



# Using social and physical variables to assess vulnerability of northwestern Montana lakes to illegal fish introductions

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**Abstract** The spread of non-native fish species is a common problem in lakes and streams worldwide. Species that establish viable populations in a new environment can seriously deplete populations of native species and desired sportfishes. In some instances, extirpation of a native species has occurred. In western North America, the most common avenue by which non-native species invade new waterbodies is illegal stocking by anglers, aquaculturists, and others. Thus, preventing further illegal fish introductions is of the utmost importance for native aquatic species. Using data collected by state agency personnel from 1953 to 2015, we examined multiple social and physical variables to determine the factors that best explain which lakes in northwestern Montana had past illegal fish introductions. An equation using elevation, surrounding population, and fishing pressure was found to best fit the data. This equation was then used to calculate an index of the vulnerability of

lakes within the region to future illegal fish introductions. The techniques used in this study have broad applicability that can be used in many regions with illegal fish introductions, and ultimately help to alleviate the problem.

**Keywords** Illegal introductions · Bucket biology · Invasive species · Social variables · Montana · Coldwater lakes

## Introduction

Invasive species are leading to declines in abundance and biodiversity of native fauna across many environments, creating irreversible global change (Sala et al., 2000; Simberloff et al., 2013). The human mediated spread of invasive species is exacerbated by other anthropogenic impacts on the landscape including habitat degradation and climate change, which make the ecological dynamics of invasion challenging and unpredictable phenomena (Engelkes & Mills, 2011; Vindstad et al., 2013). This is especially prevalent in freshwaters where introductions of non-native species have led to the extirpation and, in some cases, extinction of many sympatric vertebrates (Vitule et al., 2009). One of the most cited case-studies of this phenomenon occurred in northwestern Montana's Flathead Lake where an agency effort to boost the food

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supply of sportfish populations through the addition of freshwater shrimp (*Mysis relicta*) in an upstream waterbody, resulted in a trophic cascade that caused virtual extirpation of a valuable fishery and had irreversible food web impacts (Spencer et al., 1991; Ellis et al., 2011).

Many introductions of freshwater species were historically conducted by governmental agencies and often aided by members of the public whose goals included supplementing sources of human sustenance and increasing recreational angling opportunity (Rahel & Smith, 2018). But as fisheries management philosophies have changed in light of study on the impacts of invasive species and greater sustainability of wild fish populations (Vincent, 1987), stocking of natural waterbodies has become highly regulated. Today, illegal fish introductions by rogue anglers and aquaculturists are fast becoming the largest source of non-native fish species (Elvira & Almodovar, 2001; Rahel, 2004; Leprieur et al., 2009). This is especially true in the northern and western regions of North America where illegal fish introductions have increased in areas with fewer species of native sportfishes (Johnson et al., 2009). Indeed, historically isolated headwaters with low diversity are more prone to biotic invasions relative to habitats with high aquatic endemism which can minimize the probability of successful establishment by invasive species in undisturbed habitats (Sala et al., 2000).

From 1961 to 2017, half of the documented illegal fish introductions in Wyoming involved the deliberate release of fish by the public, introducing 10 new species to the state (Rahel & Smith, 2018). Such introductions can have devastating consequences for native fish populations as well as ecosystem functioning, and are difficult to control. The impacts of introduced freshwater fish to native species and biodiversity occur through predation, competition, hybridization, habitat modification, and transmission of disease (Gozlan, 2009). Through food web alteration, fish introductions can simplify biotic communities and lead to a loss of ecosystem resilience to other perturbations (Schindler, 1990; Folke et al., 2004). Moreover, once species become established in a waterbody, they are extremely difficult and expensive to remove, diverting resources from programs that benefit anglers, aquatic resources, and the environment (Johnson et al., 2009; Marr et al., 2010). For example, the illegal introduction of Lake Trout

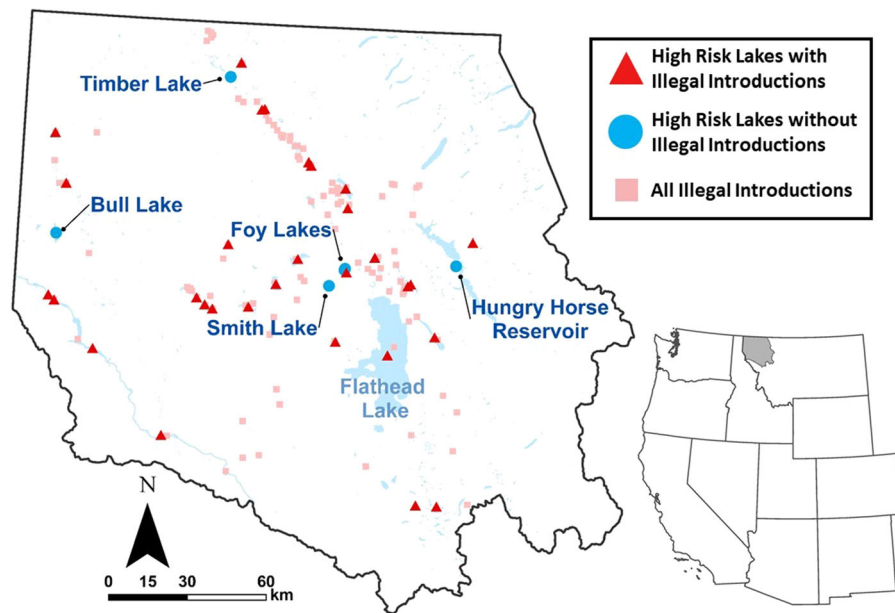
(*Salvelinus namaycush*) into Yellowstone Lake in the late 1980's resulted in an average yearly abundance decline of 11% in native Yellowstone Cutthroat Trout (*Oncorhynchus clarkii bowieri*) from 1994 to 2004 (Gresswell, 2011). Subsequent mitigation efforts have cost millions of dollars in an attempt to suppress Lake Trout populations (Johnson et al., 2009).

Nearly all states in the US have adopted laws that regulate the importation, possession, and release of fish (Courtenay & Robins, 1975). Still, illegal fish introductions have grown in prevalence, and those responsible are rarely caught. Indeed, a 2015 capture of illegally introduced Walleye (*Sander vitreus*) in Montana's Swan Lake was traced using otolith geochemical techniques to a reservoir 309 road kilometers away (Bourret & Clancy, 2018). But despite substantial reward offers for information leading to a conviction, no suspects have yet been identified. Such introductions of warmwater species are especially concerning due to calls for caution in stocking Walleye and Northern Pike (*Esox lucius*), both apex predators (McMahon & Bennett, 1996).

Unfortunately, new fish species continue to be illegally introduced and the number of aquatic ecosystems with an intact native species assemblage continues to decline. Thus, a fundamental question is what social and physical characteristics cause humans to illegally introduce new species. We hypothesized that a combination of social and physical attributes could be used to explain the prevalence of illegal fish introductions in the waterbodies of northwestern Montana. Further, we predicted this framework could be used to accurately assess the vulnerability of waterbodies to future illegal introductions. Using a novel database of illegal fish introductions collected from 1953 to 2015, our main objective in this study was to predict which waterbodies in northwestern Montana (Fig. 1) are at high risk of illegal fish introduction and should be prioritized for preventative signing, increased fish sampling frequency, educational outreach, and law enforcement patrols.

## Methods

Located in the northwestern part of the state, Montana Fish, Wildlife & Parks (MFWP) Region 1 ("Region 1" from here on) is a 38,523 km<sup>2</sup> area dominated by coldwater, oligotrophic waterbodies in a montane



**Fig. 1** The location of MFWP Region 1 (R1) within the state of Montana, USA and waterbodies in light blue. Locations of illegal introductions are indicated by the symbols in the key.

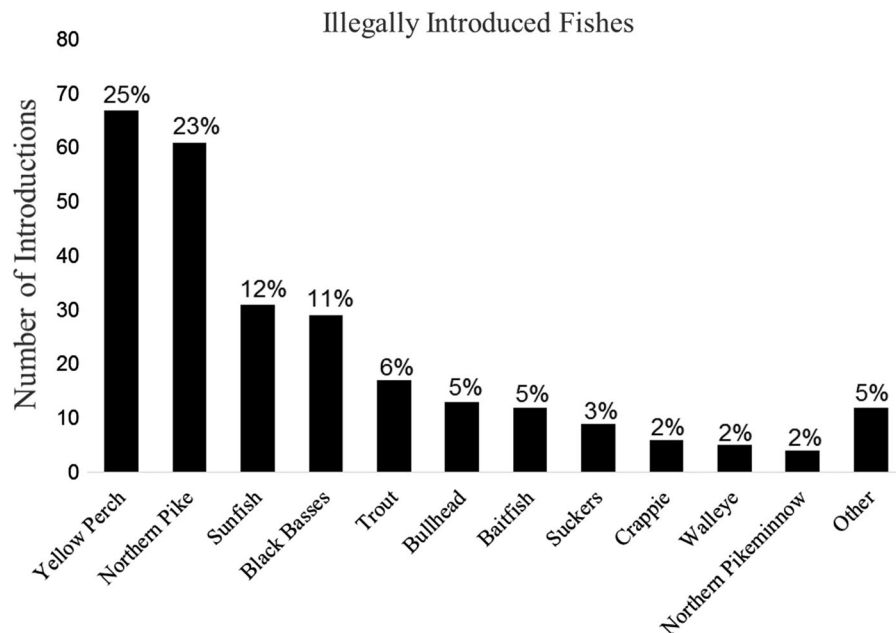
forest ecosystem (Fig. 1). There are 947 named waterbodies (lakes, reservoirs, and ponds) in Region 1, and since 1953, 265 individual illegal fish introductions have occurred in 112 unique waterbodies. Waterbodies with significant portions located in Canada (e.g., Lake Koocanusa, Upper Waterton Lake) were not included in this analysis.

Records of illegal fish introductions in Region 1 have been compiled by MFWP since 1953 and include introductions up to the 2015 Swan Lake Walleye introduction. The accuracy of detecting an illegal fish introduction is influenced by the frequency of fish sampling events in waterbodies and the persistence of the illegally introduced species. Therefore, more illegal fish introductions have likely occurred on the landscape than are reported in our database. We define an illegal fish introduction as a new occurrence of any fish in a waterbody that was not part of an agency-sanctioned introduction. Unauthorized fish introductions encompass illegal, inadvertent, and colonization pathways (Rahel & Smith, 2018), but we believe that the majority of the fish introductions in our dataset are of the illegal nature.

Each entry of an illegal introduction includes what species was introduced, where the introduction occurred, and unique waterbody data including size,

Lakes considered ‘High Risk’ without previously recorded illegal introductions are labeled. Flathead Lake is labeled for reference

elevation, fishing pressure (angler days), distance to the nearest illegal introduction, distance to a major highway, and human population within a radius of 16 km (10 miles). We hypothesized that some combination of these variables would correlate with the presence or absence of an illegal fish introduction. These variables were generated using ArcGIS 10.5 with spatial analyst extension. Acreage was calculated based on the shape of the lake feature from USGS Hydro 1:100 K, USGS Hydro 1:24 k, and NAIP imagery. The elevation of each lake was calculated by taking the center point of the feature and intersecting it with the Montana 30-m DEM. Fishing pressure was found through MFWP angling pressure surveys conducted every 2 years in current form since 2005 (see supplementary material for a detailed description of how the angler pressure variable was generated). The distance variables were generated with the near proximity geoprocessing tool. The human population within 16 km was generated using the Montana cities and town layer maintained by the Montana State Library. The datasets used in this analysis were produced and maintained by MFWP or the Montana State Library. A matching dataset of all Region 1 lakes was combined with the illegal introductions dataset



**Fig. 2** Illegal introductions in Region 1 of individual taxa that were recorded more than twice. The y-axis is the number of illegal introductions and the percent-of-total shown above each

bar. Trout includes Brown Trout, Rainbow Trout, Lake Trout, Brook Trout, Bull Trout, and Bull × Brook Trout hybrids

such that each of the 947 lakes in Region 1 were listed as having had past illegal introductions or none.

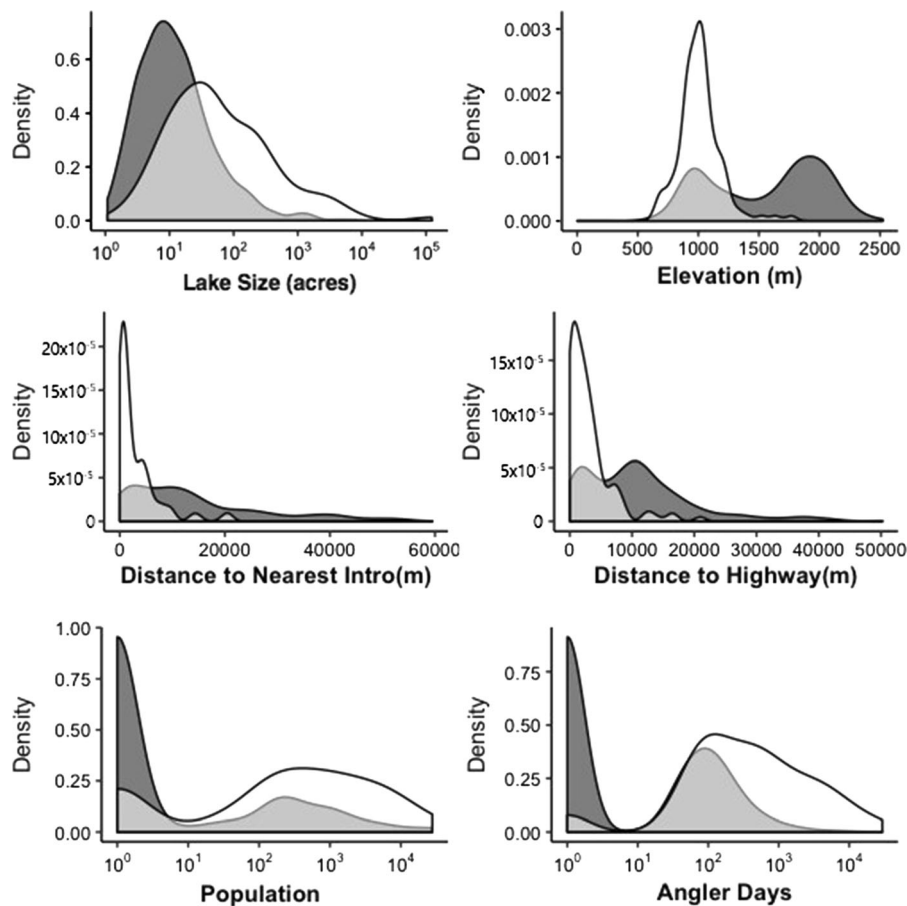
### Data Analyses

We first looked at the number of illegal fish introductions that occurred and calculated the percent frequency of all introductions by fish species in Region 1. The presence/absence of an illegal fish introduction in a waterbody was used as a binary response variable (0 or 1) in a logistic regression framework. All subsequent analyses were performed on this binary response data using generalized linear models (GLM; i.e., logistic regression).

First, possible correlation of explanatory variables was assessed with pair-wise regressions of all variables (Peterson & Carl, 2018) and by calculating variance inflation factors (Supplement 1). The variables lake elevation, lake distance to another illegal introduction, and lake distance to a major highway all showed evidence of correlation (Pearson correlations:  $ELEV-DIST_i = 0.45$ ,  $ELEV-DIST_h = 0.49$ ,  $DIST_i-DIST_h = 0.70$ ; Supplement 1). Subsequent GLMs in which these three variables were interchanged, indicated that AIC values were minimized, and model fit

maximized by using lake elevation. A candidate set of 23 single and multivariate models with and without variable interactions were tested using an information theoretic approach. We assessed model fit and significance ( $\alpha = 0.05$ ) with AIC scores and tested assumptions regarding overdispersion (Burnham & Anderson, 2002). For models with a difference in AIC scores less than two points, we chose the most parsimonious to analyze. Additionally, McFadden's pseudo- $R^2$  (McFadden, 1977; Signorell 2019) was calculated to assess explanatory power of the regression and a Hosmer–Lemeshow test (Hosmer et al., 2013) was used to evaluate goodness-of-fit (Lele et al. 2019).

Lastly, we calculated an *Introduction Vulnerability Index* (“vulnerability index”, see equation in results section) for each lake in Region 1, using the regression equation to predict if waterbodies with known illegal introductions are at higher risk than those without introductions in our original dataset. Lakes with vulnerability index values greater than zero represent those at higher risk of introduction and were placed in a “High Risk” category. Lakes with a vulnerability index value of less than zero were placed in a “Low Risk” category.



**Fig. 3** Density distributions of the six variables for Region 1 lakes with (white) and without (gray) illegal introductions

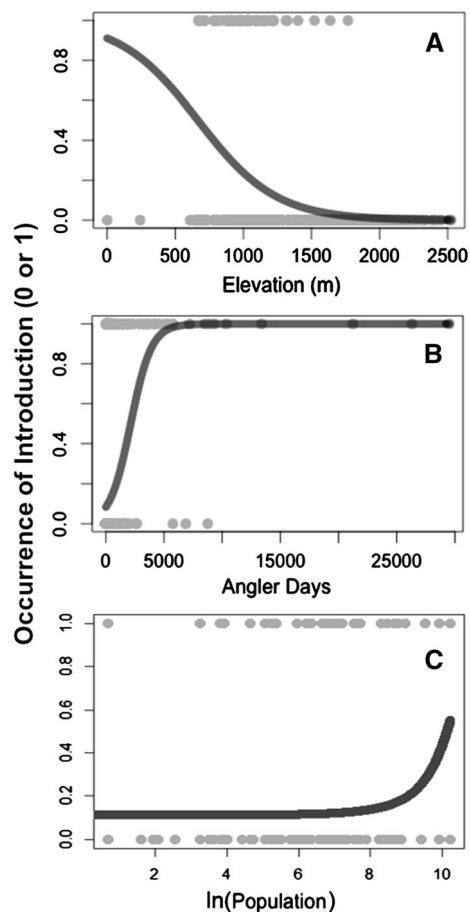
## Results

Of the 265 illegal fish introductions recorded in Region 1, Yellow Perch ( $n = 67$ ) and Northern Pike ( $n = 61$ ) account for nearly half (48.3%). Other groups making up a significant percent of introductions include *Lepomis* sunfishes (11.7%), Black Bass (*Micropterus* spp.), (10.9%), Salmonids (6.4%), and baitfish-minnows (Redside Shiner, (*Richardsonius balteatus*); Fathead Minnow, (*Pimephales promelas*); and Central Mud Minnow, (*Umbra limi*); 4.5%); (Fig. 2). Many of these illegal introductions occurred in or near habitat for native species-of-concern including Westslope Cutthroat Trout (*O. c. lewisi*), Redband Trout (*O. mykiss gairdneri*), Bull Trout (*Salvelinus confluentus*), Deepwater Sculpin (*Myoxocephalus thompsonii*), Spoonhead Sculpin (*Cottus ricei*), Torrent Sculpin (*Uranidea rhotheus*), Pygmy

Whitefish (*Prosopium coulteri*), and Trout-Perch (*Percopsis omiscomaycus*).

All six physical and social variables examined showed at least some differentiation between lakes with and without illegal introductions (Fig. 3). The lowest AIC values were obtained using a combination of lake elevation, human population, and fishing pressure (Fig. 4, Table 1), all of which indicated low collinearity (Supplement 1). The best fit equation, outputting an index of the vulnerability of a waterbody to illegal introduction, is as follows:

$$\begin{aligned} \text{Introduction Vulnerability Index} &= (1.96 - (0.00355[ELEV]) - (0.00135[POP]) \\ &+ (8.07 \times 10^{-4}[FISH]) \\ &+ (1.5 \times 10^{-6}[ELEV * POP])) \end{aligned}$$



**Fig. 4** Single-variable models (dark line) fit to illegal introduction data (gray dots): waterbody elevation (A), fishing pressure (B), and human population within a 16-km radius of a waterbody (C)

where *ELEV* is lake elevation in meters, *POP* is the human population within a 16 km radius of the lake, *FISH* is lake fishing pressure in angler days per year.

Of lakes placed in the “High Risk” category by the equation (index value > 0), 80% ( $n = 24$ ) had known illegal introductions and 20% ( $n = 7$ ) did not (Fig. 5). Goodness-of-fit and pseudo- $R^2$  tests indicated good model fit (Hosmer–Lemeshow test:  $\chi^2 = 14.056$ ,  $df = 8$ ,  $P$  value = 0.08031, where significant  $p$ -values indicate poor model fit;  $\rho^2_{McFadden} = 0.33$  where values between 0.2 and 0.4 are considered “excellent fit.”); (McFadden, 1977). The equation placed 853 of the 947 lakes in the correct category (having an introduction or not), representing 90.1% accuracy.

## Discussion

Using only three variables (elevation, surrounding population, and fishing pressure), our vulnerability equation was able to predict which Region 1 lakes did and did not have past illegal fish introductions with 90% accuracy (Fig. 5). Lake elevation was the top single variable and likely represents the difficulty for would-be bucket biologists to access high mountain lakes. In one of the few related studies, unauthorized introductions and population expansion of Small-mouth Bass (*Micropterus dolomieu*) were strongly correlated to the presence of humans, including cottages and lodges, in central Ontario, Canada (Kaufman et al., 2009). Given the complexity of predicting human behavior, we feel the vulnerability equation, coupled with the knowledge of local fisheries personnel, is the best tool to prioritize which northwestern Montana lakes are most at risk for a future illegal introduction. However, the vulnerability equation does not account for which species may be introduced and how a given species assemblage may be affected. It is likely that species-of-concern or economically important sportfishes residing in “High Risk” lakes with previous introductions would still be harmed by further illegal introductions. We therefore suggest preventative measures should be considered for all “High Risk” lakes (Table 2).

The last entry in our database of illegal introductions is from 2015. As evidence of the vulnerability equation’s applicability, one of the lakes with the highest vulnerability indexes without past illegal introductions (Bull Lake), has since experienced such introductions (M. Hensler, Montana Fish, Wildlife & Parks, *personal communication*). October 2019 surveys in Upper Thompson Lake, another Region 1 lake we categorized as High Risk (Table 2), found two illegally introduced Walleye (MFWP, 2019).

One of the lakes without introductions having a very high vulnerability index is Hungry Horse Reservoir (Fig. 1) and should be the target of preventative action. Hungry Horse Reservoir and the interconnected South Fork Flathead River drainage is largely unimpacted by anthropogenic disturbance because the headwaters of the drainage occur in the Bob Marshall Wilderness Complex. The watershed represents one of the largest interconnected habitats for iconic native fish species including genetically pure Westslope Cutthroat Trout (Liknes & Graham, 1988; Shepard

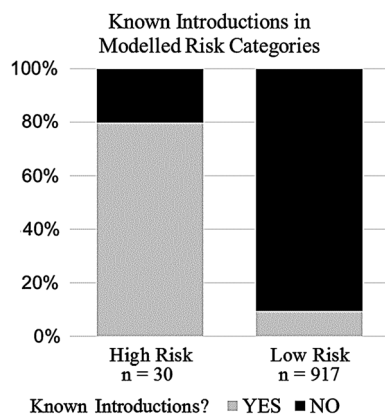


**Table 1** A subset of the variable combinations used in GLM models. The lowest AIC values represent the models that best fit the data (gray highlighted section). Models with *ELEV* hadbetter fit and AIC values than models with *DIST<sub>i</sub>*. Models with *DIST<sub>i</sub>* had better fit and AIC values than with *DIST<sub>h</sub>*

Variables included	Residual deviance	AIC	Significance ( $\alpha < 0.05$ )
ELEV*POP*FISH	456 on 939 df	472	Some variables significant
ELEV + POP + FISH + ELEV:POP	462 on 942df	472	All significant
SIZE*DIST <sub>i</sub> *POP*FISH	448 on 931 df	480	Some variables significant
ELEV + FISH	474 on 944 df	481	Both significant
ELEV*FISH	474 on 943 df	482	ELEV significant
ELEV + POP + FISH	474 on 943 df	482	ELEV, FISH significant
ELEV*POP	522 on 943 df	530	All significant
ELEV	538 on 945 df	542	significant
DIST <sub>i</sub>	548 on 945	552	Significant
DIST <sub>h</sub>	556 on 945	560	Significant
FISH	583 on 945 df	587	Significant
POP	672 on 945 df	676	Significant
SIZE	679 on 945 df	683	Marginally insignificant
SIZE*ELEV*POP*FISH	7281 on 931 df	7313	All significant

Variables: SIZE (lake size), ELEV (elevation), DIST<sub>i</sub> (distance-to-nearest introduction), DIST<sub>h</sub> (distance to maj. Highway), POP (human pop. w/in 10-mi.), FISH (fishing pressure)

+ indicates variables without an interaction, : indicates an interaction, \* indicates both

**Fig. 5** Lakes placed into “Low” and “High Risk” categories by the Introduction Vulnerability Equation are shown as bar plots. The percent of lakes with known illegal introductions is shown in gray and those without in black

et al., 2005) and Bull Trout (Kovach et al., 2018). Additionally, we propose that preventative measures be first implemented for “High Risk” lakes where healthy populations of sensitive species are found (Table 2).

The majority of illegally introduced fishes in our study were warm or coolwater species, not coldwater

species (Fig. 2). The native abundance and history of government-sanctioned salmonid stocking (Johnson et al., 2009) likely explains why trout species make up such a small portion (6.4%) of these introductions. Preventing the further spread of warmwater fishes is highly important for preserving valuable sport fisheries and native species assemblages (Koel et al., 2005; Carey et al., 2011). For example, Kaufman et al. 2009 found the combined impact of illegally introduced Smallmouth Bass and over-exploitation had detrimental impacts to native Lake Trout populations, prompting government agencies to consider alternative management actions.

Our study addresses the spread of illegal fish introductions through human vectors and therefore does not explicitly consider factors such as propagule pressure, temperature, and habitat that are related to the persistence and spread of introduced species (Jeschke & Strayer, 2006; Marr et al., 2010). However, examined variables such as waterbody size and elevation do implicitly account for some abiotic and biotic factors for which data were not available. Future research may benefit from the inclusion of other environmental variables that were unavailable for this

**Table 2** Lakes at “High Risk” for illegal fish introductions in Region 1 according to the vulnerability index

Lake name	County	Vulnerability Index	Species of concern
Smith Lake <sup>a</sup>	Flathead	565.5	NONE
Bull Lake <sup>a</sup>	Lincoln	409.6	BULL, PWF, WCT
Hungry Horse Reservoir	Flathead	401.3	BULL, PWF, WCT
Middle Foy Lake	Flathead	157.0	NONE
Timber Lake	Lincoln	82.9	NONE
Lower Foy Lake	Flathead	73.4	NONE
Flathead Lake	Flathead	2226.4	BULL, PWF, WCT
Noxon Rapids Reservoir	Sanders	2007.1	BULL, WCT
Lake Mary Ronan	Lake	1509.6	WCT
Echo Lake	Flathead	959.2	NONE
Thompson Lake, Middle	Lincoln	667.5	NONE
Swan Lake	Lake	577.6	BULL, PWF, WCT
Whitefish Lake	Flathead	570.4	BULL, PWF, WCT
Little Bitterroot Lake	Flathead	556.4	PWF
Cabinet Gorge Reservoir	Sanders	516.7	BULL, WCT
Foy Lake	Flathead	439.8	NONE
Blanchard Lake	Flathead	347.3	NONE
Lower Stillwater Lake	Flathead	317.4	WCT
Thompson Lake, Lower	Sanders	241.7	NONE
Dickey Lake	Lincoln	230.5	BULL
Thompson Falls Reservoir	Sanders	180.6	BULL
Thompson Lake, Upper	Lincoln	169.0	NONE
Glen Lake	Lincoln	135.3	BULL
Savage Lake	Lincoln	101.1	WCT
Ashley Lake	Flathead	100.7	PWF, WCT
McWeneger Slough	Flathead	98.0	NONE
Mcgregor Lake	Flathead	65.2	NONE
Island lake	Lincoln	59.8	NONE
Kilbrennan Lake	Lincoln	49.6	RB
Triangle Pond	Sanders	32.1	WCT

The sensitive species found within each waterbody is provided. Lakes above the dividing line have no record of illegal introductions while those below do  
*BULL* Bull Trout, *PWF* Pygmy Whitefish, *WCT* Westslope Cutthroat Trout, *RB* redband trout

<sup>a</sup>Contains Northern Pike—possibly illegally introduced

study such as water temperature and habitat. Interestingly, top social and physical variables in our analysis did not include distance-to-nearest illegal introduction (i.e., spatial autocorrelation) as a major driver of introductions. While “natural” spread of reproducing populations from illegal introductions certainly occurs in northwest Montana, our data suggest a high willingness of “bucket biologists” to transport species long distances (e.g., Bourret & Clancy, 2018). However, distance-to-nearest introduction is not a static variable like waterbody size or elevation, and changes with increased numbers of introductions. While our data were calculated post hoc and therefore do not account for this change over time, distance was a poor

predictor of introductions. However, two of the three waterbodies with more than 10 instances of illegal introduction (Banana Lake and Lion Lake) are near a major highway and the third waterbody (Tetrault Lake) is accessible via a state-operated fishing access site (Supplement 1). All three lakes were placed in the “Low Risk” category by our equation, likely indicating that some measure of accessibility is still an important factor to some anglers wishing to illegally introduce fish, even if not easily captured by the variables included in this analysis. These three lakes are indicative of the fact that different anglers have different priorities. Indeed, while our equation was relatively accurate in determining overall propensity



for illegal introductions, there were still 88 waterbodies with known illegal introductions that were placed in the “Low Risk” category. This may indicate that illegal introductions are highly idiosyncratic or that some latent social or physical variable, not included in our analysis, drives illegal introductions in these waterbodies.

We recognize that completely stopping all illegal fish introductions is impossible. However, preventative measures such as increased presence of game wardens, educational outreach activities, witness rewards, and signs warning anglers about the legal ramifications of dumping fish, are among the few tools available for deterrence (Rahel & Smith, 2018). Quantitatively informed decisions about where these measures may be most effective are only possible when agency personnel take the time to record all instances of illegal introductions in a common database. Many authors of scientific studies suggest that biologists collect yet more data (e.g., Murphy & Noon, 1991), and this study is no exception. But keeping records of introductions takes minimal effort on behalf of local fisheries biologists and consistent curation by individuals within a region may allow for the development of a vulnerability index most applicable to that area. Indeed, Rahel and Smith (2018) were able to create such a database retroactively by collating information from state fisheries reports, peer-reviewed articles, university theses, and personal communications from regional biologists. While we do not suggest our specific equation be applied outside of northwestern Montana, we believe this study serves as further example of the utility of this type of data and provides a method by which it can be useful. We used an approach similar to that employed by Marchetti et al. (2004) who used logistic regression to determine what life history traits led some non-native fishes to become established in California waterbodies. However, other techniques may also prove useful for this type of data.

While the role of invasive species in the decline of natives is well documented and understood (Cambray, 2003), both authorized and unauthorized stocking of non-native species remain common. In Montana, for example, at least 5.6 million non-native fishes were legally stocked in 2018 in both artificial and natural stillwaters and at least three streams (Montana Fish, Wildlife & Parks, 2019). However, potential impacts of such introductions are usually carefully weighed by

agency personnel and conducted where non-natives are already naturalized (Rahel, 2004). Unauthorized facilitation of species invasion, on the other hand, is conducted outside established processes, is known to often harm native species, and is becoming an increasingly large pathway by which freshwater ecosystems are altered (Johnson et al., 2009). These alterations can in turn lead to catastrophic changes to ecosystem structure and function (Vitule et al., 2009). Therefore, new tactics and strategies for stemming the tide of continued species invasion must continue to be developed.

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**Data availability** Data are freely available and provided as an Excel file and accompanying R code as supplementary information.

#### Compliance with ethical standards

**Conflict of interest** The authors declare that they have no conflicts of interest.

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