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Invasion risk to the United States from *Arapaima* spp. hinges on climate suitability

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ABSTRACT: Fish in the South American genus *Arapaima* Müller, 1843 (hereafter referred to as arapaimas) have attracted interest for commercial aquaculture development thanks to their rapid growth rate and high market value. However, management agencies in the United States have expressed concerns about importing and culturing arapaimas due to records of non-native establishment in certain other countries where arapaimas were released or escaped from captivity. We used the Freshwater Fish Injurious Species Risk Assessment Model (FISRAM) to estimate the probability that arapaimas would be injurious (able to cause harm) to native ecosystems, humans, or the economy of the contiguous United States. Risk assessment model inputs were elicited from arapaima experts around the world. Model results were sensitive to the estimation of climate suitability for arapaimas within the contiguous United States, with predicted probability of injuriousness ranging from 0.784 down to 0.321 with different climate suitability inputs. Expert assessors predicted that competition and predation on native species would be the most likely mechanism of impact and expressed a high degree of uncertainty about potential for impacts from pathogens and parasites. We concluded that due to the cold sensitivity of these tropically adapted fish, establishment within the contiguous United States would be highly restricted geographically, limiting potential impacts if introduced outside climatically suitable areas. Existing regulations already mitigate risk of escape from aquaculture in areas where establishment is plausible, but further research into arapaima parasites and pathogens would help reduce uncertainties and suggest opportunities to enhance biosecurity measures if needed.

KEY WORDS: Arapaima · Pirarucu · Risk assessment · Climate matching · Invasive species · Fish · Freshwater · North America

1. INTRODUCTION

The large Amazonian bony fishes commonly known as arapaima, pirarucu, or paiche (genus *Arapaima* Müller, 1843) have garnered particular interest for commercial aquaculture development due to their rapid growth rate and high market value (Valladão et al. 2018, Ohs et al. 2021). Also present in the global

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aquarium trade (Nijman 2010, Magalhães et al. 2017), arapaimas have been captured, cultured, and transported around the world to 28 countries on 5 continents (Pereira et al. 2022). In the United States, over 12 000 live arapaimas (reported as *A. gigas* [Schinz 1822]) were legally imported for commercial purposes between 2017 and 2021 (Convention on International Trade in Endangered Species of Wild Fauna and Flora [CITES] Trade Database 2023).

Export of *A. gigas* from its native range is regulated under CITES as a response to overfishing and declines in native populations. *A. gigas* and other *Arapaima* species are large-bodied, obligate air-breathing fishes that are susceptible to harvest via gill nets, harpoons, spears, and other techniques (Castello & Stewart 2010). Despite the vulnerable position of arapaimas within their native range, there are risks inherent in transporting them to locations outside the native range. Arapaimas have established non-native populations in southeastern Brazil, Bolivia, Peru, India, and Indonesia after escaping captivity during natural disasters or after intentional release (Miranda-Chumacero et al. 2012, Kumar et al. 2019, Doria et al. 2020, Marková et al. 2020, Bueno et al. 2021, Catâneo et al. 2022). Introduced arapaimas are suspected to harm native fish populations in some areas through predation and competition (Miranda-Chumacero et al. 2012, Van Damme et al. 2015, Fadjar et al. 2019). However, there have been very few attempts to measure the impacts of their introductions, and these attempts have been focused on consequences to commercial and artisanal fisheries rather than local ecosystems (Van Damme et al. 2017, Doria et al. 2020). It is unknown whether arapaima translocations have resulted in disease or parasite introductions that have negatively affected native fishes or locally adapted arapaima populations (e.g. genetically distinct subpopulations identified by Farias et al. 2019; see also Sousa et al. 2022).

Growing interest in arapaima aquaculture in the State of Florida in the United States prompted Hill & Lawson (2015) to assess the risk of invasiveness of arapaimas within that state using the Freshwater Invasiveness Screening Kit (FISK; Lawson et al. 2013). They concluded that arapaimas posed a medium risk of becoming invasive in Florida, and that low tolerance for cold temperatures would restrict potential populations to south or southeast Florida. The Florida Fish and Wildlife Conservation Commission (FFWCC) used these results to inform implementation of conditional restrictions on arapaima aquaculture (Hill & Lawson 2015), and the Florida Department of Agriculture and Consumer Services (FDACS) has allowed culture of arapaimas to proceed under strict adherence to a set of Best Management Practices (BMPs) to prevent their release into natural waterways (FDACS 2022). However, subsequent reports of deceased arapaimas discovered in the wild in Louisiana (in 2016) and Florida (in 2020; USGS 2023a), coupled with uncertainty over the impact of climate change on future establishment potential via increased environmental temperature, renewed management agency concerns about arapaima invasion within Florida and beyond. Although the origin of the Louisiana specimen is unknown, the Florida specimen was apparently released after being stolen from an aquaculture facility in southwest Florida. Its farm origin was verified by the presence of a passive integrated transponder (PIT) tag that the owner had placed in the animal (FFWCC 2021).

Responding to management agency concerns, we present a new assessment of the risk of arapaimas becoming injurious to native ecosystems, humans, or the economy of the contiguous United States. The outcome of 'injuriousness' acknowledges that, under certain circumstances, an introduced species can cause direct harm without establishing and spreading in the wild (e.g. venomous species, pathogen hosts; Marcot et al. 2019). We assessed arapaima injuriousness using the Freshwater Fish Injurious Species Risk Assessment Model (FISRAM; see our Fig. 1; Marcot et al. 2019), which allowed assessors the flexibility to integrate both the available published literature and their own expert knowledge into the assessment.

2. MATERIALS AND METHODS

2.1. Note on arapaima taxonomy

Although 5 arapaima species have been described based on morphology (Stewart 2013a,b, and references therein), all published assessments of arapaima population structure in the past 2 decades have been based on genetics alone (e.g. Farias et al. 2019) and thus, there remain uncertainties about status and distribution of those nominal taxa. Integrative analyses simultaneously comparing genetics and morphology are needed to resolve those uncertainties (e.g. Oliveira et al. 2020). In the absence of better information, much of the available biological and distributional information has defaulted to the earliest scientific name, *Arapaima gigas*. We sought to consider these information limitations in the risk assessment inputs and interpretation of the results.

2.2. Background on FISRAM

We conducted the risk assessment using FISRAM, described by Marcot et al. (2019). FISRAM is a Bayesian belief network used to predict the probability of injuriousness of a non-native freshwater fish species based on species traits and expected interactions with the landscape into which the species is introduced. The model calculates a posterior probability distribution across 3 states of injuriousness, defined as follows (from Marcot et al. 2019): (1) Yes: Invasive — significant harm coupled with medium to high establishment and spread potential; (2) No: Not invasive — low establishment potential, low spread potential, and insignificant harm; and (3) Evaluate Further — species has low potential for spread and establishment, but has high potential for harm. The model was tested and calibrated using data on 50 fish species introduced outside their native ranges with known outcomes; for every test case, the model was able to predict the correct outcome (Marcot et al. 2019).

In FISRAM, the predicted probability of injuriousness is based on 11 input variables, each with 3 possible states (Fig. 1, Table 1; Table S1 in the Supplement at www.int-res.com/articles/suppl/q016p175_supp.pdf). Seven input variables (Habitat Disturbance, Predation, Competition, Bites & Toxins, Genetics, Pathogens, and Other Trait [e.g. zoonotic, physical impact]) relate to injuriousness via a latent variable representing overall harm caused by the non-native species introduction. Four additional input variables (Human Transport, Non-Human Dispersal, Habitat Suitability, and Climate 6 Score) relate to injuriousness via latent variables representing transport, establishment, and spread of the non-native species (Fig. 1).

2.3. Assessor recruitment and model inputs

The assessment facilitator (K. Wyman-Grothem) invited participants to join the risk assessment process based on authorship of published literature on arapaima biology, ecology, and introductions. Efforts were made to identify a diverse group of potential participants, representing different subfields of bio-

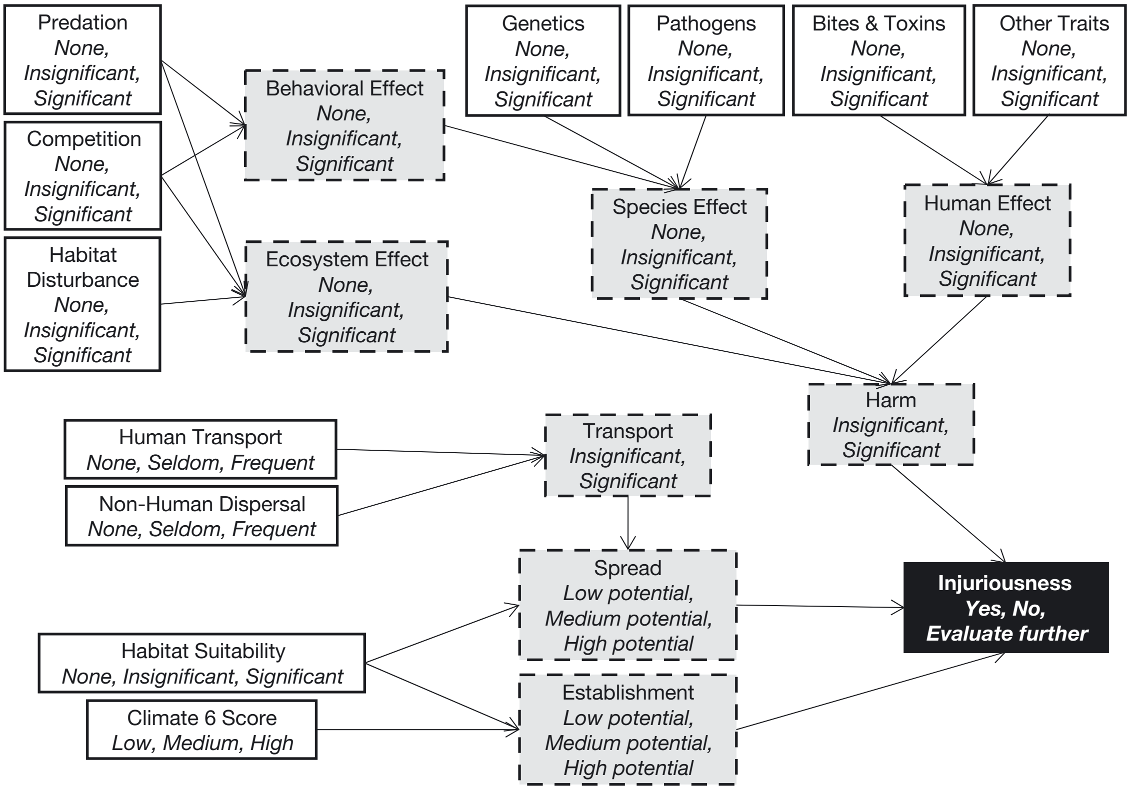

Fig. 1. Freshwater Fish Injurious Risk Assessment Model (FISRAM) influence diagram. Each box represents a variable in the model, with the variable name (plain text) given above its possible states (*italics*). White boxes: input variables; gray boxes with dashed borders: latent variables; black box: model output; arrows: relationships between variables (arrow pointing in the direction of influence). See our Table 1 & Table S1 or Marcot et al. (2019) for variable and state definitions

Table 1. Input variables for the Freshwater Fish Injurious Species Risk Assessment Model (FISRAM; Marcot et al. 2019) and their definitions. Potential states of each input variable listed in *italics*. See Table S1 for unique definitions for each variable state. For further examples and references, see the supplementary material in Marcot et al. (2019). GMO: genetically modified organism; WOAH: World Organisation for Animal Health

Input variable	Definition and variable states
Habitat Disturbance	The capacity of the non-native species to cause habitat modification (erosion, siltation, bank stability, eutrophication, sedimentation, etc.) thus causing destruction, degradation, alteration of nutrient pathways, trophic effects, etc. for affected species (*None*, *Insignificant*, *Significant*)
Predation	The capacity of the non-native species to prey on affected native species, adversely affecting native populations (*None, Insignificant, Significant*)
Competition	The capacity of the non-native species to adversely affect native species through competition for food, space, or habitat (*None, Insignificant, Significant*)
Bites & Toxins	Direct adverse effect on human health from bites, stings, or other injections, ingestion, skin contact, or absorption of venom from the non-native species; or other consequences that lead to illness. Does not include effects from captive individuals; includes effects from wild and free-roaming individuals (*None, Insignificant, Significant*)
Genetics	The capacity of the non-native species to adversely affect populations of the native species through direct genetic influences including hybridization, GMOs, and introgression (*None, Insignificant, Significant*)
Pathogens	Epizootic; Infectious diseases are caused by pathogenic microorganisms such as bacteria, viruses, parasites, or fungi; these pathogens and parasites can be spread, directly or indirectly, from one animal to another. Includes pathogens that cause WOAH-reportable diseases (*None, Insignificant, Significant*)
Other Traits (e.g. zoonotic, physical impact)	Pertains to species traits that could impart adverse effect on human health from other than bites and toxins that lead to illness, injury, paralysis, or death; or any other trait that characterizes any form of risk to humans (*None, Insignificant, Significant*)
Human Transport	Any assistance (whether intentional or unintentional) by humans for moving the subject species from one location to another and introducing the species into an environment beyond a range where it was established and can move from on its own (*None, Seldom, Frequent*)
Non-Human Dispersal	Any assistance by non-human agents for moving the subject species from its current range beyond a range where it can move on its own (*None, Seldom, Frequent*)
Habitat Suitability	Habitat that matches the known habitats of the species, whether in the indigenous or invasive range of the species (*None, Insignificant, Significant*)
Climate 6 Score	Proportion of target points scoring above the median possible value for climatic similarity with established locations of the species (*Low, Medium, High*)

logy and different known arapaima populations. Within the email invitation to participate, the facilitator provided potential participants with background on FISRAM (Marcot et al. 2019) and a published example of FISRAM application to another species (Wyman-Grothem et al. 2018). The facilitator communicated with each participant separately until after the assessors provided their initial inputs to the model.

Seven experts from Brazil, the United States, and the Czech Republic (co-authors L. Castello, D. T. B. S. Catâneo, C. R. C. Doria, A. L. B. Magalhães, J. Patoka, D. Stewart, and C. Watson) agreed to participate in the project, representing expertise in arapaima taxonomy, biology, ecology, introduction history, and aquaculture. Together, the participating experts had experience with wild populations of arapaimas in both the native and introduced ranges, as well as with captive populations. The facilitator asked each expert assessor to use the literature and their own expert opinion to assign a predicted probability distribution to the 3 states of each of 10 input variables (all input variables except Climate 6 Score; see Section 2.4 for alternative method for Climate 6 Score) and provide justification for those probability distributions within a provided spreadsheet. Except for one pair of assessors (C. R. C. Doria and D. T. B. S. Catâneo) who provided joint inputs, any assessors who happened to know the identity of other assessment participants were discouraged from discussing their inputs with each other prior to initial submission to the facilitator.

Assessors were given written definitions for all input variables and their possible states from Marcot et al. (2019; our Table 1, Table S1) as well as a copy of the US Fish and Wildlife Service (USFWS) Ecological Risk Screening Summary (ERSS) report on *A. gigas*

(USFWS 2022). ERSS reports serve as a precursor to the FISRAM process under the decision advisory system presented in Marcot et al. (2019). Each report contains a summary of the available literature relevant to assessing potential injuriousness of a species and a climate matching analysis (see Section 2.4) for the contiguous United States.

After all assessors had submitted their inputs, the facilitator combined and anonymized the predicted probabilities and justifications for each input variable across all assessors. The collection of inputs was shared with assessors via email, initiating a 10 d written discussion period to share knowledge and better understand differences of opinion. The choice to use written discussion was intended to reduce bias due to different levels of fluency in spoken English among the assessors. All assessors participated in the discussion but only one chose to revise their inputs afterward.

2.4. Climate 6 Score

Climate 6 Score is a statistic measuring climatic similarity between locations of established populations of a species and target locations to which it could be introduced (Bomford et al. 2010). Assessors were not asked to provide predicted probabilities for the variable of Climate 6 Score. Instead, the value for this input variable was taken from the climate matching analysis included in the *A. gigas* ERSS (USFWS 2022), as intended by the developers of FISRAM (Marcot et al. 2019). The ERSS climate matching analysis quantified climatic similarity between target locations across the contiguous United States and global occurrences of established arapaima populations, obtained from the Global Biodiversity Information Facility (GBIF; GBIF Secretariat 2021). All georeferenced occurrences of arapaimas in GBIF have been reported as *A. gigas*, which we interpreted to represent occurrences of *Arapaima* spp. (see Section 2.1). The analysis was implemented in the Risk Assessment Mapping Program (RAMP; version 4.0; Sanders et al. 2021, USFWS 2023) using 16 bioclimatic variables (Table 2) and CHELSA version 2.1 global climate data layers (Karger et al. 2017, 2018).

The climate matching analysis in the ERSS used the CLIMATE algorithm developed by Pheloung (1996, Crombie et al. 2008) to calculate a target point score for each of 33 461 target points distributed on a 15 km grid across the contiguous United States (Sanders et al. 2021) and then summarized the set of target point scores with the Climate 6 Score statistic. Individual target point scores were calculated as:

$$\text{target point score}_j = \text{floor}\left\{\left[1-\min_{i\in\text{sites}}\left(\sqrt{\frac{1}{k}\sum_k\frac{(y_{ik}-y_{jk})^2}{\sigma_k{}^2}}\right)\right]\times 10\right\} \quad (1)$$

where k is the number of bioclimatic variables (Table 2), i indexes global source locations, j indexes target locations, y_{ik} is the k^{th} climate variable for the i^{th} source location, y_{jk} is the k^{th} climate variable for the j^{th} target location, and $\sigma_k{}^2$ is the variance of all global points for the k^{th} climate variable (Pheloung 1996, Crombie et al. 2008). The minimum function selects the source location with the closest match to the j^{th} target as the location on which to base the overall score for that target point. Possible target point scores range from 0 to 10. A target point score of 0 indicates no climate similarity between the target point and locations of established populations, while a target point score of 10 indicates a perfect match between the target point and locations of established populations.

The Climate 6 Score was obtained from the target point scores by calculating the proportion of target points scoring above the median possible value for climatic similarity, i.e. 6 or higher on the 0–10 scale (USFWS 2023). According to the *A. gigas* ERSS, the

Table 2. Sixteen derived bioclimatic variables used by the Risk Assessment Mapping Program (RAMP; Sanders et al. 2021) to evaluate climate similarity. Quarter: period of 3 mo. Variable values obtained from CHELSA 2.1 (Karger et al. 2017, 2018). Temperatures reported in °C and precipitation amounts in mm

Code	Description
bio1	Mean annual air temperature
bio5	Mean daily maximum air temperature of warmest month
bio6	Mean daily minimum air temperature of coldest month
bio7	Temperature annual range (bio5–bio6)
bio8	Mean daily mean air temperature of wettest quarter
bio9	Mean daily mean air temperature of driest quarter
bio10	Mean daily mean air temperature of warmest quarter
bio11	Mean daily mean air temperature of coldest quarter
bio12	Annual precipitation amount
bio13	Precipitation amount of wettest month
bio14	Precipitation amount of driest month
bio15	Precipitation seasonality (coefficient of variation)
bio16	Mean monthly precipitation amount of wettest quarter
bio17	Mean monthly precipitation amount of driest quarter
bio18	Mean monthly precipitation amount of warmest quarter
bio19	Mean monthly precipitation amount of coldest quarter

Climate 6 Score for *A. gigas* in the contiguous United States was 0.017 (USFWS 2022), which is classified as a Medium match (our Table S1; Marcot et al. 2019). Therefore, when running FISRAM for each set of assessor inputs, the facilitator plugged in the probability of 1.0 for the Medium state of Climate 6 Score.

2.5. Model outputs

After obtaining the assessors' inputs (revised after group discussion as desired), the facilitator conducted separate runs of FISRAM for each set of the 6 sets of assessor inputs (Table S2) using the Bayesian network development software Netica (version 6.05, Norsys Software). Predicted probability distributions for injuriousness from each individual model run were then averaged to obtain mean predicted probabilities.

2.6. Climate match sensitivity analysis

One assessor shared concerns about the climate matching analysis in the ERSS based on past experience with arapaimas in Florida, suggesting that the Climate 6 Score may overestimate climate suitability in the contiguous United States because the model does not incorporate lower lethal temperature as a hard constraint on a species' ability to establish a new population. With the support of all assessors to investigate the issue further, the facilitator repeated the runs of FISRAM for each individual assessor's inputs with alternative probability distributions for the Climate 6 Score variable. The alternative probability distributions considered were (1) all probability assigned to the Low state of Climate 6 Score; and (2) probability evenly divided between Medium and Low states of Climate 6 Score. In these repeated runs, no other inputs were changed.

3. RESULTS

3.1. Assessor inputs related to potential harm

Assessors predicted that arapaimas introduced to the contiguous United States would have potential to cause harm, particularly through the mechanisms of predation and competition (Fig. 2). In their written justifications, assessors referenced the wide range of potential prey items for arapaimas and the energetic requirements of rapid growth to a large body size. Some also noted the lack of studies to date on competition between arapaimas and potential competitors and that environmental limits on the establishment of arapaimas would restrict interactions with native species. Most if not all assessors predicted no impacts due to habitat disturbance, bites or toxins, or genetic effects on native species (Fig. 2). A single assessor expressed concern about potential injury to aquacul-

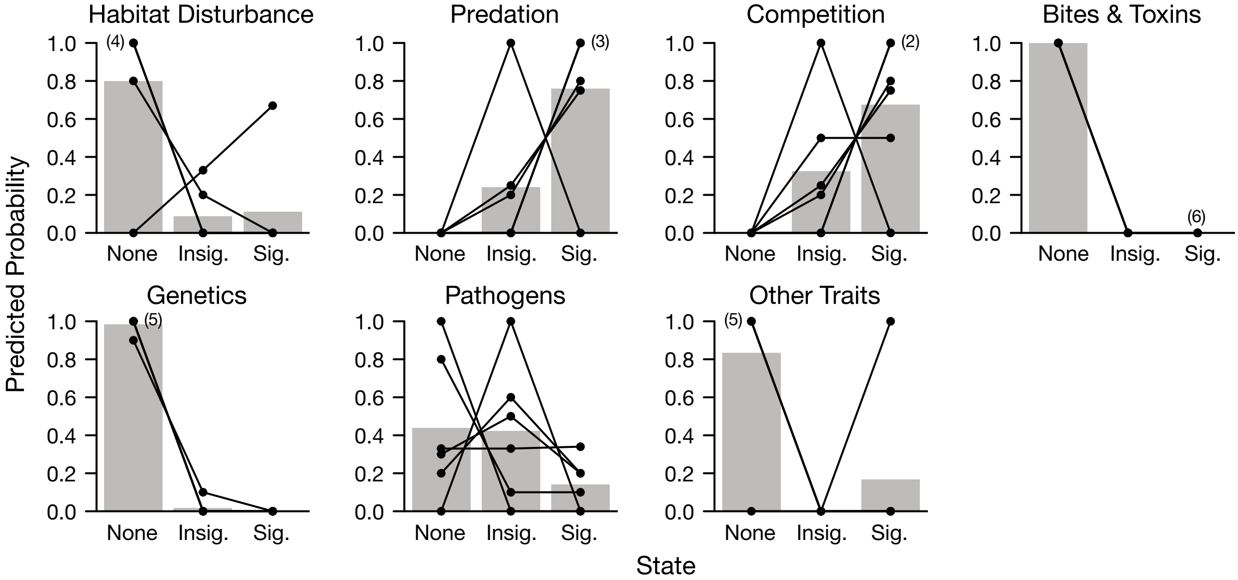

Fig. 2. Predicted probabilities for harm-related inputs to the Freshwater Fish Injurious Species Risk Assessment Model (FISRAM; Marcot et al. 2019), applied to the genus *Arapaima* within the contiguous United States. Solid bars: mean predicted probabilities; connected points: sets of individual assessor-predicted probabilities. Where multiple assessors supplied the same predicted probabilities, numbers in parentheses indicate the number of assessors with that set of predicted probabilities. Insig.: Insignificant; Sig.: Significant

ture workers (included under Other Traits) if these large fishes are improperly handled.

Across possible mechanisms for causing harm to native species or humans, the predicted impact from pathogens was the most variable across assessors (Fig. 2). In their written justifications, several assessors mentioned a lack of information about arapaima parasites and pathogens, including information on host specificity and the susceptibility of native US biota. For example, one wrote: 'To the extent pathogens are host specific (not well known for arapaima), there are no closely related fishes to arapaima in the [United States], and that could limit disease transfers. Since there have been no experiments to evaluate such possible transfers, natural experiments will start should they become established in the wild.'

3.2. Assessor inputs related to potential transport, establishment, and spread

Assessors agreed that human transport of arapaimas occurs for both aquacultural and ornamental purposes (Fig. 3). Some assessors noted that the large body size of older arapaimas could affect rates of human transport, leading to aquarium dumping if owners cannot accommodate the fish's size but reducing the frequency of transport between water bodies.

On the probability of non-human dispersal of arapaimas, predictions were variable (Fig. 3); one assessor wrote that escape from aquaculture facilities is rare, while another wrote about personal observations of arapaimas jumping over or digging under barriers. Several assessors mentioned that the genus is capable of unassisted spread through connected waterways.

Assessors predicted that at least a small amount of habitat suitable for arapaima establishment exists in the contiguous United States (Fig. 3). Many noted the importance of lentic habitat availability, especially floodplain habitat, and appropriate thermal conditions. Beyond temperature, assessors expressed divergent views on the sensitivity of the species to other abiotic environmental characteristics.

3.3. Model predictions of injuriousness and climate match sensitivity

Mean predicted probability that arapaimas would be injurious within the contiguous United States was 0.784 (range: 0.432–0.994 for individual assessors), assuming Medium Climate 6 Score (Fig. 4A). Mean predicted probability that the fish would not be injurious was 0.152 (range: 0.005–0.491). Mean predicted probability of the Evaluate Further state was 0.064 (range: 0.001–0.178).

When different probabilities were assigned to the possible states for the Climate 6 Score, the mean predicted probability of the Yes state of injuriousness decreased, down to 0.576 under the intermediate scenario (0.5 probability of Medium Climate 6 Score, 0.5 probability of Low Climate 6 Score) and to 0.321 under the Low Climate 6 Score scenario (Fig. 4B,C). The No state of injuriousness did not change substantially across scenarios (range of mean predicted probabilities: 0.133–0.162), but the Evaluate Further state (high potential for harm, low potential for establishment and spread) increased such that it had the highest mean predicted probability (0.517) of all 3 states under the Low Climate 6 Score scenario.

4. DISCUSSION

Drawing on published literature and expert opinion, our FISRAM analysis of arapaima injuriousness

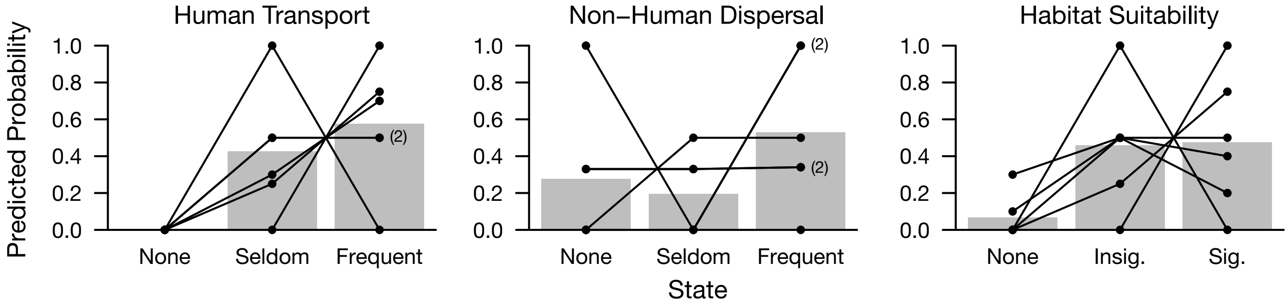

Fig. 3. Predicted probabilities for transport-, establishment-, and spread-related inputs to the Freshwater Fish Injurious Species Risk Assessment Model (FISRAM; Marcot et al. 2019), applied to the genus *Arapaima* within the contiguous United States. Solid bars: mean predicted probabilities; connected points: sets of individual assessor-predicted probabilities. Where multiple assessors supplied the same predicted probabilities, numbers in parentheses indicate the number of assessors with that set of predicted probabilities. Insig: Insignificant; Sig.: Significant

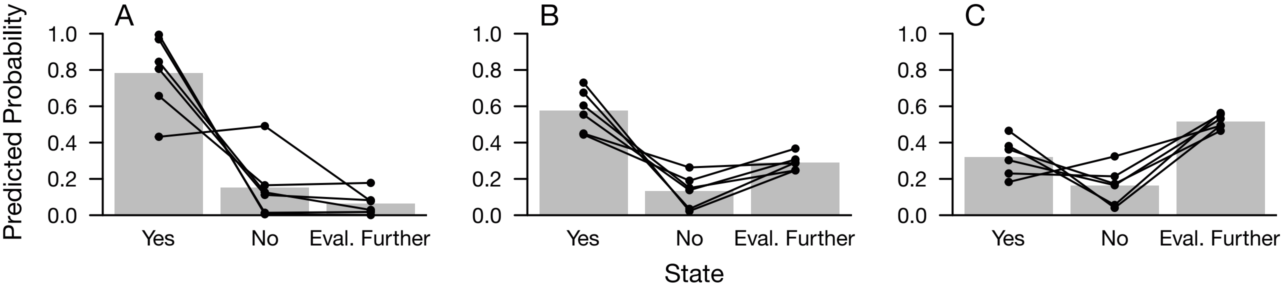

Fig. 4. Posterior predicted probabilities for states of injuriousness from the Freshwater Fish Injurious Species Risk Assessment Model (FISRAM; Marcot et al. 2019), applied to the genus *Arapaima* within the contiguous United States. Three possible probability scenarios for the input variable of Climate 6 Score were considered: (A) 1.0 probability for the Medium state; (B) 0.5 probability for the Medium state and 0.5 probability for the Low state; and (C) 1.0 probability for the Low state. Solid bars: mean predicted probabilities; connected points: sets of individual assessor-predicted probabilities. Eval. Further: Evaluate Further

concluded that introduced arapaimas could cause harm within the contiguous United States, particularly through competition and predation on native species. Potential for harm from arapaima parasites and pathogens represented a source of uncertainty in the overall prediction of harm. The climate match sensitivity analysis showed that varying predictions of climate suitability for the contiguous United States affect the predicted probability of an injurious outcome for arapaima introduction. The probability of an injurious outcome declined with decreasing climate suitability, although lower climate suitability did not increase the probability of a non-injurious outcome. Instead, lower climate suitability increased the probability of substantial harm without substantial establishment or spread. For arapaimas, harm potential is likely to be greatest in areas where they can establish and have long-term impacts, but some degree of harm may also be possible even without establishment.

4.1. Potential impacts of arapaima introduction on native species and ecosystems

Most assessors' predictions about the predatory and competitive impacts of arapaimas in the contiguous United States reflected the presumed impacts of non-native arapaimas on native fish populations elsewhere in the world (e.g. Miranda-Chumacero et al. 2012, Van Damme et al. 2015, Fadjar et al. 2019). In the absence of both stringent requirements for containment and effective oversight, arapaima aquaculture may facilitate introductions into natural environments and endanger important species (Casimiro et al. 2018, Brosse et al. 2021, Raj et al. 2021). These global observations highlight the risk associated with arapaima introduction in regions such as the southeastern United States, a global hotspot for freshwater biodiversity with a relatively high proportion of threatened and range-restricted species, including fishes (Jelks et al. 2008, Collen et al. 2014). Based on current knowledge of arapaima diets (e.g. Watson et al. 2013, Carvalho et al. 2018, Jacobi et al. 2020), potential prey species of arapaimas in the southeastern United States could include commercially and recreationally valuable fishes (Clupeidae, Centrarchidae; Murray et al. 2020, FFWCC 2023), small-bodied native freshwater fishes (e.g. eastern mosquitofish *Gambusia holbrooki* and Seminole killifish *Fundulus seminolis*), euryhaline fishes (e.g. common snook *Centropomus undecimalis*), crustaceans (e.g. riverine grass shrimp *Palaemonetes paludosus*; Everglades crayfish *Procambarus alleni*) and amphibians (J. Gálvez, USFWS, pers. comm. 2023). Potential competitors for fish, invertebrate, and amphibian prey could include native Florida bass *Micropterus floridanus*, wading birds, and alligators *Alligator mississippiensis* (Taylor et al. 2019, J. Gálvez pers. comm. 2023). In the input variable definitions provided to assessors, predictions of harm were not conditional on establishment. However, if climatic constraints on establishment are considered (see Section 4.2), predatory and competitive impacts of arapaimas on native species are more likely to be localized and transitory when the landscape lacks thermal refuges for arapaimas to overwinter.

Potential impacts of parasites and pathogens of arapaimas remain a significant source of uncertainty in the overall prediction of harm. Pathogens and parasites do not necessarily exhibit the same physiological tolerances as their hosts (Möller 1978, Franke et al. 2017), leaving the door open for non-host-specific pathogens or parasites to survive and cause harm in areas where arapaimas are unable to do so. Therefore, it is crucial to have effective sanitary inspection of imported fish. Infection of arapaimas by both host-specific and generalist pathogens has been documented (e.g. Marinho et al. 2013), as has at least 1 example of a parasite with zoonotic potential (Andrade-Porto et al. 2015). Although none of the 11 important fish diseases listed by the intergovernmental World Organisation for Animal Health (WOAH) have been documented in arapaimas (USFWS 2022, WOAH 2022), and there have been no reports to date of novel disease agents or significant disease issues in native fishes due to arapaima importation into the United States (CITES Trade Database 2023), rigorous sanitary measures and surveillance protocols remain essential to monitor and mitigate potential pathogen risks associated with arapaima imports.

4.2. Model sensitivity to climate match

The CLIMATE algorithm (Pheloung 1996), implemented in this study using RAMP (Sanders et al. 2021), can be a useful tool for rapid assessment of establishment potential across diverse non-native species (Bomford et al. 2009, 2010, Howeth et al. 2016, Moghaddas et al. 2020). The major advantages of this method include speed and simplicity due to the use of a standard set of continuous climate variables with global availability (Table 2). However, if the standard set of climate variables and their equal weighting by the algorithm are not appropriate for the species in question (e.g. a species highly sensitive to temperature but less sensitive to rainfall patterns, or vice versa), inaccurate estimates of climate suitability may be produced, skewing the results of the FISRAM process.

An important question in our assessment was about the lower thermal tolerance of arapaimas. In a laboratory study, Lawson et al. (2015) determined that captive-reared juvenile *Arapaima gigas* had a lower lethal temperature of 16°C. These data were subsequently supported by observations from a fish farm in central Florida. Starting in 2017, the farm purposely left a small number of arapaimas weighing between 3 and 16 kg in uncovered ponds to assess whether they could survive the winter. To date, not a single fish has survived temperatures below 16°C (P. Price, Horse Creek Aquafarms, Arcadia, FL, pers. comm. 2023). In addition to survival, temperature plays a critical role in feeding, growth, and reproductive success, and therefore also in population establishment. In discussions subsequent to the formal FISRAM analysis, multiple assessors reported personal observations made on wild and captive populations that arapaimas show signs of stress and have difficulty adapting to temperatures below 20°C. Within the native range, arapaimas are found in waters that remain above 20°C (Castello 2008, Arantes et al. 2013, Pereira-Filho & Roubach 2013, Stokes et al. 2021). Although arapaimas have been imported to 28 countries, successful establishment of wild reproductive populations has been limited to tropical regions (Pereira et al. 2022). We remain unaware of any wild or captive populations of arapaimas established in waters colder than 16°C. However, as arapaima taxonomy is clarified (see Section 2.1), further studies may be necessary to understand any variability in thermal tolerance across species and populations.

Because RAMP does not have the flexibility to emphasize the cold sensitivity of arapaimas in its model of climate match to the contiguous United States, many areas regularly experiencing water temperatures below 16°C were predicted to be suitable for establishment (Fig. 5). Similar to observations of butterfly peacock bass establishment (Lawson et al. 2015), predictions for tropical catfish establishment (Tuckett et al. 2023), and earlier predictions for arapaima establishment (Lawson et al. 2015), the frequency of water temperatures below 16°C in most areas of the southeastern United States suggests that the most suitable areas for arapaima establishment are in southern Florida (Fig. 5). When the Climate 6 Score was reduced to the Low state to better match the data on temperature, the overall probability that arapaimas would be injurious to the contiguous United States fell by more than half, from 0.784 to 0.321 (Fig. 4). From this example, we believe FISRAM would benefit from a more flexible definition of its climate suitability variable, allowing users to employ other models if those models have more relevance for the species in question.

4.3. Climate change implications

Modeling studies for the Amazon Basin have predicted shifts in arapaima distribution due to climate change (Oberdorff et al. 2015, Dubos et al. 2022), and expanded establishment potential under climate change was one of the management agency concerns driving this risk assessment. Rapid risk screening appeared to support this concern. The Climate 6 Score of 0.017 calculated in the *A. gigas* ERSS (USFWS 2022) and used in the FISRAM analysis was based on global climate data from 1979–2013 (Karger et al. 2017, 2018). A previous version of the ERSS (USFWS 2019) had found a Climate 6 Score of only 0.002 based on global climate data from 1950–2000 (Hijmans et al. 2005). The difference in these scores translated to different Climate 6 Score states,

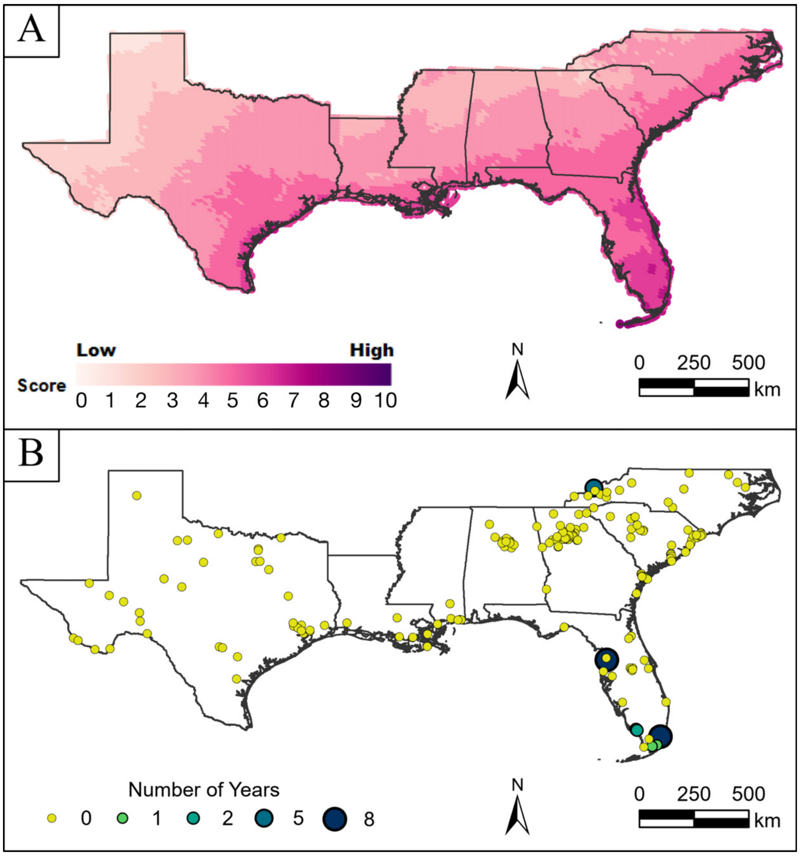

Fig. 5. (A) The Risk Assessment Mapping Program (RAMP; Sanders et al. 2021) estimated climate suitability for *Arapaima* spp. establishment in the southeastern United States (USFWS 2022), as compared to (B) the locations of US Geological Survey stream gages recording annual water temperature minimums above 16°C from 2014 through 2021 (USGS 2023b). In (B), the outlier on the northern boundary of the map represents a location 1.0 mile (1.6 km) downstream of a hydroelectric power plant, and the outlier near the base of the Florida peninsula represents a location with tidal influence. Methods used to create the map in (B) are described in the Appendix

Medium (0.017) versus Low (0.002). As discussed in the preceding section, however, neither of the Climate 6 Scores from the ERSS reports appropriately emphasized the cold sensitivity of arapaimas.

The effects of climate change on cold weather are complex. Although annual minimum temperatures across the southern United States have increased in recent decades and the number of subzero (°C) days have declined (Osland et al. 2021), the number of extreme cold events has increased as well (Cohen et al. 2021). Sudden temperature swings can have severe negative impacts on fish (Szekeres et al. 2016), and there is evidence that non-native tropical species like arapaimas are more susceptible to extreme cold events than native species (Boucek & Rehage 2014, Boucek et al. 2016, Lopez 2022). When these climate change patterns are considered alongside the cold sensitivity of arapaimas, it is unlikely that the establishment potential of arapaimas within the contiguous United States will expand considerably in the near future.

5. CONCLUSION

Because of their thermal tolerance, long-term survival of arapaimas in the wild in the contiguous United States is likely to be limited to the southeastern United States, particularly southern Florida and isolated warm water refuges elsewhere (Fig. 5). Further fine-scale modeling of invasion risk could assist managers in southern Florida with targeting prevention and surveillance efforts toward locations where arapaimas would be most likely to establish in the wild. Study of introduced populations elsewhere in the world led most FISRAM assessors to expect arapaimas to compete with and prey on native fish species, with significant negative impacts, particularly if arapaimas were able to establish populations in the contiguous United States. Continued research into the pathogens and parasites of arapaimas would also help to address uncertainty over potential impacts of introduction and allow for more robust assessment of existing biosecurity protocols.

Stringent regulations, combined with robust sanitary inspection, can greatly mitigate the risks linked to arapaima aquaculture, rendering it highly improbable for this species to pose a threat to native species and ecosystems in the contiguous United States. In southern Florida, the state's mandatory Aquaculture BMPs for certified aquaculture operations (FDACS 2022), which include additional requirements for conditional non-native species like arapaimas (68 Florida Administrative Code 5.004), can substantially reduce aquaculture-related introduction risk for all life stages. Risk could be further reduced for particularly sensitive habitats or native species populations in southern Florida through regular surveillance to detect escaped arapaimas prior to population establishment and growth. Outside of southern Florida, arapaima aquaculture is limited to indoor recirculating aquaculture systems, and escapees from aquaculture or releases from private aquaria are unlikely to survive ambient temperatures as they fluctuate across a year.

Although the BMPs in arapaima aquaculture in Florida are evident, aquarium dumping still represents a prominent alternative route of introduction, along with potential illegal aquaculture (Magalhães et al. 2017, Pereira et al. 2022). Therefore, we recommend caution when making decisions related to arapaima importation and suggest that lessons learned from improper introduction and ineffective enforcement in other regions of the world be considered. We encourage addressing these issues through (1) awareness campaigns targeting importers, wholesalers, retailers, and hobbyists (Magalhães et al. 2017); (2) provision of penalty-free opportunities for rehoming non-native fish pets (FFWCC 2024, San Marcos Parks and Recreation Department 2024); (3) enforcement of existing Florida regulations (68 Florida Administrative Code 5.003, 5.005); and (4) consideration of new restrictions on arapaima possession and trade in southeastern US States that do not have existing regulations for the genus.

Our risk assessment was restricted to the contiguous United States and focused on current and near-future climate trends. Hawaii and several US Commonwealths and territories, not to mention other countries with tropical climates, would likely benefit from further assessment and mitigation of invasion risk of arapaimas. In our model results, the predicted probability of injuriousness was very sensitive to climate match with the region of introduction. The concerns expressed by assessors in this study about the broad predatory and competitive abilities of arapaimas are likely to be especially relevant in regions where seasonal cold temperatures or extreme cold events do not limit arapaima establishment.

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Appendix. Water temperature data comparison

To visually compare RAMP results to recorded annual minimum water temperatures within the Southeast region of the United States, we obtained daily minimum water temperature data from the National Water Information System (NWIS; USGS 2023b). We queried NWIS for all stream and lake sites recording daily water temperature data between 2014 and 2021 in 8 states (Alabama, Florida, Georgia, Louisiana, Mississippi, North Carolina, South Carolina, and Texas) using the 'dataRetrieval' R package (DeCicco et al. 2022) in program R (R Core Team 2022). We obtained annual minimum water temperatures by summarizing daily data by site and year using the 'dplyr' (Wickham et al. 2022) and 'reshape' (Wickham 2007) R packages. Sites that did not record water temperature in any year between 2014 and 2021 were excluded from the final dataset. Maps were produced using ArcGIS Pro version 2.9.5 (Esri).

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