GYCC AIS Risk Analyzer

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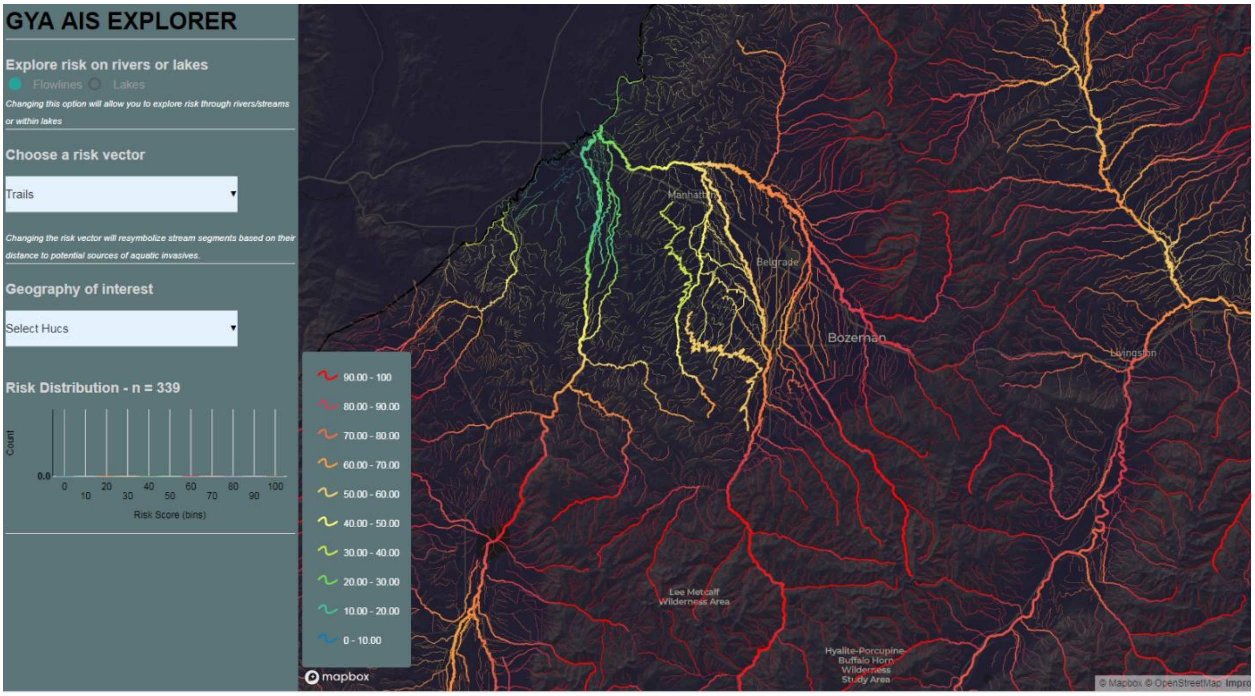

GYA AIS EXPLORER

Explore risk on rivers or lakes

● Flowlines ○ Lakes

Changing this option will allow you to explore risk through rivers/streams or within lakes

Choose a risk vector

Trails ▾

Changing the risk vector will resymbolize stream segments based on their distance to potential sources of aquatic invasives.

Geography of interest

Select Hucs ▾

Risk Distribution - n = 339

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Overview

The Aquatic Invasive Species (AIS) Subcommittee of the GYCC identified early detection surveys for AIS as a priority (McMahon *et al.* 2009). Early detection of AIS increases the probability for successful eradication or suppression and bolsters prevention efforts (Sepulveda *et al.* 2012). Given the size and remoteness of the GYA and limited budgets, it is not possible to do early detection surveillance on all GYA waters. Managers need guidance on where to allocate monitoring and prevention efforts according to risk. To fulfill this need, we developed objective criteria to predict waters most vulnerable to AIS introductions and built an easy-to-use web interface (GYA AIS Explorer) to visualize this risk. Important attributes of the GYA AIS Explorer are that users can:

- Assess risk within or regardless of jurisdictional boundaries
- Model risk relative to just those waters they manage;
- Use expert opinion to customize risk models; and
- Download risk scores at the stream reach scale

Background

Species invasions have dramatically altered earth's ecosystems and biodiversity, with no apparent end in sight (Simberloff 2013). This is especially concerning given that invasive species have devastating and often irreversible consequences, with damages and mitigation efforts costing hundreds of billions of dollars annually in the United States (Pimentel et al. 2000). Aquatic invasive species (AIS) are primarily spread by humans unintentionally by hitchhiking on any type of gear or equipment that comes in contact with AIS-contaminated water or sediment. Thus, waters that receive high human-use are most likely to be recipients of unintentional AIS introductions.

The Greater Yellowstone Area (GYA) is especially vulnerable to AIS introductions because this area receives up to 4 million visitors per year. Visitors travel from across North America and the world to the GYA, especially Yellowstone and Grand Teton national parks. Many of these visitors bring their own gear and equipment in order to fish and recreate in the GYA's lakes and rivers. Because many AIS can survive in damp environments for days to weeks (Anderson *et al.* 2014), there is the potential for overland transport of AIS to GYA waters. In fact, tourism to sites with recreation activities is a well-recognized pathway of AIS spread (Anderson *et al.* 2015). Fishing, boating and leisure activities are collectively responsible for almost 40% of aquatic species introductions in Europe (Gallardo & Aldridge 2013). Prominent examples of AIS that have been transported overland via fishing and recreation equipment include New Zealand mudsnails, zebra mussels, and Eurasian watermilfoil, and whirling disease.

Prevention strategies are the most effective and economical way of reducing AIS spread from this gear and equipment, so most federal and state agencies invest heavily in prevention efforts such as watercraft inspection stations. However, prevention will not stop all invasions so there is a need to monitor for AIS early in the invasion process. Early detection of AIS populations that are small and localized increases the probability that control efforts, including eradication, will be successful.

The GYA is a challenging region for early detection surveillance. There are over 27,000 mi. (43,500 km) of streams and numerous lakes totaling over 278,000 surface ac (112,500 ha.), and the majority of these waters are remote and require substantial effort to access. Given this large geography and limited budgets, it is not possible to survey all GYA waters. Previous GYCC efforts used expert opinion to assign introduction risk to GYA waters. Risk was treated as binary (high/low) and 2/3^{rds} of early detection survey effort were weighted to the 93 waterbodies identified as high risk, while all remaining waters were to receive 1/3rd of the effort.

Lumping GYA waters into these two categories was a tractable way to initiate AIS monitoring in the GYA in 2009. However, understanding of AIS has progressed incredibly and managers now realize that AIS introduction risk is not binary; rather it is a continuous metric with all waters having a non-zero risk of AIS introduction. In fact, several GYA managers have recently identified waters with considerable risk of invasion that are not on the high-risk list (e.g., Yellowstone National Park's Heart Lake and Bridger-Teton National Forest's Soda Lake). Furthermore, AIS in lower risk waters could be more detrimental than introductions into high risk waters for several reasons including, (1) lower risk waters often comprise the headwaters of the GYA, so AIS introduced into headwater habitats could quickly spread downstream; and (2) lower risk waters provide core habitat for a disproportionate number of sensitive and threatened species and are predicted to be important thermal refugia for taxa that are sensitive to climate change (Rahel & Olden 2008; McMahon *et al.* 2009).

To optimize early detection surveillance efforts, we have developed objective metrics to quantify AIS introduction risk by humans at hydrologic stream reaches across the GYA. Because these objective metrics are based on the least common denominator of a stream reach, as defined by the USGS National Hydrological Dataset (NHD), risk can be estimated relative to other waters within a spatial scale of management interest (e.g., the GYA vs Beaver-Deerlodge National Forest vs Gallatin County, Montana). To estimate and visualize risk at the spatial scale of interest, we have developed a graphic-user interface that allows users to tailor risk metrics and download output.

Approach

Our risk analysis assumes humans are the primary vector of AIS, so we only included metrics describing human dispersal patterns to waters in the GYA. While this assumption has not been assessed in the GYA, there is ample evidence linking human dispersal patterns to AIS spread in other systems (Padilla, Chotkowski & Buchan 1996; Leung, Drake & Lodge 2004; Bossenbroek *et al.* 2007; Rothlisberger *et al.* 2010; Anderson *et al.* 2015). Specifically, human dispersal influences the number of invaders reaching a new area (i.e., propagule pressure). It is important to note that the introduction of AIS does not necessarily mean that AIS will ultimately establish and prosper.

We used the USGS NHD digital vector dataset to define the spatial locations of waters. In the NHD dataset, a stream reach is a continuous piece of surface water with similar hydrologic characteristics. Each reach is assigned a unique 14-digit reach code. Importantly, this unique reach code can be linked to many other attributes in the NHD dataset, including catchment characteristics and mean annual flow and velocity estimates. Because of grid-cell limitations, we only included lentic waterbodies (e.g., lakes) ≥ 0.017 km^2.

Stream reaches and lakes are symbolized by adding a map overlay on top of the GYA AIS Explorer's basemap. This map overlay is built using a modern mapping technology called vector tiles. Vector tiles allow data to be sent to the map in a raw form that has not yet been rendered as a visible image tile. This allows for faster transfer between the database and the app and more flexibility in styling and interaction. Vector mapping technologies use a selective process to determine which features should be rendered at different zoom levels. For example, the GYA contains 134,172 stream reaches. It would not be possible for the app to render every one of these stream segment on a normal size monitor. For this reason, the GYA AIS Explorer will selectively display the most prominent features at larger, regional zoom levels. You will see this in the risk distribution. As you zoom in the total number of observations may increase. This is because the GYA AIS Explorer may have the ability to render smaller stream segments at differing zoom levels. Since risk vectors are based on Euclidean distance, this variability in sampling and risk distribution will be difficult to detect. Also, if users are interested in a more detailed analysis of risk distribution, raw datasets are available for download.

Stream reaches and lakes can be sampled using the map extent or by selecting Hydrologic Unit Code (HUC) 12 units or administrative boundaries. After choosing one of these sampling options, lakes and reaches are chosen within those geographic bounds. As noted above, the features available for sampling may vary depending on the zoom level. Additionally, HUC and administrative units are sometimes complicated polygons. To reduce overhead, these polygons are simplified before using as a sampling mask for lakes and stream reaches. You may see this in the display as features are selected. Again, if users are interested in more technical sampling methods, raw datasets are available for download.

We described human dispersal patterns by (1) relating the distances between a stream reach and potential human access points to GYA waters, (2) describing human behaviors at these access points and (3) by describing the attractiveness of destination waters. Potential access points included roads, boat ramps, trails and campgrounds which describe high to lower human use.

Human behavior at these access points included motorized boat use and non-motorized boat use. Attractiveness includes waterbody size, boat ramp density, elevation, and the number of boats traveling to a waterbody. A limiting factor for including other potential metrics is that data had to be available at the stream reach scale across the GYA, thus metrics such as ‘blue-ribbon stream’ and sportfish density were excluded. Below, we describe each metric and their data sources.

We used distances between a stream reach or lake and our locations of hypothesized risk as the primary means for estimating risk for two reasons. First, most humans interact with only a small number of destinations and the likelihood of these interactions decays with distance (Drake & Mandrak 2010). In other words, humans are more likely to visit multiple waterbodies that are in close proximity rather than more distant waterbodies. Second, AIS can naturally spread from their point of introduction and natural spread also follows a distance-decay relationship, where dispersal distance and frequency of dispersal are inversely related (Hastings *et al.* 2005).

For this initial iteration of GYCC risk models, we measured all distance measures as Euclidean (i.e., straight-line geographic distance) since they are easily calculated. We do recognize that Euclidean distances potentially misrepresent (e.g., underestimate) distances traveled following human movements, especially in environments where movements are constrained by topography and terrain (Drake & Mandrak 2010). Future iterations will attempt to incorporate actual patterns of human movement, such as distances traveled by road or trail, via least-cost routing.

Risk Metric Descriptions

Metrics used in GYA AIS Explorer
Roads
Motorized Boat Ramp
Non-motorized Boat Ramp
Trails
Campgrounds
Motorized Waterbody
Non-motorized Waterbody
Waterbody size
Boat Ramp Density
High Risk Lakes

Roads

Roads largely constrain human dispersal patterns to waters that are accessible via a vehicle (Kaufman *et al.* 2009; Drake & Mandrak 2010). Due to the abundance of public lands in the GYA, road-side waters are often accessible along any point of the road. Thus, distance from road is a surrogate for water body accessibility and waters that are closer to roads are assumed to have high AIS introduction risk. We estimated *Roads* as the distance from the centroid of the stream reach to the nearest road.

Road layer data sources: Road data came from statewide and federal sources. USFS districts and National Parks provided road information for lands managed by those agencies. CENSUS TIGER road data were used for all those areas not managed by USFS or NPS.

Motorized Boat Ramp and *Non-motorized Boat Ramp*

Human dispersal is further distilled to locations that provide parking, bathrooms and direct access to water recreation. Introduction risk is especially high for locations with boat ramps, since AIS hitchhike on watercrafts and trailers. We estimated *Motorized Boat Ramp* and *Non-motorized Boat Ramp* as the straight-line distance from the centroid of the stream reach to the nearest motorized boat and non-motorized boat ramp. Boat ramp locations were cross-referenced with local fisheries managers to identify dispersed ramps that were frequently used but not mapped and to correct identify ramps as motorized vs. non-motorized.

Boat ramp layer data sources: Data on boat ramps came from State wildlife agencies, NPS and USFS. After combining all available data sources, additional locations were added from managers and other experts.

Trails

For the minority of users that visit remote waters, human dispersal patterns are assumed to be constrained by established trail networks. Topography and terrain limit off-trail foot, bike, and livestock travel access. We estimated *Trails* as the distance from the centroid of the stream reach to the nearest trail.

Trail layer data sources: Trails data came from the USFS and NPS.

Campgrounds

Camping is an increasingly popular activity in the GYA. Yellowstone offers 12 campgrounds with over 2,000 sites and Bridger-Teton National Forest have over 30 developed campgrounds. Because the majority of these campgrounds are immediately adjacent to a lake or river, campgrounds serve as popular access points for water recreation. We estimated *Campgrounds* as the distance from the centroid of the stream reach to the nearest campground.

Campground layer data sources: Data on campgrounds came from the USFS, NPS and State wildlife agencies.

Motorized Waterbody and *Non-motorized Waterbody*

Motorized-boats and their trailers are thought to be responsible for the overland transport of multiple AIS, especially dreissenid mussels, because this type of trailered boat has multiple attachment points for AIS and users of motorized boats tend to be more transient (reviewed in Rothlisberger *et al.* 2010). Thus, waters and boat ramps that receive motorized-boat use are predicted to be at higher risk of AIS introduction than waters and ramps with non-motorized boat use or no boats. We estimated *Motorized Waterbody* and *Non-motorized Waterbody* as the straight-line distance from the centroid of the stream reach to the nearest motorized or non-motorized boat ramp and to the nearest stream reach or water polygon with motorized or non-motorized boat-use. Boat use was based on state and federal site descriptions and was cross-referenced with local fish managers to ensure that motorized or non-motorized boat use was common. For example, local fish managers scored stream reaches in the upper Yellowstone River as non-motorized even though motorized boat use (< 10 HP motors) is legal.

Waterbody size

Larger water bodies attract more people, likely by increased sport fishing and recreation (e.g., waterskiing) opportunities as well as through access to recreational facilities (e.g., lodging, docks, restaurants) (Drake & Mandrak 2010). We estimated *Waterbody size* as surface (m^2) only for lentic waters since we lacked information on stream reach widths.

Waterbody size data sources: Waterbody size was calculated in GIS using data from the national hydrography dataset (NHD).

Boat ramp density

The number of boaters that use a waterbody likely increase with the number of boat ramps. We described *Boat ramp density* as the number of boat ramps within a 5-km buffer of each stream reach or lake.

Boat ramp layer data sources: To calculate boat density, we buffered each stream segment midpoints by 5km and counted the total number of boat ramps which intersected the buffer.

High Risk Lakes

We used 2016 watercraft inspection station data from all watercraft inspection stations in Montana, Wyoming and Idaho to describe the number of boats destined for waterbodies with the GYA. Motorized and non-motorized watercrafts are required to stop for inspection if they pass a watercraft inspection station. When boat owners are inspected, they are asked to name their ‘next destination water body’. Next destination waterbodies that were rivers were excluded because the spatial scale was larger than the stream reach (e.g., “Snake River”). Lentic waterbodies that could not be geospatially confirmed were also excluded (e.g., “Fish Lake”). While not exhaustive of all watercrafts destined for the GYA, these data do provide a thorough sample from which we can address the relative attractiveness of waterbodies.

We found that 10,110 boats that were stopped at watercraft inspection stations in Montana, Wyoming, and Idaho had a next destination waterbody in the GYA. To ensure that exclusion of waterbodies that could not be geospatially confirmed did not influence risk metrics, we only retained those lakes that received > 1% (101 boats) of this intended boat traffic. This left 14 lakes that received 1.3 – 24% of intended boat traffic. We estimated next destination risk for stream reach or waterbody *i* (ND_i) as:

$$ND_i = \sum_{i=1}^{14} D_i L_j$$

where D is the distance between stream reach *i* and the lake *j* multiplied by L, the proportional frequency of intended boat traffic to lake *j*, summed across all 14 lakes that received >1% of intended boat traffic.

Quantifying Risk

We first standardized all risk metrics using z-scores on a 0 – 100 scale so that perceived risk increases with the value of each metric. Specifically, perceived risk increases for stream reaches and waterbody polygons that are closer distances to our respective metrics, larger, have greater boat ramp density, or have larger ND_i values.

Next, we used pairwise Pearson’s correlation coefficients to test for multicollinearity between metrics. Pairwise metrics that had Pearson’s correlation coefficients > 0.70 and *p*-values < 0.05 were considered collinear. We only conducted this analysis at the scale of the GYA rather than at smaller geographies of interest. We found collinearity between *Trails* and *Campgrounds* ($R = 0.72$, $p < 0.01$), between *Motorized Boat Ramp* and *Motorized Waterbody* ($R = 0.95$, $p < 0.01$), and between *Non-motorized Boat Ramp* and *Non-motorized Waterbody* ($R = 0.70$, $p < 0.01$). All other pairwise combinations had $R < \left|0.50\right|$. Consequently, *Campgrounds, Motorized Waterbody and Non-motorized Waterbody* were not included in any composite models.

Finally, we assessed how individual metrics and combinations of these metrics (i.e., composite models) describe known AIS introductions. However, this assessment is challenging in the GYA because there are few observed values for AIS introductions. The sparse data that are available are presence-only and were usually not products of random sampling designs. Consequently, we cannot assume that sites lacking AIS observations are true absences and we do not know how collection bias (e.g., collectors tend to visit areas which are easily accessible) affects the accuracy of available data.

We took two approaches for assessing individual and composite model fits. First, we provided flexibility in the GYA AIS Explorer for the user to apply expert opinion. Users can edit the composite risk models such that the visualization results match their knowledge about invasion risk and/or human use in their focal geography of interest. Second, we used AIS observations for New Zealand mudsnails (*Potamopyrgus antipodarum*) and for Brook trout (*Salvelinus fontinalis*) in the USGS nonindigenous aquatic species database (https://nas.er.usgs.gov/) to assess model fit since these two species have the most observations in the GYA (see Fig. 1). Mudsnails have been documented at 141 stream reaches while brook trout have been documented at 1027 stream reaches. Limitations of these data are that we cannot discern initial introduction points from secondary spread, do not know about true absence for stream reaches lacking data, and do not know how many failed introductions occurred. An additional limitation for brook trout is that they were initially stocked by federal and state agencies in the 19th and 20th centuries. Nevertheless, these data provide an initial, albeit coarse, means to assess model fit.

Model fit using known AIS observations

We used multiple lines of evidence to assess model fit. First, we bootstrapped available data to look at the distribution of risk metrics for stream reaches with and without mudsnails and brook trout. Second, we used logistic regression and model selection to identify individual and composite models most supported by the data. Third, we used area under the receiver operator characteristic (ROC) curves for these plausible models to evaluate prediction accuracy.

We bootstrapped samples for stream reaches with mudsnails or brook trout observations and for those stream reaches lacking mudsnails or brook trout. Since there were 141 and 1027 stream reaches with mudsnails and brook trout, respectively, we randomly selected with replacement 141 and 1027 stream reaches for respective bootstrap samples. Each bootstrap sample was run for 1000 iterations and summary statistics were calculated for the median value of each iteration. For each metric, we compared the average (± 1 S.E.) of these median values between stream reaches with and without mudsnails and brook trout. Because of the data limitations previously addressed, we used qualitative rather than statistical differences to identify individual metrics that were related to AIS presence.

We then used logistic regression and an information theoretic model selection framework (i.e., AICc) to identify the combination of risk metrics that were best supported by the data. Models with lower AICc values are more plausible than those with higher AICc values. Finally, we calculated area under the ROC curve (AUC) to assess how well these most plausible models separate stream reaches into those with and without AIS observations. An area of 1 represents a perfect fit and an area of 0.5 represents an uninformative fit. All statistical analyses were done in the R (v 3.3.1) programming language and code is available upon request.

Model fit results

Bootstrapping: For New Zealand mudsnails and brook trout, there was a general trend that higher median values for metrics are associated with stream reaches where New Zealand mudsnails or brook trout have been documented (Fig. 2). However, this general trend was stronger for mudsnails than brook trout. The difference between metric median values of stream reaches with and without New Zealand mudsnails was greatest for *Non-motorized Boat Ramp and High Risk Lakes*. The difference between metric median values of stream reaches with and without brook trout was greatest for *Campgrounds*.

Model selection AICc and AUC: The most supported models for New Zealand mudsnails included (1) *Roads*, *Non-motorized Boat Ramp*, *Motorized Boat Ramp*, and *High Risk Lakes* (AICc = 1705.39), (2) *Roads*, *Non-motorized Boat Ramp, Motorized Boat Ramp*, *High Risk Lakes,* and *Trails* (AICc = 1707.1) and (3) *High Risk Lakes, Non-motorized Boat Ramp*, and *Roads* (AICc = 1710.3). All other model combinations had **Δ**AICc > 6.5 (Table 2). The AUC value for these top models was 0.94, indicating that these models did a good job of separated stream reaches into those with and without mudsnails. Consequently, we provide composite model (1) as a default option in the GYA AIS Explorer.

The available brook trout occurrence data poorly supported perceived risk models, as suggested by the very high AICc values (> 11,000) and low AUC estimates (<0.64) for even the best fitting models (Table 2). Consequently, we do not provide any brook trout composite models as default options in the GYA AIS Explorer.

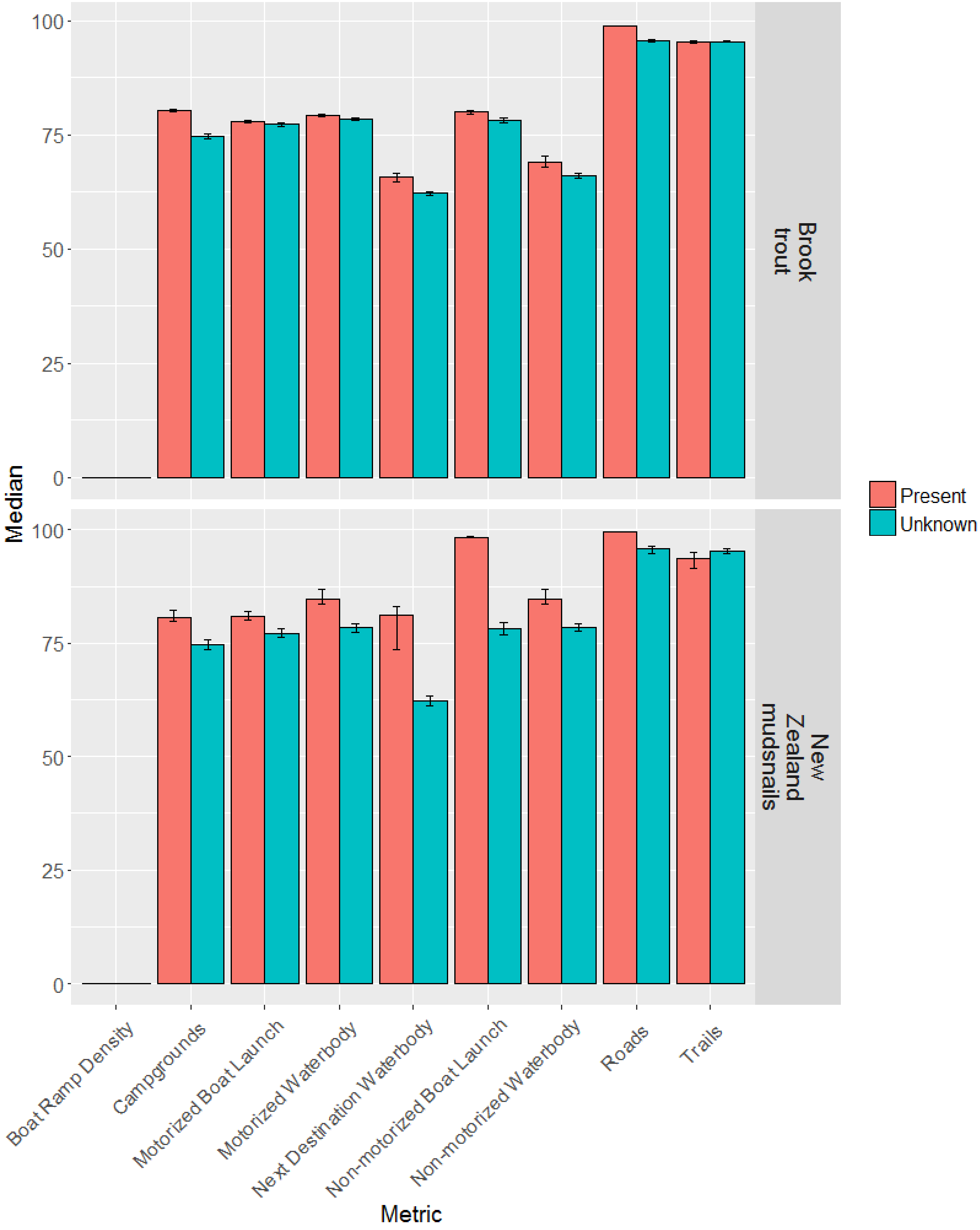


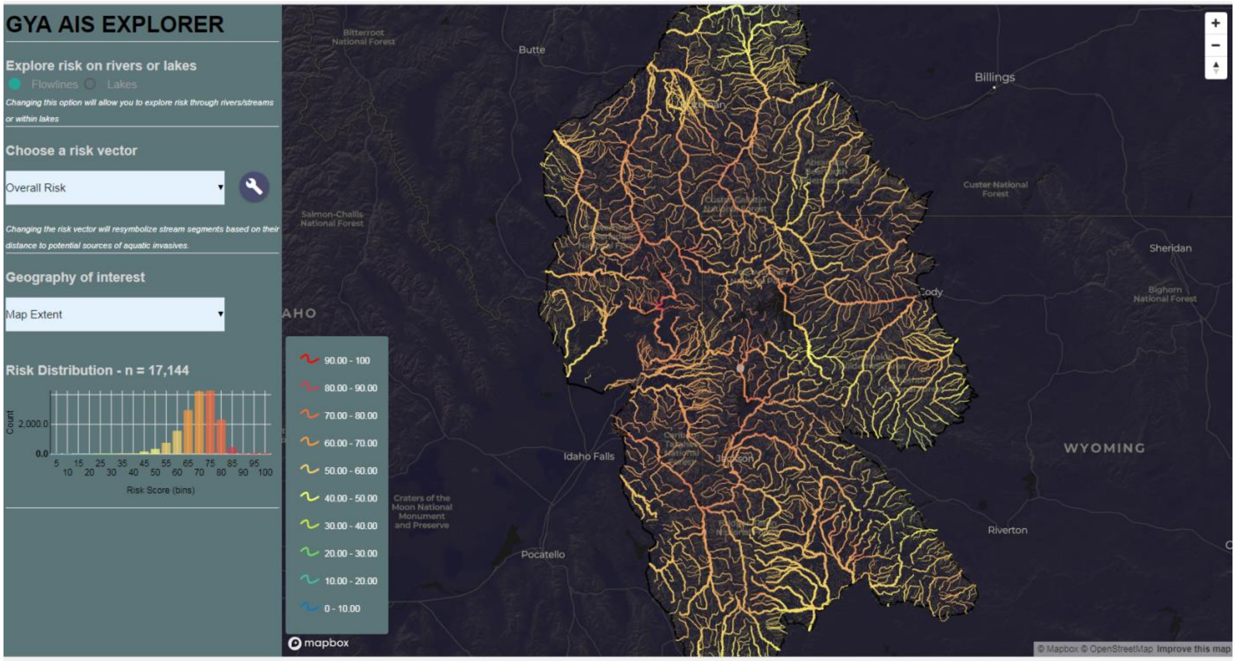
Figure 2. Average (± 1 S.E.) median estimates of risk metrics derived from bootstrap resampling of GYA stream reaches with and without brook trout and New Zealand mudsnails.

Table 1. Akaike information criterion adjusted for sample size (AICc) scores, the relative likelihood of each model (Weight), and area under the receiver operator characteristic curve (AUC) of logistic regression models describing New Zealand mudsnail and brook trout occurrence in GYA stream reaches. Only the most-support models are shown.

Species	Model	df	AICc	Weight	AUC
New Zealand mudsnails	*(1) Motorized Boat Ramp, Non-motorized Boat Ramp, High Risk Lakes, Roads*	5	1705.4	0.64	0.94
	(2) Motorized Boat Ramp, Non-motorized Boat Ramp, High Risk Lakes, Roads, Trails	6	1707.1	0.28	--
	(3) Non-motorized Boat Ramp, High Risk Lakes, Roads, Trails	4	1710.3	0.06	--
Brook trout	*(1) Boat Ramp Density, Motorized Boat Ramp, Non-motorized Boat Ramp, High Risk Lakes, Roads, Trails*	7	11,680	0.61	0.68
	(2) Boat Ramp Density, Non-motorized Boat Ramp, High Risk Lakes, Roads, Trails	6	11,681	0.30	--

Using the GYA AIS Explorer

https://gagecarto.github.io/aisExplorer/



GYA AIS EXPLORER

Explore risk on rivers or lakes

● Flowlines ○ Lakes

Changing this option will allow you to explore risk through rivers/streams or within lakes

Choose a risk vector

Overall Risk ▾

Changing the risk vector will resymbolize stream segments based on their distance to potential sources of aquatic invasives.

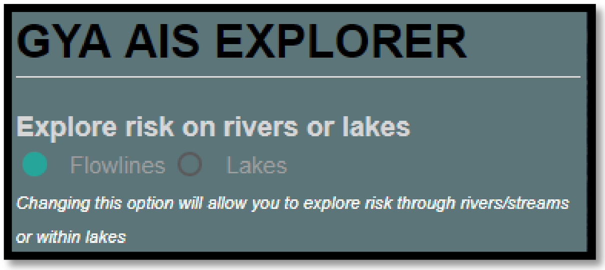
Geography of interest

Map Extent ▾

Risk Distribution - n = 17,144

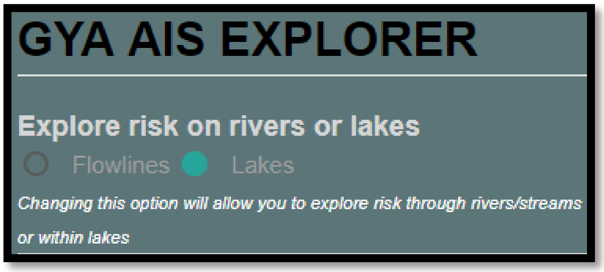
1. **Go to website**
   a. Use a web browser to navigate to https://gagecarto.github.io/aisExplorer/

2. **Explore risk on rivers or lakes**
   a. Flowline: a USGS NHD stream reach, which describes a contiguous segment of surface water with similar hydrologic characteristics. Reaches are commonly defined by a length of stream between two confluences, or a lake or pond. These flowlines include lakes or ponds, though lakes or ponds are represented by a line rather than a polygon.
      - Select "Flowlines"



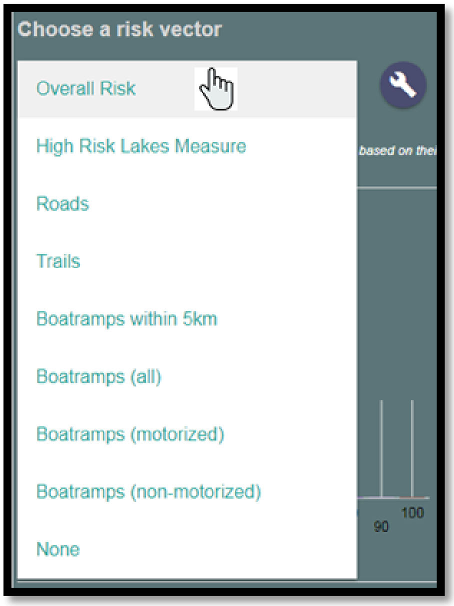
Changing this option will allow you to explore risk through rivers/streams or within lakes

   b. Lake: waterbody polygons in the USGS NHD dataset which only includes lakes, ponds and reservoirs > 0.017km^2.
      - Select "Lakes"



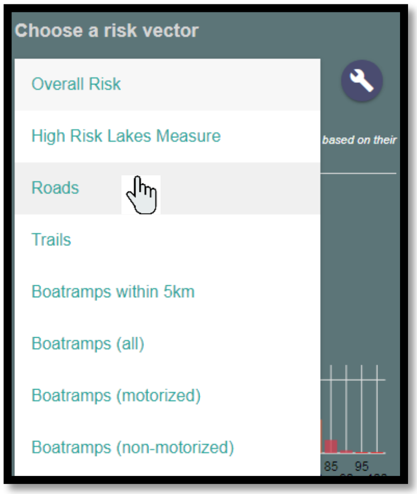
Changing this option will allow you to explore risk through rivers/streams or within lakes

3. **Characterize AIS introduction risk**
   a. Use default risk models
      - Click on the Overall Risk dropdown box to view risk using a composite model or an individual risk vector.



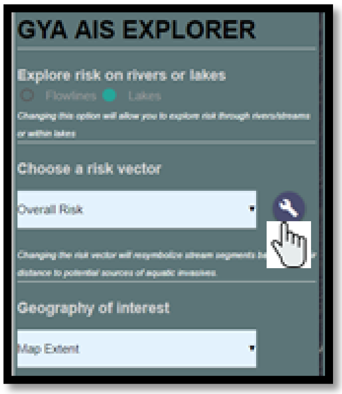
      - The Overall Risk is a composite model that quantifies risk as the sum of all uncorrelated risk vectors including: *Boat Ramp Density, Motorized Boat Launch, Non-motorized Boat Launch, Roads, Trails, and High Risk Lakes*. Each of these risk vectors has the same weight in the model.

b. Alternatively, select any single risk vector by clicking on it.



c. Or, create your own composite model that allows you to edit the weight of individual risk vectors included in the Overall Risk composite model

- Select Overall Risk model and then
- Click on wrench symbol



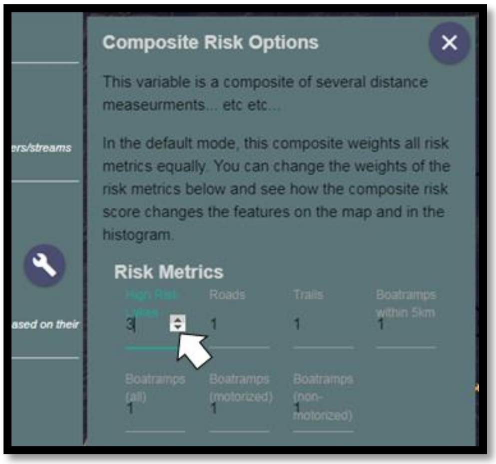
Changing this option will allow you to explore risk through rivers/streams or within lakes

Changing the risk vector will resymbolize stream segments ba... distance to potential sources of aquatic invasives.

- Edit values of individual risk metrics by mousing over vector and clicking on up or down arrow.

- A value of 0 can be used to exclude an individual risk vector

- Values of 1 – ∞ can be used to give one or more risk vectors greater relative weight.



This variable is a composite of several distance measeurments... etc etc...

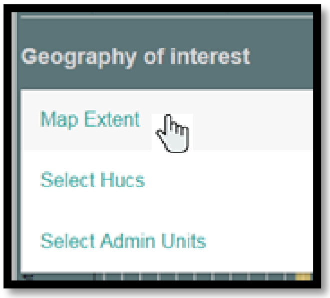
In the default mode, this composite weights all risk metrics equally. You can change the weights of the risk metrics below and see how the composite risk score changes the features on the map and in the histogram.

High Risk Lakes: 3
Roads: 1
Trails: 1
Boatramps within 5km: 1
Boatramps (all): 1
Boatramps (motorized): 1
Boatramps (non-motorized): 1

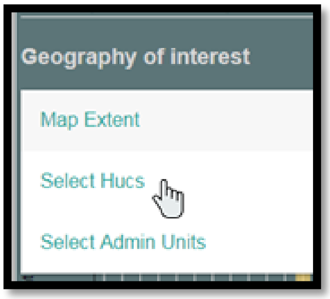
- If all individual risk vectors have a weighted value of 1, then this model is equivalent to the “Overall Risk” model.

4. **Zoom to desired spatial extent & select a basemap**
    a. Expand map extent by zooming out (minus symbol)
    b. Reduce map extent by zooming in (plus symbol).

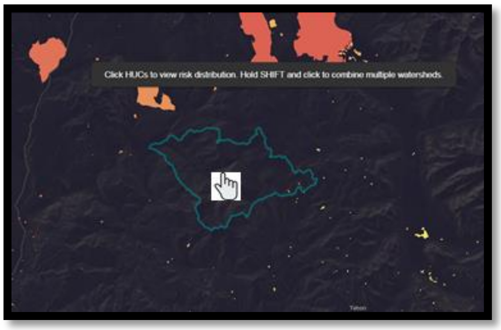
5. **Select the spatial extent (Geography of interest) for visualizing AIS introduction risk**
    a. Map Extent: the portion of area shown in the viewer.
        - Select “Map Extent”
            - Expand map extent by zooming out
            - Reduce map extent by zooming in



    b. Select Hucs: the hydrological unit code (HUC 12) that delineates tributary systems at the sub-watershed level.
        - Select “Selected Hucs”



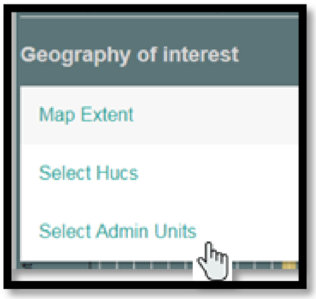
        - Mouse over map in order to see HUC12 green outline.
        - Select the HUC12 of interest by clicking on anywhere within the HUC12. The outline will go from green to white once selected.


Click HUCs to view risk distribution. Hold SHIFT and click to combine multiple watersheds.

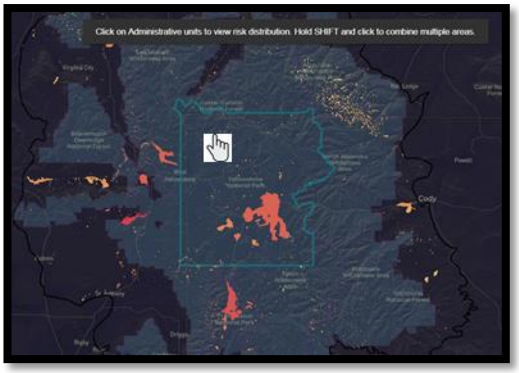
        - Multiple HUC12 units can be selected at once by holding down the Shift key while clicking on additional HUC 12s.

c. Select Admin units:

- Major administration units (e.g., Yellowstone National Park, Bridger-Teton National Forest) can be selected.
- Select "Select Admin Units"

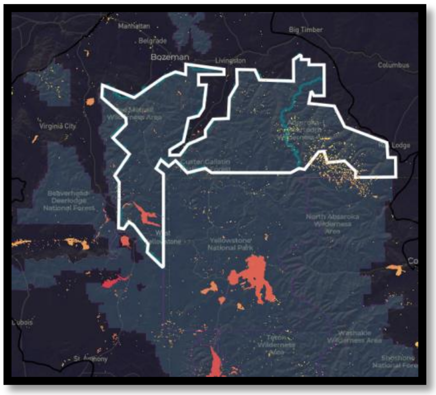


- Mouse over map in order to see Admin units in green outline.
- Select the Admin unit of interest by clicking on anywhere within the green outline. The outline will go from green to white once selected.



Click on Administrative units to view risk distribution. Hold SHIFT and click to combine multiple areas.

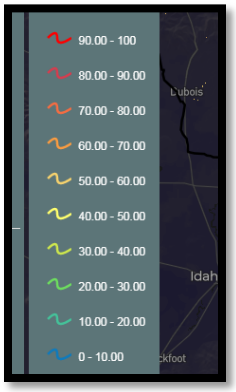
- Multiple Admin units can be selected at once by holding down the Shift key while clicking on additional Admin units.



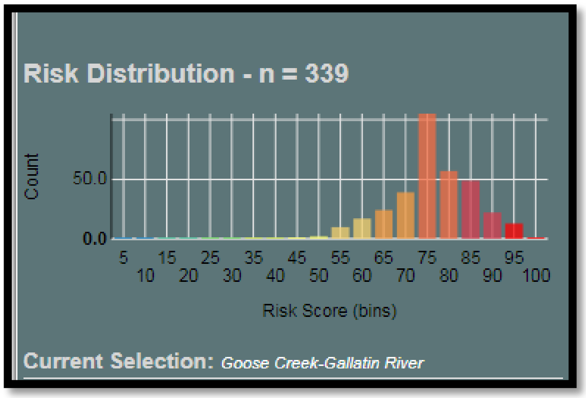
6. Viewing risk

a. The color-coded legend

- Risk scores are standardized on a 0 – 100% score across the GYA, with high values indicating greater potential risk of AIS introduction.
- Risk is binned into deciles (10% bins) relative to the spatial extent of interest, where cool colors (e.g., blue) indicate lower risk and warmer colors indicate higher risk (e.g., red).

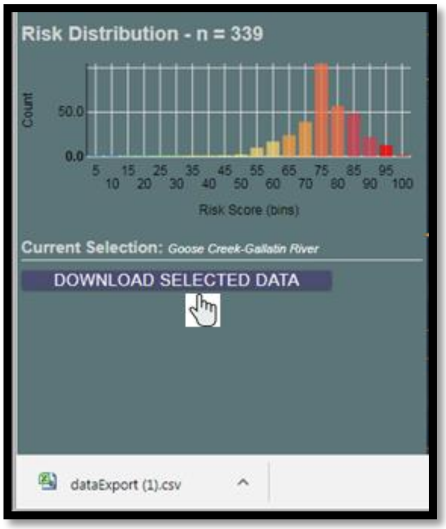


b. The Risk Distribution histogram
   - This figure displays the number of Flowlines or Lakes (y-axis) that fall into different risk score deciles (10% bins) relative to the spatial extent of interest.
   - As with the color-coded legend, higher values indicate greater potential risk of AIS introduction.



Current Selection: *Goose Creek-Gallatin River*

7. Download data
   a. Select "DOWNLOAD SELECTED DATA" to download standardized data for Flowlines or Lakes in the selected spatial extent.



Current Selection: *Goose Creek-Gallatin River*

References Available Upon Request

Anderson, LG, Rocliffe, S, Haddaway, NR & Dunn, AM (2015) The role of tourism and recreation in the spread of non-native species: a systematic review and meta-analysis. *PloS One,* 10**:** e0140833

Anderson, LG, White, PC, Stebbing, PD, Stentiford, GD & Dunn, AM (2014) Biosecurity and vector behaviour: evaluating the potential threat posed by anglers and canoeists as pathways for the spread of invasive non-native species and pathogens. *PloS One,* 9**:** e92788

Bossenbroek, JM, Johnson, LE, Peters, B & Lodge, DM (2007) Forecasting the expansion of zebra mussels in the United States. *Conservation Biology,* 21**:** 800-810

Drake, DAR & Mandrak, NE (2010) Least-cost transportation networks predict spatial interaction of invasion vectors. *Ecological Applications,* 20**:** 2286-2299

Gallardo, B & Aldridge, DC (2013) The 'dirty dozen': socio-economic factors amplify the invasion potential of 12 high-risk aquatic invasive species in Great Britain and Ireland. *Journal of Applied Ecology,* 50**:** 757-766

Hastings, A, Cuddington, K, Davies, KF, Dugaw, CJ, Elmendorf, S, Freestone, A, Harrison, S, Holland, M, Lambrinos, J & Malvadkar, U (2005) The spatial spread of invasions: new developments in theory and evidence. *Ecology Letters,* 8**:** 91-101

Kaufman, SD, Snucins, E, Gunn, JM & Selinger, W (2009) Impacts of road access on lake trout (*Salvelinus namaycush*) populations: regional scale effects of overexploitation and the introduction of smallmouth bass (*Micropterus dolomieu*). *Canadian Journal of Fisheries and Aquatic Sciences,* 66**:** 212-223

Leung, B, Drake, JM & Lodge, DM (2004) Predicting invasions: propagule pressure and the gravity of Allee effects. *Ecology,* 85**:** 1651-1660

McMahon, R, Kumar, S, Systma, M, Hall Jr, RO, Britton, D, Spaulding, S, Williams, E, Farag, A, O'Ney, S & Capurso, J (2009) AIS Inventory and Monitoring Framework for the GYA. Greater Yellowstone Coordinating Committee.

Padilla, DK, Chotkowski, MA & Buchan, LA (1996) Predicting the spread of zebra mussels (*Dreissena polymorpha*) to inland waters using boater movement patterns. *Global Ecology and Biogeography Letters***:** 353-359

Rahel, FJ & Olden, JD (2008) Assessing the effects of climate change on aquatic invasive species. *Conservation Biology,* 22**:** 521-533

Rothlisberger, JD, Chadderton, WL, McNulty, J & Lodge, DM (2010) Aquatic invasive species transport via trailered boats: what is being moved, who is moving it, and what can be done. *Fisheries,* 35**:** 121-132

Sepulveda, A, Ray, A, Al-Chokhachy, R, Muhlfeld, C, Gresswell, R, Gross, J & Kershner, J (2012) Aquatic Invasive Species: Lessons from Cancer Research. The medical community's successes in fighting cancer offer a model for preventing the spread of harmful invasive species. *American Scientist,* 100**:** 234-242

Simberloff, D (2013) *Invasive species: what everyone needs to know*. Oxford University Press.