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# Scanning the horizon for invasive plant threats to Florida, USA

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**Running head:** Florida invasive plant horizon scan

## Abstract

Early detection and eradication of invasive plants are more cost-effective than managing well-established invasive plant populations and their impacts. However, there is high uncertainty around which taxa are likely to become invasive in a given area. Horizon scanning, which pairs rapid risk assessment with consensus building among experts, can help identify invasion threats. We performed a horizon scan of potential invasive plant threats to Florida, USA—a state with a high influx of introduced species, conditions that are favorable for plant establishment, and a history of negative impacts from invasive plants. We began with a list of 2128 non-native plant species and subspecies that are crop pests or invasive somewhere in the world and used publicly available data to prioritize 100 taxa for rapid risk assessment. We derived overall invasion risk scores by evaluating the likelihood and certainty of each of the 100 taxa arriving, establishing, and having an impact in Florida. Through the rapid risk assessments and a consensus-building discussion, we identified six plant taxa with high overall risk scores ranging from 75 to 100 out of a possible 125. The six taxa are globally distributed, easily transported to new areas, found in regions with climates similar to Florida's, and can impact native plant communities, human health, or agriculture. We recommend more thorough risk assessments for each of these six species and, if appropriate, policy and management actions to limit invasive plant introduction and establishment in Florida.

## Keywords

*Avena fatua*, certainty, *Cytisus scoparius*, horizon scan, *Ligustrum vulgare*, *Phalaris arundinacea*, rapid risk assessment, prevention

## Introduction

Potential impacts of invasive species, and invasive plants in particular, are daunting given the high numbers of species introduced to novel areas each year, with rates predicted to increase in the future (Seebens et al. 2020). Governments and private landowners take responsibility for controlling invasive plant populations and mitigating their negative impacts after they arrive (Lovell and Stone 2005, Pimentel 2009) after their arrival. Preventing the introduction and initial spread of invasive plants, however, is generally less expensive than managing established populations and avoids potential ecological and economic losses (Simberloff 2003, Keller et al. 2007, Sheley et al. 2015). Unfortunately, the benefits of prevention are difficult to quantify and involve high uncertainty, making post-invasion control the more common approach (Simberloff 1997a, Finnoff et al. 2007, Early et al. 2016). Thus, programs that help identify which non-native plant taxa have a high probability of becoming problematic invaders in a given area are essential for providing the first lines of defense against plant invasions, such as informing trade policies and identifying control priorities if highly ranked taxa are discovered in a new habitat.

Horizon scanning is the systematic examination of information to identify potential threats, risks, emerging issues, and opportunities that can inform policy (Sutherland and Woodroof 2009, Amanatidou et al. 2012, Könnölä et al. 2012). This technique has been applied to a variety of topics including policy analysis (Könnölä et al. 2012), medical technology (van der Maaden et al. 2018), and various conservation issues (Gusset et al. 2014, Brown et al. 2016, Cooke et al. 2020, Sutherland et al. 2021). In Europe, horizon scanning of emerging invaders and their pathways for introduction has informed policy and guided resource allocation to research and prevention efforts (Parrott et al. 2009, Matthews et al. 2014, Roy et al. 2014, Gallardo et al. 2016, Lucy et al. 2020). However, horizon scanning has yet to be used to identify invasive species threats in the U.S. (but see Ricciardi et al. 2017), where non-native plant and animal introduction numbers are among the highest in the world (Seebens et al. 2017).

Florida is one of the most important states for regulating invasive plants in the U.S. because nearly 85% of all non-native plants imported to the contiguous U.S. enter through one of 35 shipping ports and airports in Florida (Gordon and Thomas 1997, Enterprise Florida 2021). As international trade continues to grow, so does the frequency of intentional and accidental introductions (Early et al. 2016). In addition to being an entry point for invasive species to the rest of the country, Florida is particularly vulnerable to the establishment of invasive plants due to its tropical/subtropical climate and diverse ecosystems (Simberloff 1997b, Pyšek et al. 2017). Management of invasive plants in Florida's conservation areas costs nearly \$45 million per year (Hiatt et al. 2019) and invasive species (including plants, insects, and pathogens) cost Florida's agriculture industry at least \$179 million per year (Coffman et al. 2001). Accordingly, Florida residents are highly supportive of preventing biological invasions (Huang and Lamm 2016). Identifying potential invaders before or soon after they enter Florida can reduce ecological and economic losses to the state as well as prevent the spread of invasive plants nationally—a goal of the U.S. Plant Protection Act (U.S. Congress 2000).

Our aim was to use horizon scanning to create a ranked list of non-native plants that are likely to arrive and establish in Florida and have an impact on native biodiversity, the economy, or human health within the next ten years (2020–2030). A successful horizon scan for potential invaders relies on the integration of risk assessment and consensus building (Roy et al. 2015). We began with a list of potential invasive species and subspecies generated

by the Centre for Agriculture and Biosciences International (CABI), and used publicly available data to identify the 100 plant taxa most likely to arrive and have impacts in Florida. Then, during the risk assessment phase, experts assigned scores for likelihood of arrival, establishment, and impacts in Florida to the 100 taxa. Risk assessments were peer-reviewed, and taxa were ranked based on their scores. Finally, in the consensus building phase, experts reviewed the ranked list and suggested modifications. Here, we present the ranked list of potential invasive plant threats to Florida, which can be used to inform research, management, and policy aimed at reducing invasive plant impacts in Florida.

## Methods

We adapted the horizon scanning method outlined by Sutherland et al. (2011) and Roy et al. (2014, 2015) to develop a ranked list of invasive plant threats and their potential pathways for arrival to the state of Florida over the next ten years (2020–2030). We chose a ten year time frame to capture threats in the near future and to establish a minimum frequency (once every ten years) for updating the horizon scan with new information.

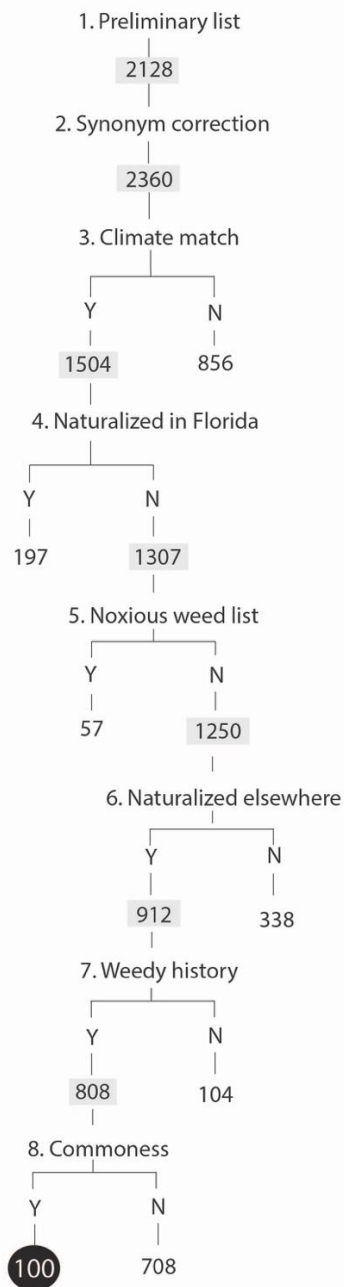
### *Expert panel and workshop*

We (the authors) formed the expert panel, providing knowledge of Florida’s natural systems and existing invasive plants, including experience in invasion ecology, botany, policy, and data analysis. We are employed by governmental, academic, and non-profit organizations (Environmental Defense Fund, Florida Department of Agriculture and Consumer Services, Florida Fish and Wildlife Commission, University of Florida, and United States Geological Survey), which supported our participation. We organized and attended a workshop in December 2019, during which we designed criteria for selecting taxa to assess (see *Assembling a list*), discussed the rapid risk assessment tool (see *Assessing and scoring the taxa*), and identified online resources for completing the rapid risk assessments.

### *Assembling a list*

Using the horizon scan tool developed by CABI (an inter-governmental not-for-profit organization that provides information and expertise on agriculture and the environment), we generated a preliminary list of invasive taxa and crop pests that are not known to be present in Florida based on CABI’s databases (CABI 2018). The tool consolidates information from the CABI Invasive Species Compendium and Crop Protection Compendium, which are science-based encyclopedic databases. The tool generated a list of 9629 taxa, 2128 of which were in the kingdom Plantae.

We first corrected the preliminary list for synonyms by compiling accepted names and synonyms from the Atlas of Florida Plants (Wunderlin et al. 2019), the Taxonomic Name Resolution Service (TNRS; Boyle et al. 2015), and the Integrated Taxonomic Information System (ITIS; ITIS n.d.; see Suppl. material 1: Methods S1 for more details), which increased our list to 2360 taxa. The modified CABI list was then trimmed based on several criteria (Fig. 1), including: climatically matched to Florida, not naturalized in Florida (i.e., a self-sustaining population), not on a Florida or federal noxious weed list, naturalized outside of its native range, historically weedy, and commonness (Suppl. material 2: Table S1). If taxa met a criterion, they were retained for further assessment in the next stage. We assessed commonness by the number of global occurrences (GBIF.org 2021a) and selected the top 100 (12%) for further assessment, which was the largest number of taxa that the experts felt they could feasibly evaluate.



**Figure 1.** Criteria for selecting taxa for rapid risk assessment. The criteria included the following systematic steps: (1) a preliminary list of 2128 taxa; (2) correcting for synonyms, which increased the original list to 2360; (3) climate matching with Köppen-Geiger climate zones (Kottek et al. 2006, CABI 2018), which identified 1504 taxa that could potentially become established in Florida if climate were the only limiting variable; (4) 197 taxa were already naturalized in Florida (Wunderlin et al. 2019) and removed from the list; (5) 57 taxa were already listed on state or federal noxious weed lists (State of Florida 2008, 2020, USDA 2017, FISC 2019) and were removed from the list; (6) taxa that were naturalized somewhere outside of their native range (van Kleunen et al. 2019), suggesting the ability to establish in habitats where they did not co-evolve with other species, were selected (912 taxa); (7) taxa with a record of “weediness”, suggesting the ability to produce a self-sustaining population and have at least mild impacts on the surrounding environment (Randall 2017), were selected

(808 taxa); (8) the top 100 taxa, ranked by number of global occurrences (GBIF.org 2021a), were selected. More details on the datasets used to inform these criteria can be found in Suppl. material 1: Methods S1.

We used expert opinion to remove and add taxa from the list before and after finalizing the top 100. *Pastinaca sativa* was previously assessed by one of the experts and determined to be not a threat to Florida (removed before commonness was assessed). Two taxa were removed from the list of 100 taxa: *Rosmarinus officinalis* and *Galeopsis tetrahit*. *Rosmarinus officinalis* was known by experts to be naturalized in Florida and found to have 13 recent herbarium records. There was not enough information on *Galeopsis tetrahit* available to complete the rapid risk assessment and very few of its GBIF occurrences were inside Florida's Köppen-Geiger climatic zones (*Galeopsis tetrahit* L. in GBIF Secretariat 2021). Because GloNAF, the database used for criterion 6 (Fig. 1), only included vascular plants (van Kleunen et al. 2019), an undesirable side effect of the filtering process was that non-vascular plants were removed without taking other criteria into account. To more rigorously evaluate non-vascular plants, we added the non-parasitic terrestrial and freshwater taxa from the initial CABI list that were in the phyla Chlorophyta, Heterokontophyta, Phaeophyta, Rhodophyta, or Streptophyta (the phyla Bryophyta, Marchantiophyta, and Anthocerophyta were not in the original list) to the list: *Aegagropila linnaei* and *Campylopus introflexus*. We therefore ended with 100 taxa (two removed and two added).

#### Assessing and scoring the taxa

Nine of us evaluated taxa using a rapid risk assessment tool modified from Roy et al. (2014). First, we used a species not included in the final list to assess the tool for clarity of instructions, the time it took to complete the assessment, and inconsistencies across assessments. Then, we completed rapid risk assessments with a standardized set of resources: the tool, instructions, a list of taxa to assess and their synonyms, the list of websites compiled during the workshop, information about Florida's plant hardiness zones (USDA 2012) and Köppen-Geiger climate zones (Kottek et al. 2006), and a list of search terms for search engines. Because the risk assessment tool is designed to be completed rapidly, we aimed to spend less than two hours assessing each taxon. Eight of us completed ten assessments each and one of us completed twenty.

We scored the likelihood of arrival, establishment, and negative impacts (environmental, socioeconomic, and human health) on a scale of 1 (very low) to 5 (very high). To estimate the likelihood of arrival, experts considered the current distribution of the taxon, the availability of the taxon for purchase, history of invasion by the taxon in other regions, and the presence of a plausible arrival pathway (Table 1). To estimate the likelihood of establishment (i.e., developing a self-sustaining population), experts considered the occurrences and distribution of the taxon within regions with Köppen-Geiger climate zones matching Florida (Table 1). Experts also considered ecological properties of both the taxon and Florida habitats, including time to reproductive maturity, reproduction rate, dispersal mechanism, propagule pressure, tolerance of a broad range of environmental conditions, amount of nurturing required, resource availability, and natural enemies. To estimate the likelihood of negative impacts, experts used a scoring rubric modified from the Invasive Species Environmental Impact assessment protocol (Branquart 2009), the Environmental Impact Classification of Alien Taxa (EICAT; Blackburn et al. 2014, Hawkins et al. 2015), and the Socio-Economic Impact Classification of Alien Taxa (SEICAT; Bacher et al. 2018; Table 1). The overall risk score was the product of arrival, establishment, and impact likelihood scores. We provided brief justifications for our scores and assigned certainty scores that ranged from very low



(i.e., all scores were equally likely) to high (i.e., could confidently eliminate all other scores). The overall certainty score was the score most consistent with three component certainty scores.

**Table 1.** Rubrics for scoring likelihood of arrival, establishment, and impacts of potential invasive plants in Florida.

Category	Criteria	Score
<b>Arrival<sup>†</sup></b>	Closest observation to Florida <sup>‡</sup> and closest online seller to Florida <sup>§</sup> are outside of the contiguous U.S.	1
	Closest observation to Florida is within the contiguous U.S., but not in the southeastern <sup>  </sup> U.S., and the closest online seller to Florida is outside of the contiguous U.S.	2
	Closest observation to Florida and closest online seller to Florida are within the contiguous U.S., but not in the southeastern U.S. or closest observation to Florida is in the southeastern U.S., but not in Florida, and the closest online seller to Florida is outside the contiguous U.S.	3
	Closest observation to Florida is within the southeastern U.S., but not in Florida, and the closest online seller is within the contiguous U.S. or the southeastern U.S., but not in Florida.	4
	The taxon has been observed or sold within Florida.	5
<b>Establishment<sup>†</sup></b>	No observations in areas with matching Köppen-Geiger (KG) zones to Florida <sup>¶</sup> .	1
	Few observations in one area with matching KG zones to Florida.	2
	Many observations in one area or few observations in multiple areas with matching KG zones to Florida.	3
	Many observations in multiple areas with matching KG zones to Florida.	4
	Criteria for score 4 plus evidence of a biological strategy that aids establishment or evidence of establishment in Florida.	5
<b>Impact</b>	Unlikely to cause negative impacts on the native biota or abiotic environment, human well-being, or economic systems.	1
	Likely to cause (a) declines in the performance (e.g., biomass, body size) of native biota, but no decline in native population sizes or (b) income loss, minor health problems, higher effort or expense to participate in activities, increased difficulty in accessing goods, or minor disruption of social activities, but no significant impact on participation in normal activities. The taxon has no other impacts that would cause it to be classified in a higher impact category.	2
	Likely to cause (a) declines in the population size(s) of native species, but no changes to the structure of communities or to the abiotic or biotic composition of ecosystems or (b) changes in the size of social activities, with fewer people participating, but the activity is still carried out. These changes to social activities could be linked to accessibility to the activity area or mild effects to human health (e.g., allergies). The taxon has no impacts that would cause it to be classified in a higher impact category.	3
	Likely to cause (a) the local or population extinction of at least one native species, leading to reversible changes in the structure of communities, the abiotic or biotic composition of ecosystems or (b) the local disappearance of a social or economic activity from all or part of the area invaded by the alien taxon, collapse of the specific activity, switch to other activities, abandonment of activity without replacement, emigration from region, or moderate effects to human health. The taxon has no impacts that would cause it to be classified in a higher impact category.	4
	Likely to cause (a) the replacement and local extinction of native species and will produce irreversible changes in the structure of communities and the abiotic or biotic	5



	composition of ecosystems or (b) local disappearance of a social or economic activity from all or part of the area invaded by the alien taxon or major effects to human health.	
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†Arrival and Establishment rubrics were applied during the review phase rather than the assessment phase. Scores were adjusted by up to one point based on additional information in the assessments.

\*Observations based on GBIF.org (2020) or information provided by the assessor or reviewer.

§Sellers located with PlantScout (2020), Betrock’s Plant Search (Rosenthal 2020), and google.com.

For our purposes (proximity to Florida), southeastern states include Georgia, Alabama, South Carolina, North Carolina, Tennessee, and Mississippi.

\*Observations based on GBIF.org (2020) or information provided by the assessor or reviewer. Florida’s Köppen-Geiger zones include Af, Am, Aw, and Cfa (Kottek et al. 2006).

We identified one or more potential pathways for the taxa to arrive in Florida based on an established framework (Hulme et al. 2008, CBD 2014, Harrower et al. 2018). Briefly, the pathways included “release in nature” (intentional release, such as for erosion control), “escape from confinement” (intentional commodity that escapes, such as a horticultural taxon), “transport contaminant” (associated with the transport of a specific commodity, such as a seed contaminant), “transport stowaway” (other forms of unintentional transport, such as through soil on equipment), “corridor” (through human infrastructure linking previously unconnected areas, such as a waterway), and unaided (natural dispersal).

### *Reviewing and modifying scores*

In the first round of reviews, ten of us reviewed ten assessments each. We searched for each taxon in references that we found helpful when completing risk assessments and filled in information where the assessor indicated that the certainty was “low” or “very low”. We changed scores, edited justifications, and wrote comments, differentiating our text from the original assessor by using red font (Suppl. material 3: Table S2). We aimed to complete the reviews efficiently, spending 30 minutes or fewer on each. We then ranked the taxa by their overall risk score and all group members read the reviewed risk assessments.

### *Consensus building*

During the two hour virtual meeting, we discussed taxa in descending order of scores. We spent extra time discussing taxa with more controversial scores, such as taxa with large discrepancies between scores assigned by the assessor and reviewer, which were reviewed again following consensus building. In addition, *Solidago canadensis* was removed from the list, creating a final list of 99 taxa. Taxonomic subunits of *S. canadensis* are difficult to distinguish (CABI 2021), creating ambiguity about whether *S. canadensis* is already established in Florida (Wunderlin et al. 2019, GBIF.org 2021b). We therefore could not evaluate the risk of *S. canadensis* arriving in Florida.

We determined overall risk score thresholds to categorize taxa as high, medium, or low risk: a taxon scoring  $\geq 64$  (i.e., an average score of 4 for each variable of arrival, establishment, and impact) was categorized as high risk, a taxon with a score between 27 (i.e., an average score of 3 for each variable) and 63 as medium risk, and a taxon with a score less than 27 as low risk.

### *Analysis of risk scores*

We evaluated whether peer-review and consensus building significantly affected overall risk scores with a paired two-sample *t*-test, comparing scores from the first assessments to those

of the final list. We also evaluated how variation among experts and characteristics of the taxa affected the overall risk scores. We fit a generalized linear regression with a negative binomial error structure to the overall risk scores with the expert who completed the assessment ( $N = 9$ ), expert certainty about the overall score (very low, low, medium, or high), whether the typical habitat of the plant taxon is terrestrial or aquatic, the number of records of the taxon in the U.S., and the year of the earliest record of the taxon in the U.S. as independent variables. To determine the number of records and the earliest record of each taxon in the U.S., we used the package ‘rgbif’ (Chamberlain et al. 2021) to extract all GBIF records in the U.S. for each taxon, selecting records that had coordinates and no geospatial issues (GBIF.org 2021b). One taxon had no records in the U.S., so we used the current year for its earliest record value. Number of records and earliest record were centered and scaled and were not significantly correlated with each other ( $r = 0.04$ ,  $P = 0.68$ ). We fit the model using the ‘MASS’ package (Venables and Ripley 2002), evaluated the fit using the ‘DHARMA’ package (Hartig and Lohse 2020), tested the significance of each independent variable using likelihood ratio tests, and compared factor levels using the ‘emmeans’ package (Lenth et al. 2021). All analyses were conducted in R version 4.0.2 (R Core Team 2020).

### *Taxa characteristics*

We evaluated whether plant taxonomic families were under- or overrepresented in the CABI plant list and in the final list using a resampling procedure (Daehler 1998). We first extracted all accepted species names and their family names from The Plant List using the taxize package (Chamberlain and Szoecs 2013, TPL 2013), resulting in a dataset of 373,847 taxa. The CABI list contained 158 families (with 2091 taxa) in The Plant List (vascular plants and bryophytes). We re-sampled 2091 taxa without replacement from The Plant List dataset 10,000 times. Taxa were replaced between iterations and we counted the number of taxa per family each iteration. We set the threshold for statistical significance to  $P < 0.0003$  (0.05 divided by the number of families, consistent with a Bonferroni correction; Daehler 1998). Therefore, families with fewer than three iterations during which the sampled number of taxa was greater (less) than or equal to the number of taxa in the CABI list from that family were considered overrepresented (underrepresented). We repeated this procedure with different values for the final list: 34 families with 98 taxa, 1,000 iterations,  $P < 0.0015$ , and families with one or fewer iterations.

To evaluate the native and introduced ranges of taxa in the final list, we researched their distributions using the Plants of the World database (for 95 of the 99 taxa; POWO 2021), the CABI Invasive Species Compendium (CABI 2021), the Global Compendium of Weeds (Randall 2017), and GBIF (GBIF.org 2020). One species, *Aegagropila linnaei*, was removed from the analysis because its native range is unclear. We summarized distributions using the World Bank Development Indicator regions in the ‘countrycode’ package (Arel-Bundock et al. 2018).

## **Results**

### *High risk taxa*

Six plant taxa received risk scores greater than or equal to 64 (Fig. 2), indicating that these taxa are likely to invade Florida in the next 10 years. We had high certainty about the risk scores for four taxa: *Ligustrum vulgare*, *Cytisus scoparius*, *Phalaris arundinacea*, and *Avena fatua*. We had medium certainty for the other two taxa: *Agrostis capillaris* and *Persicaria hydropiper*. Three of the taxa were considered very likely to arrive in Florida (arrival score = 5 out of 5): *L. vulgare*, *A. fatua*, and *P. hydropiper*. This conclusion was based on: herbarium specimens indicating historic, but not current, presence in Florida; observations of presence

without naturalization within the last 20 years (fewer than three records in wild areas); and records of seeds sold within the U.S. at the time of the assessment (Suppl. material 3: Table S2). All six taxa were considered very likely to establish in Florida (establishment score = 5 out of 5) because they occur in other regions of the world with climates similar to Florida and in some cases, the taxon is known to have high reproductive capacity (Suppl. material 3: Table S2). While none of the taxa were considered very likely to cause economic or environmental impacts in Florida, four taxa received the next highest impact score (impact score = 4 out of 5; *L. vulgare*, *C. scoparius*, *P. arundinacea*, and *A. capillaris*). These four taxa have impacted native vegetation through competition, produce pollen that can be a human allergen, and some are agricultural weeds (Suppl. material 3: Table S2). Information about the six species from a handful of sources can help inform potential future policy actions (Table 2): the taxa are native to a number of regions in the eastern hemisphere and have global distributions; they have cultural and economic uses that have facilitated their introduction to new regions in the past; they can disperse through unintentional pathways; they are managed through various, often integrated, approaches; and they are included in U.S. state noxious weed lists or laws.



**Figure 2.** The six taxa that were designated as high risk for invasion potential in Florida. Overall risk scores are in white circles (maximum possible score is 125). (Photos: Meneerke bloem, Isidre blanc, Andreas Eichler, Stefan.lefnaer, CC BY-SA 4.0; Robert Flogaus-Faust, CC BY 4.0; Rasbak, CC BY-SA 3.0; Willow, CC-BY 2.5; Mary Joyce, Katrice Baur, scottq1, rae117, CC BY-NC 4.0; Christian Grenier, CC0 1.0).

**Table 2.** Characteristics of the six high risk species.

Species	Native range <sup>†</sup>	Introduced countries <sup>‡</sup>	Arrival pathways and uses <sup>§</sup>	Management approaches <sup>  </sup>	States listed <sup>¶</sup>
<i>Ligustrum vulgare</i>	Europe, western Asia, northern Africa	Argentina, Australia, Brazil, Canada, New Zealand, South Africa, United States,	agroforestry, escape from confinement/garden, graft stock, landscape improvement, medicinal, ornamental, shade	mechanical (pulling, digging, cutting), chemical (cut and spray, stem injections)	11
<i>Phalaris arundinacea</i>	Asia, Europe, Central America,	Ethiopia, Kenya, Tanzania, Uganda	erosion control, fodder crop, fiber, ornamental	burning, discing, mowing, herbicides	10



	North America <sup>†</sup> , southern/eastern/ northern Africa				
<i>Cytisus scoparius</i>	Europe	Argentina, Australia, Bolivia, Brazil, Canada, Chile, China, India, Iran, Japan, New Zealand, South Africa, United States	animal-assisted, ballast water, botanical gardens and zoos, disturbance, escape from confinement/garden, fiber, garden waste disposal, hedge/windbreak, medicinal, transport stowaway, ornamental, waterways	burning (with other approaches), grazing, mulching, pulling (outlying plants), chemical (cut and spray, foliar spray, stem injections), biological control	14
<i>Agrostis capillaris</i>	central/western/ southwestern Asia, Europe, North Africa,	Argentina, Australia, Bhutan, Brazil, Canada, Chile, Greenland, India, New Zealand, Saint Helena, Saint Pierre and Miquelon, South Georgia and the South Sandwich Islands, United States	animal-assisted, disturbance, erosion control, fodder, grass contaminant, horticulture, pasture, landscape rehabilitation, turf grass (lawns and golf), wind and water	crop rotations, mechanical (pulling, ploughing, grubbing and harrowing), herbicides	5
<i>Avena fatua</i>	Central Asia	Canada, United States (present in 74 other countries, but “introduced” status not provided)	fodder, forage, gene source for disease and drought resistance, medicinal, seed contaminant, transport stowaway	burning, crop rotation, herbicides, soil cultivation, soil solarization	4
<i>Persicaria hydropiper</i>	Europe	“Introduced” status not provided, but present in 48 countries	culinary, medicinal	herbicides, pulled	1

<sup>†</sup>Geographic regions where the taxon is native (CABI 2021, Native Plant Trust 2021)

<sup>‡</sup>Countries where the taxon has been introduced (CABI 2021)

<sup>§</sup>Known pathways for arrival and human uses (CABI 2021)

<sup>||</sup>Approaches used to control the taxon (CABI 2021)

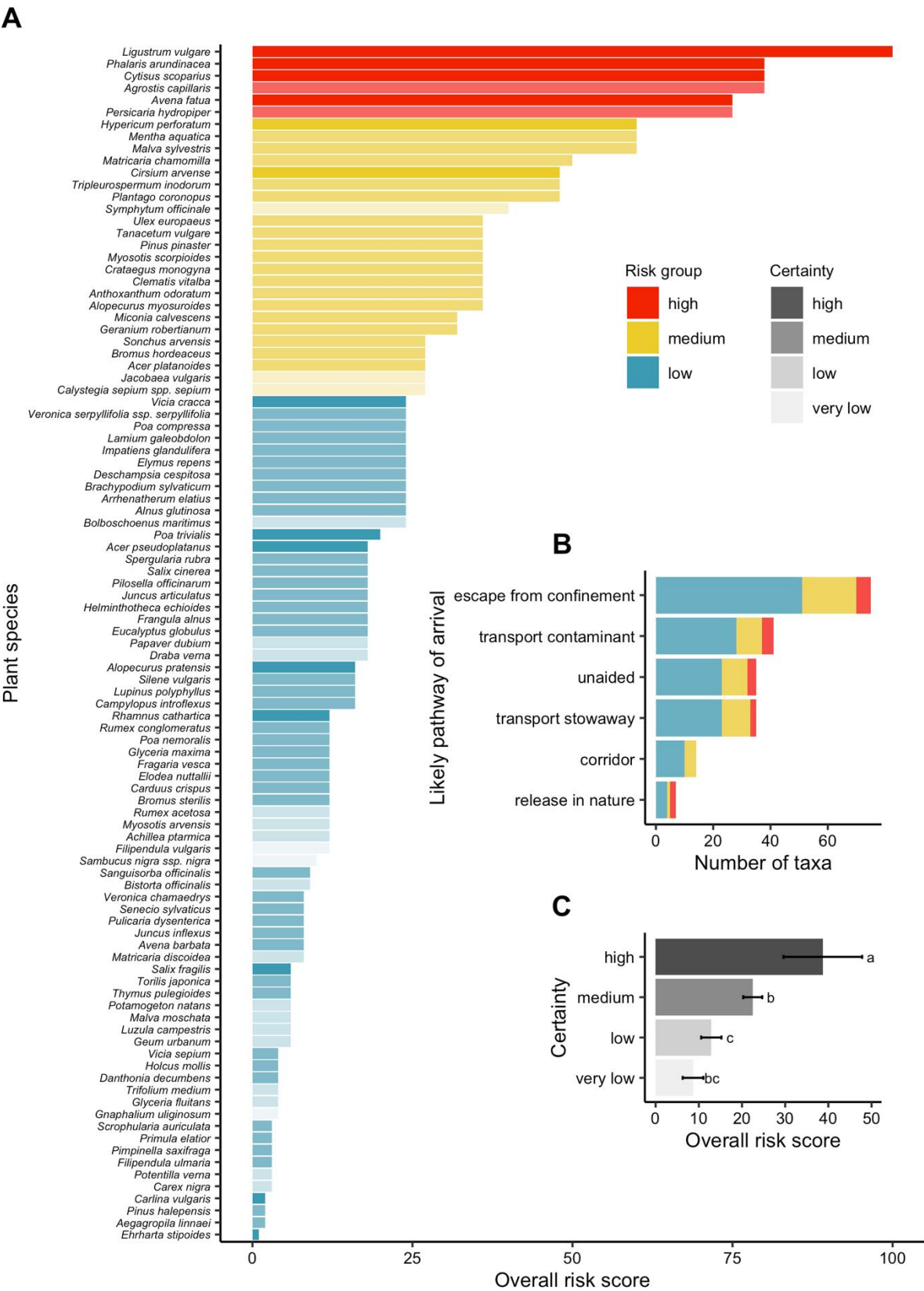
<sup>¶</sup>U.S. states in which the taxon is included in a prohibited list or law (EDDMapS 2021)

<sup>#</sup>See *Taxa characteristics* section for more details

### Medium risk taxa

Twenty-three taxa received medium risk scores (greater than or equal to 27, but less than 64; Fig. 3). Two taxa, *Matricaria chamomilla* and *Symphytum officinale*, were considered very likely to arrive in Florida (score = 5) because there were occurrence records in Florida, including two for *S. officinale* that suggested escape (it is planted as an ornamental, Table S2). *Symphytum officinale* was considered likely to establish in Florida (establishment score = 4), but unlikely to have impacts (impact score = 2). Four taxa were considered very likely to establish in Florida (establishment score = 5)—*Hypericum perforatum*, *Malva sylvestris*, *Matricaria chamomilla*, and *Mentha aquatica*—because they occur in areas with climate similar to Florida and *M. chamomilla* readily self-seeds (Table S2). *Hypericum perforatum*, *M. sylvestris*, and *M. aquatica* were considered likely to arrive in Florida (arrival score = 4) and potentially likely to have negative impacts (impact score = 3), but *M. chamomilla* was considered likely to have only minimal negative impacts (impact score = 2). These four taxa are sold as ornamental plants within the U.S., have been reported in the southeastern U.S. in the past 20 years, and can naturally disperse (Table S2). None of the plant taxa in the medium

368 risk group were considered very likely to have negative impacts. We had high certainty about  
369 the scores of two taxa, medium certainty about the scores for 18 taxa, and low certainty about  
370 the scores for three taxa. The three taxa for which we had low certainty about their scores  
371 received relatively low risk scores: *Symphytum officinale* (overall risk score = 40), *Jacobaea*  
372 *vulgaris* (overall risk score = 27), and *Calystegia sepium* spp. *sepium* (overall risk score =  
373 27).  
374



**Figure 3.** Horizon scan scores. **A** The overall risk scores for 99 taxa, divided into groups of high risk (score  $\geq 64$ ), medium risk ( $27 \leq \text{score} < 64$ ), and low risk (score  $< 27$ ) and shaded by overall certainty score. **B** The number of taxa associated with each of the pathways of arrival. Multiple pathways could be assigned to a single taxon. **C** The relationship between

certainty and the overall risk score, averaged across all taxa. Letters above bars indicate significant differences in overall risk score among certainty scores with  $P < 0.05$ .

### Low risk taxa

Seventy taxa received low risk scores (less than 27; Fig. 3). One taxon, *Poa trivialis* (overall risk score = 20, overall certainty = high), was considered very likely to arrive in Florida (arrival score = 5) because it is in the southeastern U.S., has been used in at least one research experiment in Florida, and it is planted in golf courses in the southeast both intentionally and unintentionally (seed contaminant). *Poa trivialis*, however, is unlikely to establish in Florida (establishment score = 2) and have impacts (impact score = 2). *Sambucus nigra* ssp. *nigra* (overall risk score = 10, overall certainty = very low), was considered very likely to establish in Florida (establishment score = 5) because the species *Sambucus nigra* occurs in multiple locations with climate similar to Florida (Table S2). However, the subspecies has few recorded occurrences globally, which led to very low certainty about the establishment score. In addition, *Sambucus nigra* ssp. *nigra* is very unlikely to arrive in Florida (arrival score = 1) and unlikely to have impacts (impact score = 2). None of the plant taxa in the low risk group were considered very likely to have negative impacts. We had high certainty about the scores of eight taxa, medium certainty about the scores of 43 taxa, low certainty about the scores of 16 taxa, and very low certainty about the scores of three taxa. The three taxa for which we had very low certainty about their scores were *Filipendula vulgaris* (overall risk score = 12), *S. nigra* ssp. *nigra* (overall risk score = 10), and *Gnaphalium uliginosum* (overall risk score = 4).

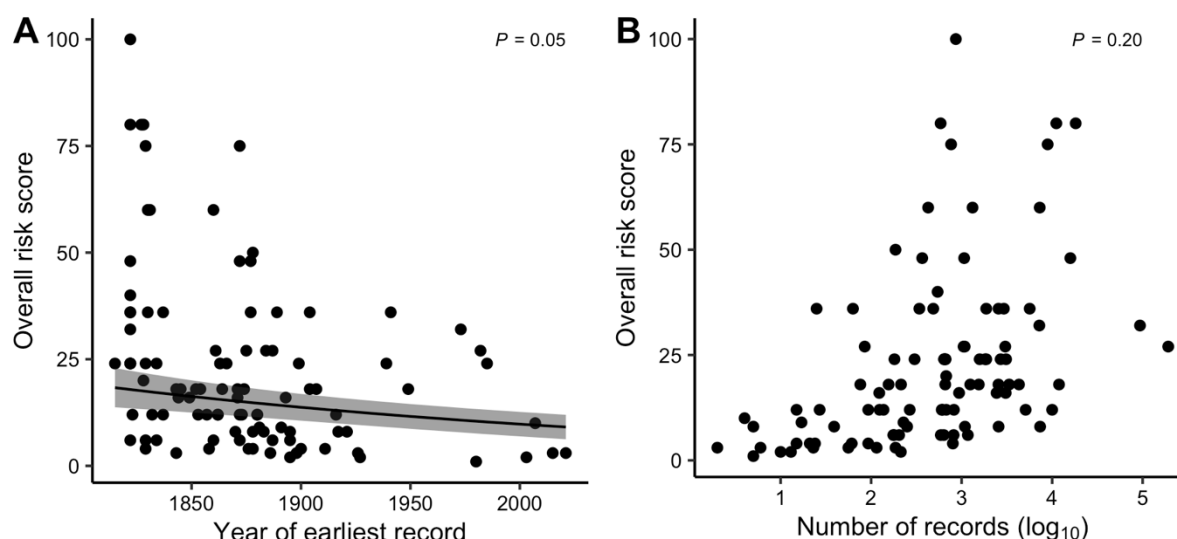
### Pathways of arrival

The most likely pathway of arrival for the taxa on the final list was escape from confinement (Fig. 3B). Taxa are also likely to arrive in Florida as transport contaminants, transport stowaways, or with unaided dispersal. It is less likely that plants will arrive through intentional release into nature or through a constructed corridor.

### Analysis of risk scores

There was no significant difference in the overall risk scores before and after peer-review and consensus building ( $t = -1.41$ , 95% CI = -4.43–1.61, df = 97,  $P = 0.357$ ) with an average score ( $\pm$  SE) of  $21.3 \pm 2.1$  before and  $22.7 \pm 2.1$  after. The assessor ( $\chi^2 = 27.0$ , df = 8,  $P < 0.001$ ), certainty level ( $\chi^2 = 21.4$ , df = 3,  $P < 0.001$ ), and earliest record in the U.S. ( $\chi^2 = 3.9$ , df = 1,  $P = 0.050$ ) significantly affected the overall risk score, while the habitat (terrestrial vs. aquatic;  $\chi^2 = 0.07$ , df = 1,  $P = 0.787$ ) and number of records in the U.S. ( $\chi^2 = 1.7$ , df = 1,  $P = 0.196$ ) did not. Four out of 36 pairwise comparisons of assessors were significantly different with  $P < 0.05$ . Taxa with higher overall certainty scores also had higher overall risk scores (Fig. 3C). Taxa with earlier first records in the U.S. received higher overall risk scores than taxa with later first records (Fig. 4A), but taxa with more records in the U.S. did not receive significantly higher overall risk scores than taxa with fewer records, although there was a positive trend (Fig. 4B).



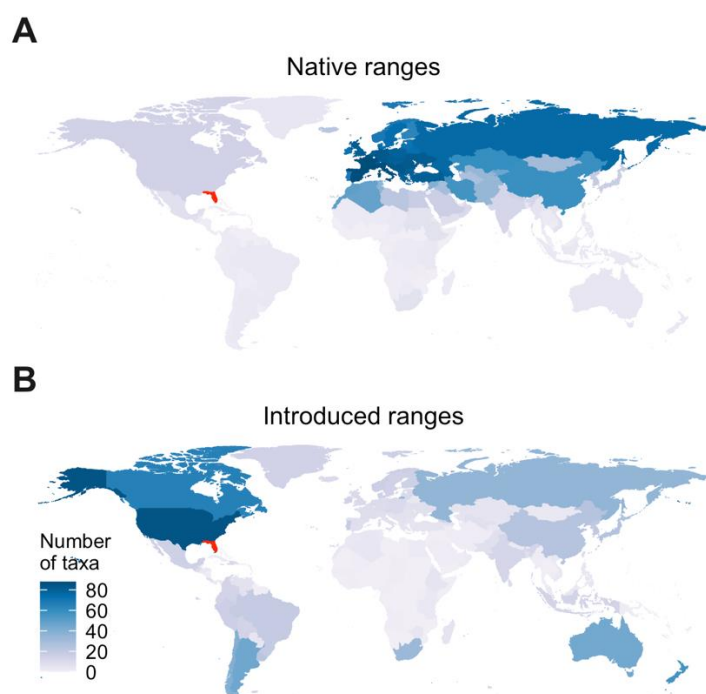


**Figure 4.** Earliest record and number of records. The overall risk score and **A** the year of the earliest record in the U.S. and **B** the number of records (displayed on a log<sub>10</sub> scale for clarity) in the U.S. for the 99 taxa on the final list. Points represent data while lines and shading represent model-estimated mean  $\pm$  SE.

#### Taxa characteristics

Four families were significantly overrepresented in the final list of 99 taxa compared to the number of accepted species in the family (Suppl. material 4: Table S3): Juncaceae (3 taxa out of 581 accepted species), Poaceae (21 taxa/11883 accepted species), Polygonaceae (4 taxa/1584 accepted species), and Rosaceae (7 taxa/5325 accepted species). These four families were also significantly overrepresented in the CABI list (Suppl. material 5: Table S4): 21 taxa (1% of the CABI list) were in Juncaceae, 226 taxa (11%) were in Poaceae, 37 taxa (2%) were in Polygonaceae, and 80 taxa (4%) were in Rosaceae. None of the families present on the final list were significantly underrepresented.

Ninety three percent of taxa on the final list had native ranges that included Europe and Central Asia, 75% included the Middle East and North Africa, and 67% included East Asia and the Pacific (Fig. 5A). Other regions were included in 43% or fewer of the taxa's native ranges. The United States was included in the native ranges of 11 taxa: *Bolboschoenus maritimus*, *Carex nigra*, *Deschampsia cespitosa*, *Elodea nuttallii*, *Fragaria vesca*, *Geranium robertianum*, *Juncus articulatus*, *Lupinus polyphyllus*, *Phalaris arundinacea*, *Potamogeton natans*, and *Sanguisorba officinalis*. Although some native populations of *P. arundinacea* exist in North America, the majority of populations are Eurasian genotypes (Jakubowski et al. 2014, Kettenring et al. 2019). The remaining ten taxa are native to some U.S. states, but are not in Florida (USDA 2019). Eighty nine percent of the taxa on the final list have been introduced to North America (Fig. 5B). This region was followed closely by East Asia and the Pacific (79% of taxa), Europe and Central Asia (71% of taxa), and Latin America and the Caribbean (69% of taxa). Other regions were included in 40% or fewer of the taxa's introduced ranges.



**Figure 5.** Ranges of taxa. **A** Native and **B** introduced ranges of the final list of taxa generalized at the country level. Countries with darker shades indicate a greater number of taxa native or introduced to the area. The state of Florida is in red.

## Discussion

Our analysis of the 99 plant taxa most likely to be introduced to Florida identified six that have a high risk of becoming invasive in the state in the next ten years (2020–2030). The horizon scanning process helped us identify taxa that should undergo more thorough risk assessments and potentially receive policy restrictions or research priority. The process we used is a reproducible methodology that can be applied to future horizon scans.

Four taxa (*Ligustrum vulgare*, *Cytisus scoparius*, *Phalaris arundinacea*, and *Avena fatua*) had high risk scores with high certainty. We recommend that these taxa receive more thorough risk assessments followed by consideration for monitoring or regulation by the relevant state agencies. *Phalaris arundinacea* was assessed by the University of Florida Institute of Food and Agricultural Sciences Assessment of Non-native Plants in Florida's Natural Areas, which uses a predictive tool of 49 questions, and found to be a high invasion risk (University of Florida 2014). In our rapid risk assessments, two taxa (*Agrostis capillaris* and *Persicaria hydropiper*) had high risk scores, but assessors had medium certainty about these scores. Competition studies should be conducted with *A. capillaris* to increase certainty, as experts were unsure how *A. capillaris* would fare in competition with native Florida grasses. Experts also identified the need for agricultural impact studies of *P. hydropiper*, which interferes with crops and grazing in other regions (Suppl. material 3: Table S2). If the high level of risk assigned to the top six taxa is supported following additional research and more thorough risk assessments, we recommend regulators consider policy actions to limit the introduction of these taxa to Florida. Specifically, the industries that use or unintentionally disperse these taxa (Table 2) should limit their potential for escape. U.S. states in which the taxa are included in noxious weed lists or laws (EDDMapS 2021) could be consulted for prevention approaches.

We identified “escape from confinement” as the most likely pathway for taxa on our final list to arrive in Florida’s natural areas. This pathway includes escape from agriculture, botanical gardens, forestry, horticulture, ornamental sources other than horticulture, and research (CBD 2014). Indeed, most terrestrial plant species in a global database of invasive species and in lists of non-native species in Europe arrived by escaping confinement (Hulme et al. 2008). Domestication of species for food, ornamental purposes, and biofuel can select for traits that increase invasion risk, including fast growth rates, high fecundity, and the ability to hybridize (Petri et al. 2021). However, selection for traits that reduce invasion risk and do not interfere with the commercial purposes of plants could help prevent escape from confinement (Petri et al. 2021). For example, scientists at the University of Florida have developed sterile, low risk cultivars of the invasive species *Lantana camara* for landscape use within the state (Czarnecki et al. 2012).

Taxa on our final list were also likely to arrive in Florida’s natural areas as transport contaminants, transport stowaways, or through unaided dispersal. Florida’s seaports are some of the most active in the country (US Army Corps of Engineers 2018), hosting global and domestic imports and exports, as well as millions of cruise passengers (Florida Department of Transportation 2017). Florida is also a top tourist destination, attracting well over 100 million visitors from within and outside of the U.S. each year (VISIT FLORIDA 2020). These high movement rates provide ample opportunities for plant propagules to enter the state. The risk of introducing taxa through consistent trade routes, however, can be mitigated by identifying steps in the process of importing, processing, and storing goods that can be modified to reduce plant survival (Hulme 2009).

The identity of the assessor, the assessor’s certainty level, and the invasion history of the taxa in the U.S. significantly affected the overall risk scores of the assessed taxa. Two experts, who had extensive experience completing plant risk assessments, scored taxa consistently higher than two other experts, who had less experience completing plant risk assessments. To address this issue, future horizon scans could calibrate scores among experts with a set of test taxa prior to beginning the rapid risk assessments. We hypothesize that overall risk scores are correlated with overall certainty scores because more available data on a taxon contributes to higher certainty and can provide more pieces of evidence that a taxon may arrive, establish, or have impacts. Similarly, we hypothesize that taxa with earlier and more records of occurrence in the U.S. are likely to be better represented in English-language texts than taxa that are less common or more recently detected, leading to more evidence for arrival, establishment, and impacts, which could explain their generally higher risk scores. Efforts to synthesize and standardize information about invasive species (Simpson et al. 2019, CABI 2021) could reduce these potential sources of bias.

The families Juncaceae, Poaceae, Polygonaceae, and Rosaceae were significantly overrepresented in both the final horizon scan list and the initial CABI list compared to the number of accepted species in these families. These families, especially Poaceae, Polygonaceae, and Rosaceae, are similarly overrepresented in global lists of naturalized plants (Daehler 1998, Pyšek 1998, Pyšek et al. 2017). Rushes (Juncaceae) can produce large amounts of seed, expand clonally, and resist herbivory through low palatability (Ashby et al. 2020). Grasses (Poaceae) have wide ranges of environmental tolerance, are frequently transported for human uses, and can grow quickly, outcompete resident species, tolerate disturbances, and alter ecosystem processes (Pyšek 1998, Canavan et al. 2019). In addition, mis-identified invasive rushes and grasses may go undiscovered for long periods, allowing them to establish self-sustaining populations before being controlled (Scott and Hallam 2003,

Pyšek et al. 2013). Knotweeds (Polygonaceae) are diverse in growth form (i.e., perennial herbs, shrubs, trees, and vines) and include some aggressive invasive species (Brandbyge 1993, Gerber et al. 2008). Roses (Rosaceae) are also diverse in growth form and are frequently planted by humans as crops, ornamentals, and medicinals (Hummer and Janick 2009). Although none of the families included in the final horizon scan list were significantly underrepresented, some large families, such as Orchidaceae, were completely absent and are underrepresented in larger lists of naturalized species (Daehler 1998, Pyšek 1998, Pyšek et al. 2017). Such general trends can help identify families on which to concentrate risk assessment resources.

Most of the taxa that made our final list were native to Europe, Asia, and North Africa. Europe is the native range for a disproportionately high number of naturalized plant species relative to the number of native plant species (van Kleunen et al. 2015), which may be influenced by plant adaptations to European pastoralism and cultivation—practices that have been adopted in regions outside of Europe (MacDougall et al. 2018)—and historical exchange between Europe and other geographic regions (Pyšek et al. 2015). Temperate Asia is also a major source of global naturalized plant species (van Kleunen et al. 2015). Because Florida's Köppen-Geiger climate zones most consistently overlap with Central and South America, central Africa, and southern and eastern Asia (Kottek et al. 2006), our final list likely omits key high-risk taxa. However, propagule pressure significantly contributes to invasive species success (Lockwood et al. 2005, Cassey et al. 2018) and Europe is one of the top sources of tourists and merchandise imports for Florida (VISIT FLORIDA 2020, U.S. Department of Commerce 2021), suggesting that the taxa in the final list are of legitimate concern. Future horizon scans could focus on taxa from geographic regions with strong trade and tourism ties to the focal area, allowing for more targeted assessments.

GBIF is a powerful tool, connecting organizations and institutions that collect and store biodiversity data and making that data publicly available (GBIF.org 2020). We used GBIF data multiple times during our horizon scan: to select the top 100 taxa based on global occurrences, to evaluate arrival risk based on how close occurrences were to Florida, and to evaluate establishment risk based on whether taxa were found in areas with the same Köppen-Geiger zones as Florida. Two potential sources of bias introduced by the GBIF dataset are amateur identification of plants and records collected non-systematically across geographies. Some plant species and subspecies are difficult to differentiate from one another, leading to inaccurate records by amateur botanists (Scott and Hallam 2003). However, of the 461,876 U.S. occurrences in GBIF for taxa in our final list, only 0.06% of them were recorded by iNaturalist users (GBIF.org 2021b, iNaturalist 2021), who include amateur botanists. Non-systematic sampling likely concentrates records in populated areas. Therefore, taxa that can inhabit disturbed areas, are moved around by people, and that are visually charismatic likely have more records. These traits, however, are associated with non-native species introductions (Hobbs and Huenneke 1992, Hulme et al. 2008, Jarić et al. 2020), so they would bias our estimates of arrival risk appropriately.

This horizon scan of invasive plant threats to Florida provides a first step in reducing the impacts of invasive species on Florida's natural systems. Like other horizon scans of invasive species, the generated list informs future research efforts and policy (e.g., Matthews et al. 2014, Roy et al. 2014, Gallardo et al. 2016, Lucy et al. 2020). Our horizon scan departs from previous invasive species horizon scans, however, in important ways. First, we began with a list of 2128 potential invasive taxa that was too large to perform rapid risk assessments in a reasonable timeline. We therefore developed data-based criteria to filter the list to 100 taxa.

These methods could be applied to other horizon scans with similar resource constraints. Second, the rapid risk assessment tool and associated rubrics led to enough consensus among experts that our final rankings relied much more on scores than on discussion and consensus building (e.g., in contrast to Roy et al. 2014, Lucy et al. 2020). A drawback of this approach is the loss of nuanced expert opinion that falls outside of the rubrics, which is an important component of horizon scans when information on a potential invasive species is limited in peer-reviewed literature (Verbrugge et al. 2019). A major advantage, however, is that this approach can be used with non-experts, which is relevant for efforts limited by available expertise (Meyers et al. 2020).

## Conclusion

Here we presented a horizon scan of 2128 plant taxa, identifying six with a high invasion risk for Florida over the next ten years and 93 with medium or low invasion risk. The horizon scan process therefore can reduce the potential number of taxa requiring thorough risk assessments by three orders of magnitude. Although the process has room for improvement, the results provide researchers, regulators, and private and public land managers with a clear list of high risk species to focus on. Given the substantial impacts and costs of invaders in Florida, the ability to differentiate and focus efforts on high probability bad actors is critical.

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## Competing interests

The authors have declared that no competing interests exist.

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## Figure legends

**Figure 1.** Criteria for selecting taxa for rapid risk assessment. The criteria included the following systematic steps: (1) a preliminary list of 2128 taxa; (2) correcting for synonyms, which increased the original list to 2360; (3) climate matching with Köppen-Geiger climate zones (Kottek et al. 2006, CABI 2018), which identified 1504 taxa that could potentially become established in Florida if climate were the only limiting variable; (4) 197 taxa were already naturalized in Florida (Wunderlin et al. 2019) and removed from the list; (5) 57 taxa were already listed on state or federal noxious weed lists (State of Florida 2008, 2020, USDA 2017, FISC 2019) and were removed from the list; (6) taxa that were naturalized somewhere outside of their native range (van Kleunen et al. 2019), suggesting the ability to establish in habitats where they did not co-evolve with other species, were selected (912 taxa); (7) taxa with a record of “weediness”, suggesting the ability to produce a self-sustaining population and have at least mild impacts on the surrounding environment (Randall 2017), were selected (808 taxa); (8) the top 100 taxa, ranked by number of global occurrences (GBIF.org 2021a), were selected. More details on the datasets used to inform these criteria can be found in Suppl. material 1: Methods S1.

**Figure 2.** The six taxa that were designated as high risk for invasion potential in Florida. Overall risk scores are in white circles (maximum possible score is 125). (Photos: Meneerke bloem, Isidre blanc, Andreas Eichler, Stefan.lefnaer, CC BY-SA 4.0; Robert Flogaus-Faust, CC BY 4.0; Rasbak, CC BY-SA 3.0; Willow, CC-BY 2.5; Mary Joyce, Katrice Baur, scottq1, rael17, CC BY-NC 4.0; Christian Grenier, CC0 1.0).

**Figure 3.** Horizon scan scores. **A** The overall risk scores for 99 taxa, divided into groups of high risk (score  $\geq 64$ ), medium risk ( $27 \leq \text{score} < 64$ ), and low risk (score  $< 27$ ) and shaded by overall certainty score. **B** The number of taxa associated with each of the pathways of arrival. Multiple pathways could be assigned to a single taxon. **C** The relationship between certainty and the overall risk score, averaged across all taxa. Letters above bars indicate significant differences in overall risk score among certainty scores with  $P < 0.05$ .

**Figure 4.** Earliest record and number of records. The overall risk score and **A** the year of the earliest record in the U.S. and **B** the number of records (displayed on a  $\log_{10}$  scale for clarity) in the U.S. for the 99 taxa on the final list. Points represent data while lines and shading represent model-estimated mean  $\pm$  SE.

**Figure 5.** Ranges of taxa. **A** Native and **B** introduced ranges of the final list of taxa generalized at the country level. Countries with darker shades indicate a greater number of taxa native or introduced to the area. The state of Florida is in red.

## Supplementary materials

**Suppl. material 1.** Methods for trimming the list of potential invasive species based on several criteria.

**Suppl. material 2: Table S1.** Potential invasive plant species provided by the CABI Horizon Scan Tool, their synonyms, and their values for criteria described in Suppl. material 1.

**Suppl. material 3: Table S2.** Reviewed rapid risk assessments of the 99 plant species in the final list, ordered by overall score.

**Suppl. material 4: Table S3.** Test of under- or overrepresentation of plant families in the final horizon scan list based on resampling of accepted species from The Plant List database.

**Suppl. material 5: Table S4.** Test of under- or overrepresentation of plant families in the initial CABI list based on resampling of accepted species from The Plant List database.

#### **Data Availability**

Raw data and code are available at <https://github.com/aekendig/fl-plants-horizon-scan>. This repository will be assigned a DOI and archived with Zenodo following acceptance of the manuscript.