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Development and application of a multilingual electronic decision-support tool for risk screening non-native terrestrial animals under current and future climate conditions

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Abstract

Electronic decision-support tools are becoming an essential component of government strategies to tackle non-native species invasions. This study describes the development and application of a multilingual electronic decision-support tool for screening terrestrial animals under current and future climate conditions: the Terrestrial Animal Species Invasiveness Screening Kit (TAS-ISK). As an adaptation of the widely employed Aquatic Species Invasiveness Screening Kit (AS-ISK), the TAS-ISK question template inherits from the original Weed Risk Assessment (WRA) and related WRA-type toolkits and complies with the 'minimum requirements' for use with the recent European Regulation on invasive alien species of concern. The TAS-ISK consists of 49 basic questions on the species' biogeographical/historical traits and its biological/ecological interactions, and of 6 additional questions to predict how climate change is likely to influence the risks of introduction, establishment, dispersal and impact of the screened species. Following a description of the main features of this decision-support tool as a turnkey software application and of its graphical user interface with support for 32 languages, sample screenings are provided in different risk assessment areas for one representative species of each of the main taxonomic groups of terrestrial animals supported by the toolkit: mammals, birds, reptiles, amphibians, annelids, insects, molluscs, nematodes, and platyhelminths. The highest-scoring species were the red earthworm *Lumbricus rubellus* for the Aegean region of Turkey and the New Zealand flatworm *Arthurdendyus triangulatus* for Croatia. It is anticipated that adoption of this toolkit will mirror that of the worldwide employed AS-ISK, hence allowing to share information and inform decisions for the prevention of entry and/or dispersal of (high-risk) non-native terrestrial animal species – a crucial step to implement early-stage control and eradication measures as part of rapid-response strategies to counteract biological invasions.

Keywords
AS-ISK, biological invasions, decision-makers, turnkey application, TAS-ISK, WRA

Introduction

The steady increase in recent times in the number of invasive non-native species worldwide and its implications for wildlife conservation emphasise the importance of developing user-friendly decision-support tools for scientists to inform decision-makers about the prioritisation of management actions in response to non-native species' impacts (Dana et al. 2014; González-Moreno et al. 2019). The identification and assessment of hazards is a crucial aspect of environmental risk analysis, which consists of three steps: risk screening (identification), risk assessment, and risk communication and management (Canter 1993; UK Defra 2003; Booy et al. 2017; Robertson et al. 2021). In the risk analysis process applied to non-native species, risk screening identifies which non-native species are likely to be invasive in a given risk assessment area. This facilitates the development of policy and management procedures for that risk assessment area to prevent and/or mitigate the impacts of biological invasions (Copp et al. 2016a). In particular, risk screening of non-native species assists decision-makers in the allocation of resources to predict which species pose an elevated threat to native species and ecosystems and therefore require full (follow-up) risk assessment. This involves detailed examination of the likelihood and magnitude of risks of introduction, establishment, dispersal and impacts of a non-native species (Copp et al. 2005, 2016a; Baker et al. 2008; Mumford et al. 2010). To this end, it is crucial to distinguish between risk screening and risk assessment: this distinction is often overlooked in environmental risk analysis, where decision-support tools are often compared and evaluated together (e.g. González-Moreno et al. 2019; Marcot et al. 2019; see also Hill et al. 2020). In this regard, the present study will focus on the first step of the risk analysis process, i.e. the risk screening, and this will include discussion of any related decision-support tools.

Decision-support tools have been developed for screening aquatic and terrestrial non-native species as well as pathogens (Pheloung et al. 1999; Copp et al. 2005, 2009, 2016b, 2021; D'hondt et al. 2015; Drolet et al. 2016). Amongst the most widely applied is the Weed Risk Assessment (WRA) for terrestrial plants (Pheloung et al. 1999) and its adaptations to various biogeographic regions and to the screening of aquatic plants (Gordon et al. 2008). The WRA question template formed the basis to create the Fish Invasiveness Screening Kit (FISK) for freshwater fish (Copp et al. 2005; Vilizzi et al. 2019) and its 'sister' -ISK toolkits for other aquatic organisms (Copp 2013). More recently, the -ISK toolkits were combined into the taxon-generic Aquatic Species Invasiveness Screening Kit (AS-ISK) to screen freshwater, brackish and marine aquatic organisms under current and future climate conditions (Copp et al. 2016b; Vilizzi et al. 2021). Other risk screening tools include Harmonia^{+} and Pandora^{+} (D'hondt et al. 2015) for plants, animals and their pathogens, and the Canadian Marine Invasive Screening Tool (CMIST: Drolet et al. 2016) for marine organisms.

A common feature of these risk screening tools is their availability in spreadsheet format, but with the AS-ISK only being designed as a 'turnkey' application (Copp et al. 2016b). This is contrary to the 'automated workbook' format of the other toolkits, which can make their usage time-consuming, if not counter-intuitive, to the end user. For this reason, the recent development of the AS-ISK as a user-friendly, dialog-driven electronic decision-support tool (Copp et al. 2016b) has resulted not only in a shortening of the risk screening process and, possibly, the follow-up decision-making (Matthies et al. 2007) but has also ensured exchangeability and seamless deployment of data and information across users (Copp et al. 2021). A 'fully fledged' electronic decision-support tool such as the AS-ISK, however, is currently available only for the screening of aquatic organisms. In contrast, for terrestrial organisms the (semi-automated) spreadsheet-based WRA (and its various adaptations: Gordon et al. 2008) is the only available tool for screening weeds (Dana et al. 2014). At the same time, most decision-support tools have been developed mainly in English (see Copp et al. 2021). This limitation increases the linguistic uncertainty associated with risk screenings undertaken by non-native English assessors (scientists) who ultimately need to communicate the risk outcomes to decision-makers in the country's native/official language. To meet these requirements, the 32 languages available to users of the AS-ISK are meant to enhance communication of non-native species' risks to local authorities and within/amongst non-English-speaking countries (Copp et al. 2021).

Despite the successful adoption and implementation of the WRA-type toolkits worldwide (Gordon et al. 2008; Vilizzi et al. 2019, 2021), there is currently no similar decision-support tool for screening terrestrial animals, as exemplified by the recent use of the AS-ISK as a 'surrogate' for screening terrestrial reptiles (Kopecký et al. 2019). To address this gap, this paper describes the development and application of a 'sibling' toolkit to the AS-ISK that will allow to share information and inform decision-makers about the prevention of entry and/or dispersal of (high-risk) non-native terrestrial animal species – a crucial step to implement early-stage control and eradication measures as part of rapid-response strategies to counteract biological invasions (Piria et al. 2017; Copp et al. 2021). The aims of this study were threefold: (i) to develop a turnkey application based on the AS-ISK template to produce the Terrestrial Animal Species Invasiveness Screening Kit (TAS-ISK) and describe the main elements of the toolkit's interface and functionality (including some additional features introduced since the release of AS-ISK v1: Copp et al. 2016b); (ii) to review the questions and guidance for aquatic species in the AS-ISK template for adaptation to non-native terrestrial animal species in the TAS-ISK; and (iii) to implement a trial screening of the TAS-ISK on one representative species for each of the main terrestrial animal taxonomic groups supported by this new toolkit.

Methodology

Toolkit features

As an 'offshoot' of the AS-ISK, the TAS-ISK is also designed to comply with the 'minimum standards' for screening non-native species under EC Regulation No. 1143/2014 on the prevention and management of the introduction and spread of invasive alien species (EU 2014). The TAS-ISK consists of 55 questions (Qs). The first 49 Qs comprise the Basic Risk Assessment (BRA) and address the biogeography/invasion history and biology/ecology of the screened species. The last 6 Qs include the Climate Change Assessment (CCA) and require the assessor to predict how predicted (future) climatic conditions are likely to affect the BRA with respect to risks of introduction, establishment, dispersal and impact. The BRA questions consist of two sections with eight categories: Section A Biogeography/Invasion History including Categories Domestication/Cultivation, Climate, distribution and introduction risk, and Invasive elsewhere; Section B Biology/Ecology, including Categories Undesirable (or persistence) traits, Resource exploitation, Reproduction, Dispersal mechanisms, and Tolerance attributes. The CCA questions comprise Section C (and Category) Climate change (see Suppl. material 1: Table S1).

To achieve a valid screening, the assessor must provide for each question a response, a level of confidence for the response (see below), and a justification based on literature sources. The outcomes are a BRA score, which ranges from –20 to 68, and a (composite) BRA+CCA score, which ranges from –32 to 80 (i.e. after adding or subtracting up to 12 points to the BRA score or leaving it unchanged in case of a CCA score equal to 0). Confidence levels in the responses to questions are ranked using a 1–4 scale (1 = low; 2 = medium; 3 = high; 4 = very high) as per the Intergovernmental Panel on Climate Change (see Copp et al. 2016a). Based on the confidence level (CL) allocated to each response, a confidence factor (CF) is obtained as:

$$CF = \sum(CL_{Qi})/(4 \times 55) \ (i = 1, \ldots, 55)$$

where CL_{Qi} is the CL for Qi, 4 is the maximum achievable value for confidence (i.e. very high: see above) and 55 is the total number of questions comprising the TAS-ISK questionnaire. The CF ranges from a minimum of 0.25 (i.e. all 55 Qs with a confidence level equal to 1) to a maximum of 1 (i.e. all 55 Qs with a confidence level equal to 4). For the CF, the CF_{Total}, CF_{BRA} and CF_{CCA} (based on all 55 Qs, on the 49 Qs comprising the BRA, and on the 6 Qs comprising the CCA, respectively) are computed. For further details about implementation of the overall risk screening process, see Vilizzi et al. (2022).

Toolkit development

Questions and related guidance of the AS-ISK v2.3.x template (noting that this toolkit is now available in its release v2.3.2: www.cefas.co.uk/nns/tools) were critically reviewed for application to terrestrial animal taxa. Following modification to the relevant questions and related guidance for adaptation to terrestrial animals, the resulting template was finalised by a consensus meeting to improve clarity, conciseness and accuracy in the text of both questions and guidance. The final template was then circulated amongst the author-translators (see below) for translation into the corresponding native language of the parts of text modified relative to the original AS-ISK template.

Similar to the AS-ISK, the TAS-ISK is designed as a 'turnkey application' (*sensu* Walkenbach 2007). This represents the most advanced level of Excel VBA software development as it allows complete distinction (separation) between graphical user interface, business logic, and data access/storage tiers. This is ensured by separating the data (i.e. the spreadsheet) and the graphical user interface (consisting of tightly controlled dialogs) from the underlying code. All these features offer major benefits: (i) for the end user, by allowing the assessor to work seamlessly on the database spreadsheet(s) located on the local computer or accessible from a network (e.g. under a 'cloud system'); and (ii) for the developer, by facilitating provision of feedback and support by software updates that will replace previous releases of the toolkit whilst ensuring full backward compatibility in data access. The TAS-ISK graphical user interface is available in 32 languages, which allows it to be used in some 161 countries worldwide (see also Copp et al. 2021): English, Albanian, Arabic, Bulgarian, Chinese (simplified), Croatian, Czech, Dutch, Filipino, French, Georgian, German, Greek, Hebrew, Hungarian, Italian, Japanese, Korean, Macedonian, Persian, Polish, Portuguese, Romanian, Russian, Slovak, Slovenian, Spanish, Swedish, Thai, Turkish, Urdu, Vietnamese. This extent of language support is the most advanced allowed by the Excel VBA code (Walkenbach 2007), as it includes support of right-to-left languages (i.e. Arabic, Hebrew, Persian, Urdu) and double-byte-character-set languages (i.e. Chinese, Japanese, Korean).

The TAS-ISK is available for download at www.cefas.co.uk/nns/tools in its release v2.3.2. This first release number of the toolkit mirrors that of the latest version of the AS-ISK (see above), with which the TAS-ISK, as already emphasised, shares most of the underlying code. The TAS-ISK allows the screening of nine taxonomic groups of terrestrial animals (classification mainly after Zoological Record indexing service: https://www.ebsco.com/products/research-databases/zoological-record): Mammals, Birds, Reptiles, Amphibians, Annelids, Insects, Molluscs, Nematodes, Platyhelminths, Other arthropods, Other eukaryote taxa.

Trial screenings

Trial screenings were conducted for one representative taxon (hereafter, for simplicity 'species') of each of the main taxonomic groups of terrestrial animals (i.e. except for 'Other arthropods' and 'Other eukaryote taxa'). In total, eight experts (= assessors) were involved in the resulting nine screenings, with seven species screened each by a single assessor, one species screened by two joint assessors and another species screened by three joint assessors. One assessor screened two species and another assessor four species (Table 1). Notably, each assessor chose the non-native species for screening in which they were more knowledgeable in terms of its environmental biology and risk assessment area.

Each species was categorised *a priori* into non-invasive or invasive based on a search made of: (i) the Centre for Agriculture and Bioscience International Invasive Species Compendium (CABI ISC: www.cabi.org/); (ii) the Global Invasive Species Database (GISD: www.iucngisd.org); and (iii) the Invasive and Exotic Species of North America list (IESNA: www.invasive.org). If the species was not categorised as invasive in any (or all) of the previous three databases, a Google Scholar (literature) search was performed to check whether at least one peer-reviewed reference was found that 'demonstrates' (hence, not 'assumes') invasiveness/impact. The latter was then taken as 'sufficient evidence' for categorising the species as invasive; whereas, if no evidence was found in this last step, then the species was categorised as non-invasive (see also Vilizzi et al. 2022).

As a result of the *a priori* categorisation, there were eight species categorised *a priori* as invasive: the aoudad/Barbary sheep *Ammotragus lervia* (Mammals), the common pheasant *Phasianus colchicus* (Birds), the common house gecko *Hemidactylus frenatus* (Reptiles), the red earthworm *Lumbricus rubellus* (Annelids), the western corn rootworm *Diabrotica virgifera virgifera* (Insects), the Spanish slug *Arion vulgaris* (Molluscs),

Table 1. Taxa evaluated with the Terrestrial Animal Species Invasiveness Screening Kit (TAS-ISK) for their potential risk of invasiveness in different risk assessment areas. For each species, the *a priori* categorisation outcome into Non-invasive and Invasive is provided (after Vilizzi et al. 2022).

Taxonomic group	Taxon name	Common name	Assessor(s)	Risk assessment area	*A priori* categorisation
Mammals	*Ammotragus lervia*	aoudad/Barbary sheep	NS, TR, MP	Europe	Invasive
Birds	*Phasianus colchicus*	common pheasant	TR	Croatia	Invasive
Reptiles	*Hemidactylus frenatus*	common house gecko	BS, MP	Pannonian region of Hungary	Invasive
Amphibians	*Bombina variegata*	yellow-bellied toad	OC	Anatolia (Turkey)	Non-invasive
Annelids	*Lumbricus rubellus*	red earthworm	NK	Aegean region of Turkey	Invasive
Insects	*Diabrotica virgifera virgifera*	western corn rootworm	DL	Croatia	Invasive
Molluscs	*Arion vulgaris*	Spanish slug	IŠ	Croatia	Invasive
Nematodes	*Ditylenchus destructor*	potato rot nematode	MP	Croatia	Invasive
Platyhelminths	*Arthurdendyus triangulatus*	New Zealand flatworm	MP	Croatia	Invasive

the potato rot nematode *Ditylenchus destructor* (Nematodes), and the New Zealand flatworm *Arthurdendyus triangulates* (Platyhelminths). The only species categorised *a priori* as non-invasive was the yellow-bellied toad *Bombina variegata* (Amphibians). For seven species the risk assessment area was Europe or part of it, and for two species it was Anatolia and Aegean regions of Turkey in Asia (Table 2).

Differences in CF between components (BRA, BRA+CCA) were tested with permutational ANOVA. Analysis was implemented in PERMANOVA+ for PRIMER v7, with normalisation of the data and using a Bray-Curtis dissimilarity measure, 9999 permutations of the raw data, and with statistical effects evaluated at $\alpha = 0.05$.

Results

Toolkit development

Modification of the original AS-ISK questionnaire (template) for adaptation to terrestrial animals resulted in changes only to the text for one question, only to the guidance for 14 questions, and to both text and guidance for 10 questions. This resulted in 25 questions being modified out of the 55 in total (i.e. 45.5%), with changes to the text involving all Sections and Categories therein except for the six climate change questions for which only a minor removal of text from the guidance to Q53 was sufficient. In particular: for Domestication/Cultivation, changes involved the guidance for Qs 1 and 2; for Climate, distribution and introduction risk, only the guidance for Q8; for Invasive elsewhere, the text and guidance for Q11 and guidance for Q13; for Undesirable (or persistence) traits, the text and guidance for Qs 15 and 23, text for Q18, and guidance for Qs 19, 22 and 24; for Resource exploitation, the guidance for Q26; for Reproduction, the guidance for Qs 28, 32 and 34; for Dispersal mechanisms, the text and guidance for Qs 36–39 and guidance for Q41; for Tolerance attributes, the text and guidance for Qs 44, 45 and 48 and guidance for Q47; for Climate change, the guidance for Q53 (Suppl. material 1: Table S1).

The graphical user interface of the TAS-ISK consists of six 'dialogs' (i.e. user interface elements that enable communication and interaction between the user and the software program). Below, a concise description of the dialogs is provided (for a full description see the User Guide downloadable with the toolkit):

- **Start** – TAS-ISK requires a spreadsheet (Database tab) and offers the options of opening either an Existing or a New spreadsheet. The user can select to carry out the screening in any of the 32 available Language options, noting that the toolkit will open by default in the language of the Excel version installed on the local computer. The Colour scheme of choice (seven options) can also be selected. Two new features (relative to AS-ISK v1) are the Background (tab) shading (light to dark) and the size of the Dialogs view (tab), which automatically resize to adapt to low-resolution screens.
- **Main Assessment Workspace** – This is the core dialog (launched from Start) where all screening-related data information is displayed and data manipulations can

be performed (i.e. Wizard, Assessment, Thresholds, Report, Utilities tabs). As a new feature (relative to AS-ISK v1), the Report tab offers the option to generate the report for the screened species in Excel spreadsheet format, PDF or MHTML.

- **Wizard** – This new dialog (relative to AS-ISK v1) allows the assessor to generate the basic template quickly for one or (usually) more screenings as part of the risk screening of several species for the risk assessment area under study.
- **New/Edit** – In this dialog, the assessor provides all details of the screened species, either by creating a new screening, editing an existent screening, or batch-editing multiple screenings.
- **Replicate** – In this dialog, replication of a screening selected from the Main Assessment Workspace is generally performed as part of the risk screening of several species for the risk assessment area under study.
- **Q&A** – In this dialog, the screening for the species selected from the Main Assessment Workspace is carried out by responding to the 55 questions, ranking the level of confidence/certainty associated with the response, and providing references and/or other information as justification for each question-related response.

Trial screenings

The highest scoring (*a priori* invasive) species were *Lumbricus rubellus* for the Aegean region of Turkey and *Arthurdendyus triangulatus* for Croatia (Table 2). Both species were recognised as 'invasive elsewhere' and obtained the highest score amongst all screened species for the Biology/Ecology section, with *Arthurdendyus triangulatus* also achieving the highest possible increase (+12 points) for the CCA. The other *a priori* invasive species *Arion vulgaris*, *Diabrotica virgifera virgifera*, *Ditylenchus destructor* and *Phasianus colchicus*, all screened for Croatia, and *Ammotragus lervia*, screened for Europe, obtained BRA scores ≥ 22. These species have been recognised as invasive elsewhere and gained overall high scores for their Undesirable (or persistence) traits. The CCA increased the BRA score for *Ammotragus lervia*, *Diabrotica virgifera virgifera* and *Ditylenchus destructor*, but decreased that of *Arion vulgaris*. At the same time, there was no change in outcome score relative to the BRA (cf. BRA+CCA) for *Phasianus colchicus*. For *Hemidactylus frenatus* screened for the Pannonian region of Hungary, there was a substantial increase in the BRA+CCA relative to the BRA score. Finally, the *a priori* non-invasive *Bombina variegata* screened for Anatolia (Turkey) obtained the lowest outcome score of all species (Table 2). The TAS-ISK combined report for the nine screened species is provided as Suppl. material 2.

The highest confidence factor in responses for the BRA was found for *Diabrotica virgifera virgifera* and *Ditylenchus destructor*, and for the CCA for *Ammotragus lervia* and *Arion vulgaris*. *Bombina variegata* and *Phasianus colchicus* had confidence factors for both components below 0.60 (Table 2). The mean CF_{Total} was 0.697 ± 0.034 SE, the mean CF_{BRA} 0.699 ± 0.036 SE, and the mean CF_{CCA} 0.672 ± 0.043 SE, and there were no differences in CF between BRA and CCA (F^{MC} = 0.002, P^{MC} = 0.970; MC = Monte Carlo permutational value, best for small sample sizes).

Table 2. Scoring output for the terrestrial animal taxa screened with the TAS-ISK (see Table 1). BRA = Basic Risk Assessment; CCA = Climate Change Assessment. See also Suppl. material 1: Table S1.

Section/Category	*Ammotragus lervia*	*Phasianus colchicus*	*Hemidactylus frenatus*	*Bombina variegata*	*Lumbricus rubellus*	*Diabrotica virgifera virgifera*	*Arion vulgaris*	*Ditylenchus destructor*	*Arthurdendyus triangulatus*
A. Biogeography/Historical	12	15.5	9	5	24	21	15	19	17
1. Domestication/ Cultivation	2	4	4	2	4	2	0	0	–2
2. Climate, distribution and introduction risk	1	1	2	1	2	1	1	1	1
3. Invasive elsewhere	9	10.5	3	2	18	18	14	18	18
B. Biology/Ecology	17	12	15	3	24	9	7	12	19
4. Undesirable (or persistence) traits	8	8	5	3	6	9	4	7	5
5. Resource exploitation	5	5	7	0	5	0	0	7	2
6. Reproduction	1	5	1	1	6	–3	6	–2	4
7. Dispersal mechanisms	–2	–2	2	–3	4	0	–1	–1	2
8. Tolerance attributes	5	–4	0	2	3	3	–2	1	6
BRA Score	**29**	**27.5**	**24**	**8**	**48**	**30**	**22**	**31**	**36**
C. Climate change	4	0	8	2	6	4	–10	2	12
BRA+CCA Score	**33**	**27.5**	**32**	**10**	**54**	**34**	**12**	**33**	**48**
Confidence									
BRA	0.76	0.57	0.59	0.59	0.61	0.82	0.79	0.81	0.78
CCA	0.92	0.58	0.71	0.50	0.54	0.71	0.79	0.63	0.67
Total (BRA+CCA)	0.77	0.57	0.61	0.58	0.60	0.81	0.79	0.79	0.76

Discussion

Toolkit development

The successful employment of the WRA-type toolkits for screening weeds (cf. WRA and its derivatives) and aquatic organisms (cf. WRA, -ISK toolkits and AS-ISK) is testified by the vast number of applications worldwide (Gordon et al. 2008; Vilizzi et al. 2019, 2021, 2022). An additional value of these risk screening applications is the high degree of accuracy (cf. discriminatory power *sensu* Hosmer et al. 2013) achieved in the classification of low-to-medium- and high-risk species for a variety of risk assessment areas in different climates and biogeographic regions and, since the development of the AS-ISK, under both current and predicted future climate conditions (Vilizzi et al. 2019, 2021, 2022).

The advantages of a multilingual decision-support toolkit have been described in detail in Copp et al. (2021). In the case of the screening of terrestrial animals with the TAS-ISK, the same benefits are expected in terms of enhanced communication of species-specific risk outcomes between assessors (scientists) and decision-makers by providing screening reports in the native language. This has already been exemplified by some of the AS-ISK applications conducted in the native language of the country's risk assessment area (Vilizzi et al. 2021), including publication and discussion of the corresponding risk outcomes also in the native language (i.e. Moghaddas et al. 2020; IAVH 2021; Li et al. 2021; Wei et al. 2021b).

Trial screenings

The risk outcomes for the nine non-native terrestrial animal species screened with the TAS-ISK highlighted which species are likely to pose the greatest threat of invasiveness (e.g. *Lumbricus rubellus* and *Arthurdendyus triangulatus*), hence should be prioritised for full (follow-up) risk assessment and potentially targeted by prevention measures and related management strategies (Copp et al. 2016a). Confidence in the BRA questions was similar to that in the CCA questions, which reflected the large availability of literature resources for the screened species and the overall knowledge/expertise by the assessors in both the screened species and related risk assessment areas.

Lumbricus rubellus was the highest scoring of the species screened – a finding that is likely to apply to risk assessment areas with warm-temperate and continental climate other than Anatolia (Tiunov et al. 2006). *Lumbricus rubellus* has been introduced in many continents outside its native range in Western Europe, but it is considered invasive only in North America and New Zealand (Greiner et al. 2012; Kim et al. 2015). The species' native distribution is still unclear, as it may originate from the Pyrenees, with its native range extending across France, southern Germany, Austria, Hungary and Romania (Gates 1972). The uncertainty about the origin of *L. rubellus* is to be ascribed to the extensive agricultural and fishing activities that have occurred over the last 2000 years involving the unintentional transport of this species in the soil (i.e. by transportation of plants rooted in soil contaminated with different life stages of this species) and as fish bait (Keller et al. 2007; Crumsey et al. 2014). *Lumbricus rubellus* is harmful in forest ecosystems (Crumsey et al. 2014) and its introduction may change soil structure and chemistry, nutrient dynamics, microbial community content, and even plant community composition (Greiner et al. 2012). Furthermore, the species' hermaphroditism, tolerance of low pH (3.0–7.7) and resistance to low temperatures are all traits that increase the chance for its successful colonisation of novel environments (Tiunov et al. 2006; Wironen and Moore 2006; Kopp et al. 2012). Climate change appears to increase the competitiveness of *L. rubellus* because of its high tolerance of a wide range of temperatures, though not of a reduction in soil water content (Singh et al. 2019).

The second highest scoring species *Arthurdendyus triangulatus* is not yet found in Croatia (the risk assessment area in this study). The species' high risk of invasiveness confirms recent findings using a different risk assessment tool (Thunnissen et al. 2022) and justifies its inclusion in the Invasive Alien Species of Union Concern C/2019/5360 (European Commission 2019). *Arthurdendyus triangulatus* is a free-living terrestrial flatworm native to New Zealand introduced mainly by trade in containerised plants to the British Isles and the Faroe Islands (Murchie and Gordon 2013). This species is considered harmful mainly due to its predation on earthworms with consequent reduction of soil fertility and earthworm-feeding wildlife (Thunnissen et al. 2022). Based on the Köppen-Geiger climate classification system (Peel et al. 2007), *A. triangulatus* could become established in the northern part of Europe including The Netherlands, Denmark, Sweden and also Iceland due to its tolerance of the *Cfb*-type (warm-temperate, fully humid, warm summer) climate (Boag and Yeates 2001; Thunnissen et al. 2022). As this species prefers *Cs*-type (i.e. warm-temperate) climate conditions (typical of its native range on the South Island of New Zealand), it is very likely to establish in Croatia, where a similar climate is present. Although *A. triangulatus* is expected to become less widespread in the U.K. due to climate change (Hulme 2017), in Croatia it may considerably increase its establishment success as winter temperatures in New Zealand are milder compared to other areas of similar latitude (Sturman and Wanner 2001).

The two agricultural pests *Ditylenchus destructor* (not yet present in Croatia) and *Diabrotica virgifera virgifera* (already introduced to Croatia) gained similarly high BRA and BRA+CCA scores. *Ditylenchus destructor* and *D. virgifera virgifera* may cause severe crop damage resulting in financial losses and management expenditures (Tinsley et al. 2013; Benjamin et al. 2018). *Ditylenchus destructor* is a harmful endoparasite of roots and underground-modified plant parts in Europe and North America and is characterised by behavioural plasticity (Spencer et al. 2009; EFSA Panel on Plant Health 2016). Economically, it is the most important pest of the potato *Solanum tuberosum*, although it acts also as a pest of the sweet potato *Bulbous iris*, cultivated mushrooms, garlic *Allium sativum*, and several other cultivated plants (EFSA Panel on Plant Health 2016; Dobosz et al. 2020). Although the impact of *D. destructor* on crops in Europe is negligible due to precautionary measures, in Australia this species is regarded as posing a potentially high risk of invasiveness (Singh et al. 2015; EFSA PLH Panel 2016). Plants for potting are a pathway for the introduction and spread of *D. destructor*, which may cause severe impacts on their intended use. Climate conditions in Europe are favourable to the completion of the species' life cycle, and all of its developmental stages can overwinter successfully throughout Europe (EFSA Panel on Plant Health 2016). *Diabrotica virgifera virgifera* was introduced by at least five independent events from northern USA into Europe (Ciosi et al. 2008), where it is currently successfully established, including in the risk assessment area of Croatia (Lemic et al. 2015). This species is a major pest of corn *Zea mays* but may also affect alternative host species such as soybean *Glycine max* or crops of pumpkin *Cucurbita* sp. (Manole et al. 2017a, b). *Diabrotica virgifera virgifera* poses a challenge to management actions because of its invasive nature and adaptability (Toepfer and Kuhlmann 2006; Toth et al. 2020). Climate is one of the most critical environmental factors for the species' colonisation success (Aragón et al. 2010; Dupin et al. 2011), and as a result of climate change the future distribution of this species may extend northward with the resulting risk of outbreaks at higher latitudes (Aragón and Lobo 2012).

Ammotragus lervia is native to North Africa and established in Croatia, Czechia, Italy and Spain following intentional introductions for hunting purposes (Šprem et al. 2020). *Phasianus colchicus*, partly native to Europe, has a long history of introductions and re-introductions with populations established across the continent (Ashrafzadeh et al. 2021). Both *A. lervia* and *P. colchicus* are highly adaptable and plastic in their use of available food resources, resulting in their distribution expanding rapidly (Hoodless et al. 2001; Šprem et al. 2020). *Phasianus colchicus* is already widespread across Europe including the risk assessment area (Croatia), where it may be favoured by proximity to human-affected land cover (i.e. agriculture, orchards and plantation forests; Ashoori et al. 2018). It has been observed that populations of *P. colchicus* in Croatia have been declining for the past 30 years. However, intended population reinforcements with captive-bred individuals may have negatively affected population size by outbreeding depression, introduction and fast spread of diseases and parasites from birds introduced from foreign sources (Ashrafzadeh et al. 2021). As a result, it seems that further population expansion of this species is not to be expected under current conditions. Also, the distributional range of *P. colchicus* already covers a variety of climate conditions and habitats (Ashoori et al. 2018); hence, further benefits in terms of range expansion under climate change conditions in the risk assessment area remain low. On the contrary, the intense desertification process that is taking place in Mediterranean regions (cf. south-east Spain) as a result of lowered rainfall regimes and increased mean annual temperatures, may result in substantial habitat changes that may favour the expansion of a desert caprid such as *A. lervia* (Acevedo et al. 2007). Thus, particularly in the Mediterranean region of European countries, the threat posed by *A. lervia* population expansion under future climate conditions may become higher.

The native distributional range of *Arion vulgaris* is still uncertain as this species is thought to be native to the Iberian Peninsula (Zemanova et al. 2016) and southern France (Zając et al. 2020). *Arion vulgaris* has extended its distributional range to several European countries (Zemanova et al. 2016) and is classified as one of the 100 most invasive terrestrial invertebrate species in Europe (Vilà et al. 2009). *Arion vulgaris* may pose severe damage to agriculture and horticulture, is responsible for the defoliation of wild plants and trees and has also caused severe impacts in terms of decline in abundance and also disappearance of its congener red slug *A. rufus* as a result of hybridisation (Zemanova et al. 2017). However, mitochondrial diversity of *A. vulgaris* is lower than that of its congeners with a weak association of genetic structuring amongst geographically distant populations in Europe, which suggests a human contribution to the species' ongoing expansion (Zemanova et al. 2016). Based on predicted future temperature increase scenarios for Europe, the broad range of suitable areas for the establishment of *A. vulgaris* may slightly decrease (Zemanova et al. 2018).

There is still no evidence of established populations in Europe of *Hemidactylus frenatus*, which is native to Southeast Asia, although specimens have been recorded in Italy and Portugal as hitchhikers (Weterings and Vetter 2018). This species has been classified as highly invasive in tropical regions of America, Africa, Asia and Australasia (Lei and Booth 2014) due to its competition for food and space with native geckos and transmission of endo- and ecto-parasitic mites (Dame and Petren 2006; Diaz et al. 2020). Recently, several adult specimens of *H. frenatus* were found in Hungary (B. Szajbert, unpulbished data) but it was assumed that this species cannot overwinter outdoors due to its intolerance to the low winter temperatures present in the Pannonian region (Lei and Booth 2014). However, it was recently noted that *H. frenatus* captured in winter has cold tolerances 1–2 °C lower than those captured in summer, suggesting that tropical invaders can adjust their temperature tolerance downwards via phenotypic plasticity (Lapwong et al. 2021). Such changes may allow tropical invaders to expand their geographic range into colder regions of their non-native ranges (Lapwong et al. 2021). This could increase the probability of establishment of *H. frenatus* in the Pannonian region of Hungary under future climate change conditions (Rödder et al. 2008).

The lowest scoring species *Bombina variegata* is protected under the EU Habitat Directive and has been classified as 'Least concern' in the IUCN Red List of Threatened Species since 2004 (Kuzmin et al. 2009). The Atlantic and continental populations of *B. variegata* are classified as in 'bad' condition and others in 'poor' condition, with only a Greek lineage of this species being reported as self-sustaining on a long-term basis and classified as in 'good' condition (https://eunis.eea.europa.eu/species/638#threat_status). The *B. variegata* lineage (subspecies *B. variegata scabra*) originating from Greece (Sotiropoulos 2020) has recently extended its distributional range to Kurtkaya-Enez (Edirne) in Turkey, where it has established self-sustaining populations (Bülbül et al. 2016). According to the Köppen-Geiger climate system, areas with suitable climate conditions will increase in the risk assessment area of Anatolia (Rubel and Kottek 2010), thereby favouring the dispersal of *B. variegata*. This species has been introduced to Great Britain and Northern Ireland (Roy et al. 2020), where no detrimental impacts have been observed. The lowest score amongst the screened species obtained by *B. variegata* in this study is a further indicator of the applicability and reliability of the newly released TAS-ISK.

Conclusions

Given the current dearth of risk screening applications for non-native terrestrial animals (but see Baiwy et al. 2015; Schaffner and Ries 2019; Ries et al. 2021; Thunnissen et al. 2022), it is anticipated that the availability of the TAS-ISK as a multilingual turnkey application will allow for a 'quantum leap' in this field of research in conservation biology. Accordingly, prospective applications of this newly released decision-support tool may focus on: (i) lists of potentially invasive non-native species (both extant and horizon) for selected risk assessment areas, which would allow for local 'calibration' (i.e. setting of a threshold to distinguish between low-to-medium and high-risk species) (e.g. Clarke et al. 2020; Interesova et al. 2020; Killi et al. 2020; Uyan et al. 2020; Li et al. 2021; Moghaddas et al. 2021; Radočaj et al. 2021; Ruykys et al. 2021; Wei et al. 2021a, b), (ii) global (meta-analytical) studies for setting taxonomic group and/or climate-specific thresholds (e.g. Tarkan et al. 2021; Vilizzi et al. 2021), and (iii) individual non-native and (potentially) invasive species regarded as 'high priority' in terms of e.g. importation/commercial exploitation/evaluation of existing impacts for a specific risk assessment area (e.g. Castellanos-Galindo et al. 2018; Suresh et al. 2019; Baduy et al. 2020; Zięba et al. 2020; Haubrock et al. 2021; Kumar et al. 2021; Yoğurtçuoğlu et al. 2021).

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Supplementary material 1

Table S1

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Data type: docx file

Explanation note: List of the 55 questions (Qs) making up the Terrestrial Animal Species Invasiveness Screening Kit (TAS-ISK v2.3.1). Sector codes (in parentheses): C = Commercial; E = Environmental; S = Species or population nuisance traits. Changes of questions relative to AS-ISK v2.3.1: G = Guidance; Q = Question (text). For each Q, the corresponding Question (text), Guidance and choice of Response (with coding as displayed in report and score) are indicated.

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Supplementary material 2

Combined TAS-ISK report

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Data type: pdf file

Explanation note: Combined TAS-ISK report including the nine screenings for the sample terrestrial animal species.

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