For this analysis, we excluded the Great Lakes due to the complex regulatory governance; jurisdiction over the Great Lakes is shared by multiple state and Federal governments, and the Lakes are often managed separately from other waterbodies in each state's regulatory framework. We also ignored baitfish prohibitions that are imposed only during some parts of the year.

Spatial analysis was performed in the statistical programming software R [32] using the packages *terra* [33], *sf* [34,35], and *usmap* [31]. We also used the packages *ggplot2* [36], *tidyterra* [37], and *gt* [38] for visualization.

Results

Use of regulatory mechanisms

Beginning with the results for the use of regulatory mechanisms, the analysis revealed a significant divergence in the use of regulatory mechanisms across states (Figure 1). Most states use at least one regulatory mechanism to govern each of the three activities that we consider (importation of baitfish, use of baitfish, and wild harvest of baitfish). However, there was major variation in the number of regulatory mechanisms applied by each state.

The analysis of regulatory mechanisms identified five states with a complete prohibition on the possession or use of live baitfish: Alaska, Idaho, Oregon, Utah, and Washington. There were a further five states with a prohibition on the import of live baitfish from other states: Maine, Minnesota, Montana, and Hawaii (*de facto*).

On the other end of the spectrum, the analysis revealed that some states use only a handful of regulatory mechanisms. For example, Delaware, Louisiana and South Carolina each use 5 regulatory mechanisms across all three activities. (Further detail about every state's regulatory frameworks, including the specific regulatory mechanisms used, is available in the Supplemental Information.)

Interestingly, regulatory strength appeared to vary systematically by the spatial location of states (Figure 2). States with more stringent regulatory frameworks tended to be located in the west along the Pacific coast or north-west along the Canadian border. In contrast, states that utilized fewer regulatory mechanisms tended to be located in the south or the east along the Atlantic coast.

At the Federal level, there were two court opinions that directly addressed issues relating to the live baitfish trade. In *Hughes v. Oklahoma* 441 US 322 (1979), the US Supreme Court addressed an Oklahoma law that made it illegal to harvest baitfish inside Oklahoma and then transport those baitfish outside of the state for sale. The Court found that this law violated the Commerce Clause of the US Constitution. The Court also found that a law can only discriminate against interstate commerce if the law "serves a legitimate local purpose that cannot be promoted as well by alternative non-discriminatory

means". In *Maine v. Taylor* 477 US 131 (1986), the US Supreme Court upheld Maine's prohibition on the importation of baitfish. The Court found that while Maine's import prohibition discriminates against interstate commerce, the prohibition serves the legitimate local purpose of preventing the introduction of AIS. Lastly, a handful of state court opinions directly addressed issues relating to baitfish, but none were sufficiently impactful to concretely influence live baitfish regulations to the present day.

Water are covered by baitfish prohibitions

Turning now to the coverage of live baitfish prohibitions by water area, the spatial analysis of waterbodies also revealed substantial variation (Figure 3). Many states do not prohibit the use of live baitfish at all, and further states prohibit the use of live baitfish on a handful of waterbodies that add up to only a few percent of the state's river length or the lake area as captured in the spatial data (Table 1). For example, Delaware prohibits live baitfish use on a number of rivers, but these rivers add up to about 3% of the state's total river length captured by the spatial data. Likewise, New York prohibits live baitfish use on a number of lakes, which add up to about 9% of the state's total lake surface area captured by the spatial data.

In contrast, a number of states have implemented prohibitions on the use of live baitfish across large areas of the state. For example, Colorado and Montana each prohibit live baitfish in large eastern sections of the state, corresponding to 63% and 57% of those states' river length respectively and 45% and 97% of those states' lake surface area respectively. Wyoming, while permitting baitfish in a handful of locations, prohibits the use of live baitfish in 96% of the river area and 91% of the lake surface area of the state. Some eastern states, including Pennsylvania and West Virginia, have moderate coverage.

Discussion

In this study, we have derived detailed maps of the landscape of regulations governing live baitfish across the US. These detailed maps fill an important gap in our knowledge about this important pathway for the spread of AIS.

The analysis revealed numerous states that have adopted a thorough regulatory framework for addressing the risks posed by live baitfish. For example, Alaska, Idaho, Oregon, Utah, and Washington completely prohibit the possession or use of live baitfish. This demonstrates that states can and do adopt stringent regulations to address the live baitfish pathway and its risk of contributing to the spread of AIS. Moreover, other states have coupled import bans and multiple further regulatory mechanisms with prohibitions on the use of live baitfish in substantial swathes of those states' waterbodies—this approach has been utilized by Maine and Montana. Taken together, the examples set by these states provide optimism that state governments can adopt stringent regulations to address the risks posed by the live baitfish trade while also meeting the needs of a given state's particular context [39,40].

In contrast, the analysis revealed that some states have very weak regulations governing live baitfish, utilizing few regulatory mechanisms and permitting the use of live baitfish on almost any waterbody in the state. This was most common in the eastern and southern regions of the country. This demonstrates that there remain numerous gaps in state regulations, which may facilitate the spread of AIS in these states via the live baitfish pathway [7,41].

Our results build on the literature in a number of ways. Most notably, we have mapped the landscape of live baitfish regulations at the state level across the entire US. In fact, our spatial analysis was conducted at a scale even finer than the state level, allowing stakeholders to understand how baitfish regulations vary within a state across different waterbodies. This builds on previous studies that have either limited their focus to the regional level or to only part of the country [7,10].

Mulligan *et al.* [10] surveyed government departments to understand governments' focus on regulations, education, and inspections across the regions of the US. The authors found that governments

focused on all three tools to a stronger degree in the Great Basin in the west of the country and in the Missouri Basin in the centre-north, while governments had less focus on all three tools in the Mississippi basin in the south and the South-Atlantic in the south-east. Our results exhibited similar spatial patterns of stronger regulations in the west and centre-north of the country than in the eastern and southern states. Gunderson [7] surveyed the regulations governing live baitfish by states in the Mississippi River Basin. Gunderson found that regulations vary significantly across states, with different states utilizing different regulatory mechanisms, but that all states recognize the risks to local aquatic ecosystems posed by the live baitfish pathway. This supports our findings from the present study, which has illustrated how all states have implemented at least some baitfish regulations even if the strength of these regulations varies significantly.

Our analysis suffered from a number of limitations. A state's use of regulatory mechanisms, while a highly informative description of the government's approach to regulation, does not in itself capture the intensity of a particular regulatory mechanism—a state can use many regulatory mechanisms to weak effect, or few mechanisms to great effect. This limitation was partially mitigated by introducing the second measure of live baitfish regulations, the area of waterbodies covered by live baitfish prohibitions. The spatial analysis of waterbody area also involved a number of necessary limitations. Spatial data describing rivers and lakes in the US is limited and cannot capture every small pond or stream that exists somewhere in the country. Likewise, some regulations specified that baitfish were prohibited on segments of waterbodies, and it was not feasible to capture the detailed segment specification in the spatial data; in these cases, the entire waterbody was marked as "Live baitfish use prohibited". Other waterbodies failed to match with the data, which was most common for very small waterbodies and/or waterbodies with very common names. We also note that measuring the length of coastlines and waterbodies is a fraught exercise even in theory [42].

Future research could build on our results in a number of ways. It would be fruitful to combine our results with baitfish trade data to illustrate major baitfish trade flows between states, which could shine further light on areas of risk. For example, a state with strong baitfish regulations that frequently

imports baitfish from weak regulations might place its own environment at risk, reducing the efficacy of those strong regulations. Interstate baitfish trade data is not systematically published in the US, but it may be possible to compile trade data by surveying bait vendors and other industry actors or by lodging freedom-of-information requests with the appropriate government bodies [7,11,43]. Furthermore, it would be enlightening to examine the effectiveness of different regulatory approaches. In this study, we have categorized state regulations into a range of mechanisms (e.g. regulating species used, regulating the movement of bait, regulating specific waterbodies, and so on). But not all regulatory mechanisms are created equal, and interrogating the efficacy of these different mechanisms—perhaps using quantitative simulation and modelling studies, which could also account for the level of enforcement [14]—would provide further insight for policymakers into how to craft the most effective regulations. Finally, detailed socioeconomic studies could provide further information about the social and economic benefits of live baitfish regulations and about how costs vary by regulatory mechanism [3,44–46].

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Figures and tables

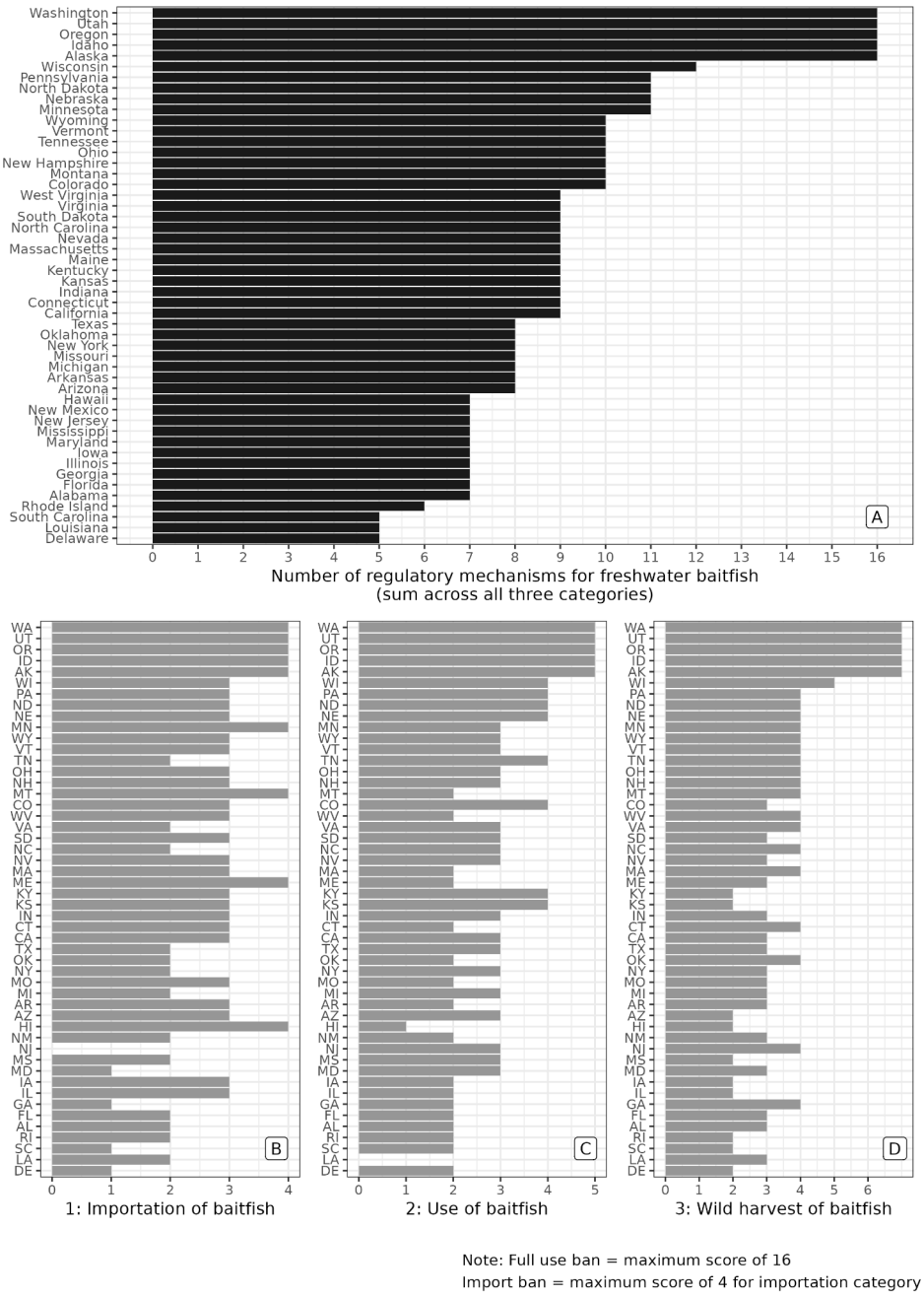

Figure 1: Number of regulatory mechanisms used to regulate baitfish by state, as calculated using the framework in this study. (A) sum across all three categories; (B) strength of regulations addressing importation of baitfish; (C) strength of regulations addressing use of baitfish; (D) strength of regulations addressing wild harvest of baitfish. States are ordered from most to fewest total mechanisms used.

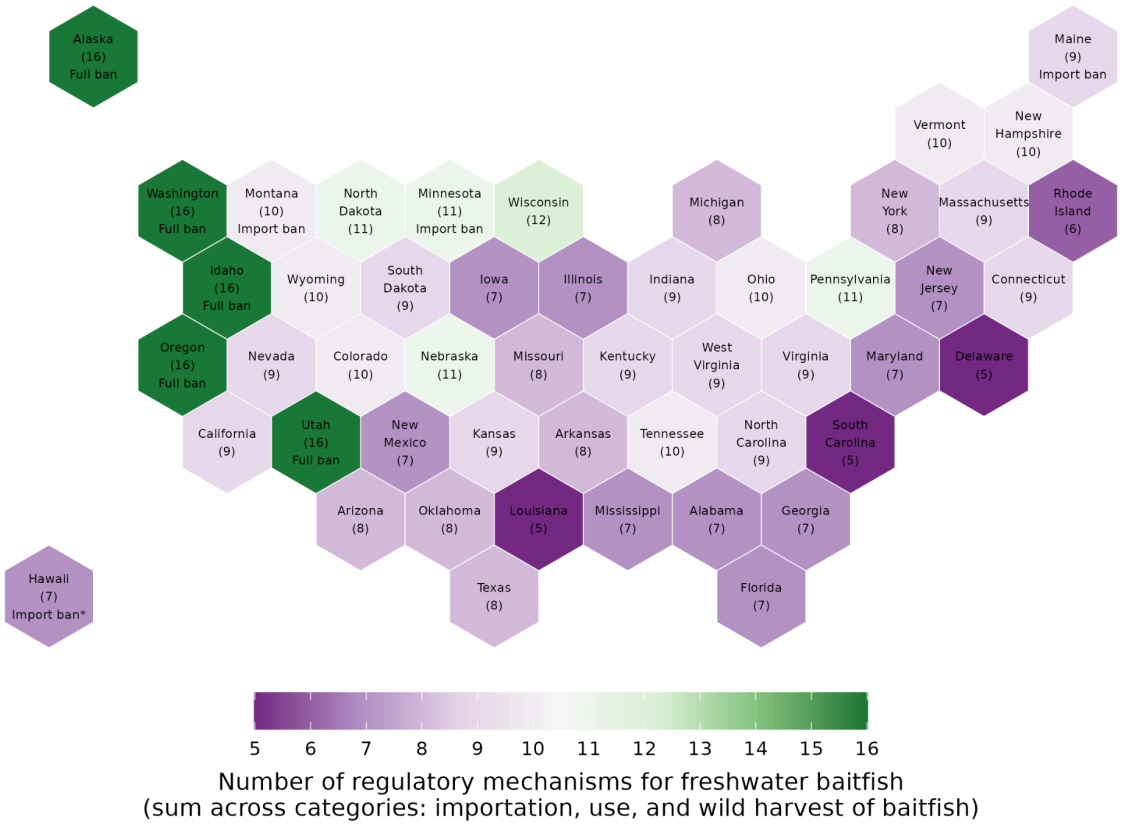

Figure 2: Hexagon grid map visualizing the number of regulatory mechanisms used to regulate baitfish by state, as calculated using the framework in this study. Color represents the sum of the number of regulations across all three regulatory categories (importation of baitfish, use of baitfish, and wild harvest of baitfish), and this number is also listed for each state inside the corresponding cell. The eight states with bans on the use of baitfish ("full ban") or on the importation of baitfish ("import ban") are labelled. Asterisk (*) denotes a *de facto* import ban. Base map by Andrew Hill (https://team.carto.com/u/andrew/tables/andrew.us_states_hexgrid/public/map).

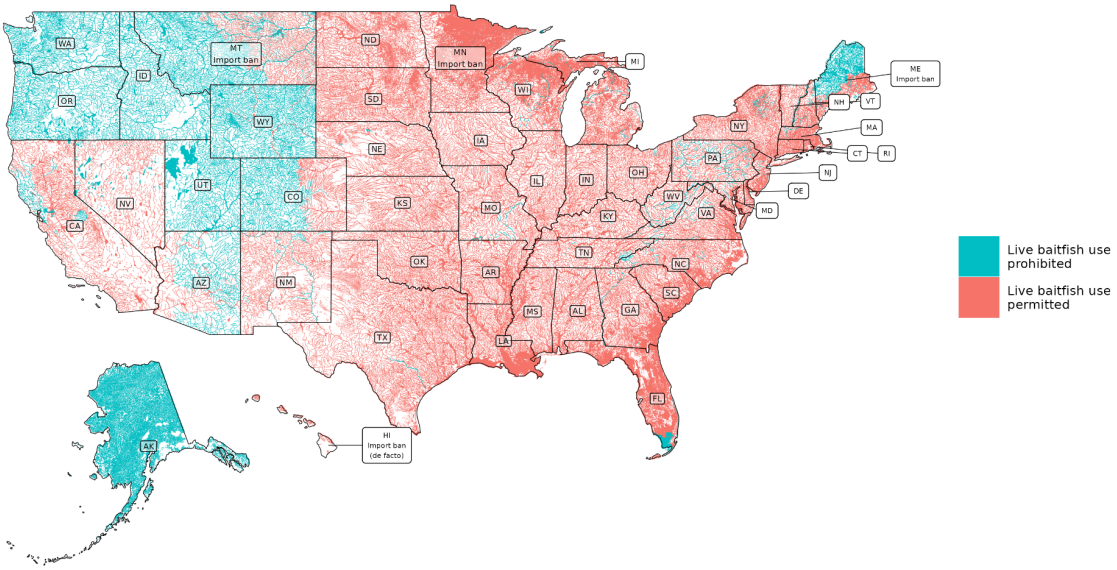

Figure 3: Map of waterbodies (rivers and lakes) in the United States, distinguishing between live baitfish use prohibited and live baitfish use permitted. Import bans are noted.

Table 1: The percentage of river length and lake surface area where baitfish are prohibited for each US state.

State	River length (mi) captured by data	River length where baitfish prohibited (percent, estimated)	Lake area (mi^2) captured by data	Lake area where baitfish prohibited (percent, estimated)
AK	207,044	100%	NA	NA
AL	12,975	0%	1,487	0%
AR	15,423	0%	1,373	0%
AZ	18,342	71%	459	0%
CA	27,024	11%	2,863	10%
CO	24,635	63%	482	45%
CT	1,932	0%	167	0%
DE	533	3%	174	0%
FL	8,454	5%	15,458	14%
GA	12,581	3%	3,590	0%
HI	1,751	0%	NA	NA
IA	13,446	0%	436	0%
ID	15,840	100%	922	100%
IL	13,855	0%	648	0%
IN	9,585	0%	354	0%
KS	19,864	0%	732	0%
KY	12,452	1%	395	0%
LA	13,340	0%	13,023	0%
MA	2,546	6%	521	0%
MD	2,259	11%	903	0%
ME	9,844	64%	2,969	53%
MI	14,667	7%	6,661	1%
MN	21,001	0%	16,006	1%
MO	17,309	5%	832	0%
MS	11,920	0%	1,079	0%

MT	41,564	57%	1,812	97%
NC	13,100	5%	3,648	0%
ND	15,070	0%	2,087	0%
NE	17,351	0%	589	4%
NH	2,694	17%	381	5%
NJ	1,975	6%	753	0%
NM	21,650	9%	468	1%
NV	15,579	0%	1,527	73%
NY	14,920	0%	1,910	9%
OH	12,203	1%	551	0%
OK	18,698	0%	1,506	0%
OR	20,092	100%	1,383	100%
PA	12,857	27%	472	0%
RI	314	0%	95	0%
SC	6,738	0%	3,244	0%
SD	22,656	0%	1,480	0%
TN	11,471	3%	930	0%
TX	58,981	1%	4,608	0%
UT	14,772	100%	5,367	100%
VA	11,275	8%	1,410	0%
VT	2,477	0%	180	1%
WA	14,949	100%	1,407	100%
WI	14,637	7%	5,812	0%
WV	6,647	18%	84	2%
WY	26,891	96%	751	91%