A peer-reviewed open-access journal
NeoBiota
Advancing research on alien species and biological invasions

NeoBiota 92: 61–83 (2024)
DOI: 10.3897/neobiota.92.113013

Research Article

Towards integrating and harmonising information on plant invasions across Australia

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Academic editor: Maud Bernard-Verdier
Received: 22 September 2023
Accepted: 23 February 2024
Published: 19 March 2024

Citation: Martín-Forés I, Guerin GR, Lewis D, Gallagher RV, Vilà M, Catford JA, Pauchard A, Sparrow B (2024) Towards integrating and harmonising information on plant invasions across Australia. NeoBiota 92: 61–83. https://doi.org/10.3897/neobiota.92.113013

Abstract

Terminology for the invasion status of alien species has typically relied either on ecological- or policy-based criteria, with the former emphasising species' ability to overcome ecological barriers and the latter on species' impacts. There remains no universal consensus about definitions of invasion. Without an agreement on definitions, it is difficult to combine data that comes from a range of sources. In Australia, information on plant invasions is provided by a collection of independent jurisdictions. This has led to inconsistencies in terminology used to describe species invasion status at the national level, impeding efficient management. In this paper, we review and discuss the steps taken to harmonise the different terminologies used across Australia's states and territories. We identified mismatches in definitions and records of invasion status for vascular plant taxa across different jurisdictions and propose prioritisation procedures to tackle these mismatches and to integrate information into a harmonised workflow at the national scale. This integration has made possible the creation of a standardised dataset at the Australian national scale (the Alien Flora of Australia). In Australia, having an integrated workflow for referring to and monitoring alien flora will aid early warning and prevent species introduction, facilitate decision-making and aid biosecurity measures.

Keywords: Alien flora, biological invasions, biosecurity, invasion status, plant census, standardised dataset, terminology

Introduction

The importance of having high quality, easy-to-access, standardised and unified data sources is widely recognised among researchers and practitioners working with species invasions (Latombe et al. 2017). Having standardised datasets at large spatial scales allows tracking biological invasions, making future predictions and prioritising invasion-based management actions (Hulme et al. 2009; Le Roux et al. 2020). Ongoing debates include discussions about the taxonomy of biological invasions (Pyšek et al. 2013), the terminology and definitions related to invasion (Colautti and Richardson 2009; Young and Larson 2011; Catford et al. 2016), the determinants of invasion success (Fristoe et al. 2021; Daly et al. 2023) and the significance of impacts (Simberloff et al. 2013), as well as how to delimit and define native range (Guiaşu 2016). Hence, inconsistencies have arisen, subsequently impacting the accuracy of classifying plant species into native and alien and the derived implications of these classifications (Guiaşu 2016).

There are many terms to refer to 'species occurring in ecosystems to which they are not indigenous', including non-indigenous, non-native, exotic, and alien. The term 'alien' was introduced by the Convention on Biological Diversity (CBD) in Nairobi in 1992 without providing any specific definition (United Nations 1992). To alleviate the confusion around plant invasion terminology, Richardson et al. (2000) proposed the concept of the introduction-naturalisation-invasion continuum, by which a species introduced into a new area received different names according to the barriers it overcame. As such, casual aliens are those that have been transported beyond the limits of their native range but do not establish populations; only a fraction of casual aliens become naturalised, that is, forming self-sustaining populations in the invaded range; and only a fraction of those naturalised become invasive, overcoming local dispersal barriers and spreading in the new region. According to Richardson et al. (2000), the subset of invasive species able to impact the nature of the environment were called 'transformers', whereas 'weed' was a common term for undesired species (classically used for plants interfering with crop production) regardless of their native or alien origin (Fig. 1a).

The same year, the International Union for Conservation of Nature (IUCN) incorporated the concept of negative impact into the definition of invasive species as "alien species which becomes established in natural or semi-natural ecosystems or habitats, and are an agent of change, threatening native biological diversity" (IUCN, 2000). Two years later, in 2002, the CBD recognised invasive alien species (IAS) as "species introduced outside their native range that have become successfully established and cause substantial impacts on the environment" (Fig. 1b). In 2006, the IUCN Invasive Species Specialist Group (ISSG) developed the Global Register for Introduced and Invasive Species (GRIIS) as a concept and prototype to be subsequently reviewed before implementation across several countries globally. The methods underpinning GRIIS, and associated guidelines for the checklists of alien species to be implemented by individual countries, were not published until 2018 (Pagad et al. 2018) and only implemented in subsequent years. In 2022, a collation of GRIIS data across 196 countries was published into the country compendium of GRIIS (Pagad et al. 2022). GRIIS follows the impact-based notion of invasive species, to refer to those having a harmful impact on native biodiversity (Fig. 1b).

In 2011, a decade after the definitions for invasive species were proposed by Richardson et al. (2000) and the CBD (2002), Blackburn et al. (2011) published a unified framework on biological invasions to address terminological inconsistencies. The framework is very comprehensive and integrative, and successfully reconciles different synonyms to refer to similar invasion stages along the introduction-naturalisation-invasion continuum (Fig. 1c). It also reconciles terminology, concepts and definitions across different taxonomic groups (e.g., animals and plants), which had largely been addressed separately hitherto in the scientific literature. According to Blackburn et al. (2011), invasive species are alien species that have been introduced in a new area, have naturalised and have successfully undergone dispersal and spread. The question of invasion impacts falls outside this framework as Blackburn et al. (2011) recognised that certain introduced species can have impacts in a novel environment even if their populations are not naturalised. Other prominent invasion status frameworks also exist, such as Darwin Core (Darwin Core Maintenance Group 2021a). Proposed by the Biodiversity Information Standards (TDWG), Darwin Core is a vocabulary standard and includes a glossary of terms intended to facilitate the sharing of information about biological diversity. Darwin Core published concepts to refer to biological invasions in 2020 based on Blackburn et al. (2011) and classifies species regardless of their impact but adds a dimension of complexity. According to Darwin Core, the vocabulary standard is split into two terms: establishment means (Darwin Core Maintenance Group 2021b), which refers to species origin (i.e., native, introduced or uncertain) and degree of establishment (Darwin Core Maintenance Group, 2021c), which refers to the position along the introduction-naturalisation-invasion continuum. What Blackburn et al. (2011) had simplified and unified, Darwin Core divided into more specific categories introducing new stages such as 'reproducing', 'colonising', or 'widespread invasive' (Fig. 1d).

Despite several attempts to harmonise different concepts and ideas, the terminology to refer to further invasion stages within the continuum has not become consistent over time. This is mainly caused by the scientific community and international regulations proposed by policymakers adhering to two different frameworks, Blackburn's and IUCN's, respectively (however, note that within the scientific community there are also discrepancies with the use of 'invasive'). More recent attempts to clarify definitions, with and without intrinsically including impact, proposed to refer to invasive species with negative impact as 'harmful invasive' (Essl et al. 2020).

In federally managed countries, biosecurity regulations involve a complex interplay between different scales of jurisdiction, including federal, state/territory/

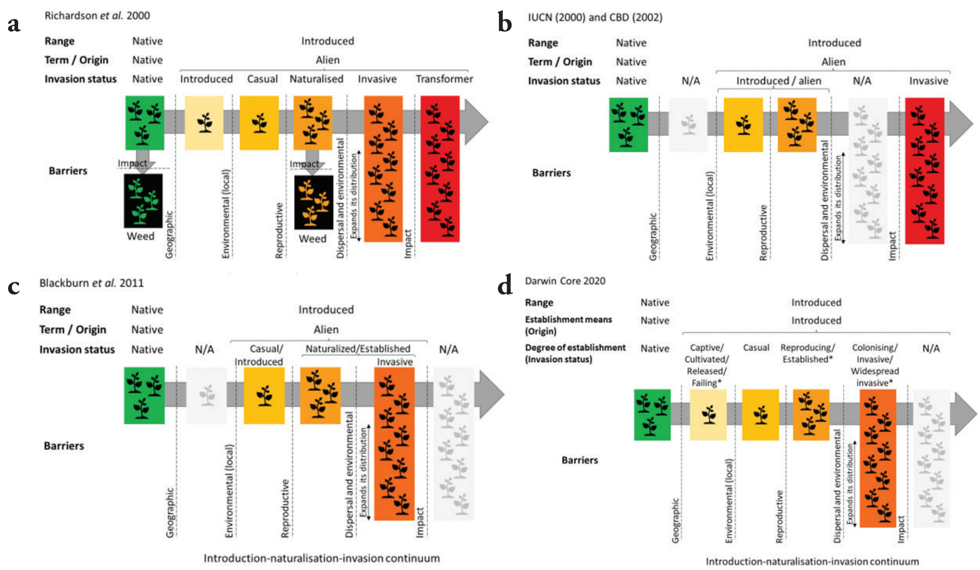

Figure 1. Frameworks on biological invasions adopted by **a** Richardson et al. (2000) **b** CBD and IUCN **c** Blackburn et al. (2011) and **d** Darwin Core. Terminology marked with * in Darwin Core varies according to specific details within the considered barrier; therefore, the terms are not interchangeable. N/A refers to stages that have not been considered in the respective framework.

province, and local levels. The distribution of powers and responsibilities is influenced by the country's federal structure, which allocates certain authorities to the national government and others to the provinces. This division of responsibilities is often based on the principles of subsidiarity, where decisions are made at the most local level possible. Although this idiosyncrasy can lead to a complex and sometimes confusing regulatory landscape, it is intended to allow for tailored responses to local conditions while maintaining a coordinated national approach to tackle biological invasions. The rationale behind having both federal and state-level scoring of species introduction status often stems from the need to address invasive species management comprehensively while acknowledging the diversity of ecosystems and environmental conditions within a large country.

Australia is a clear example of inconsistencies among plant censuses data sources, making the integration of the recorded information on plant invasion an arduous task. Australia is the sixth largest country in the world, with an overall surface comparable to the European continent. It is a biodiversity hotspot and has one of the highest levels of endemism (Gallagher et al. 2021). Despite having one of the strongest biosecurity systems in the world, it does not have unified nation-wide data on alien species, and the number of taxa introduced in Australia increases steadily over time (CSIRO 2020).

Australia's jurisdictions comprise six independent states (New South Wales – NSW; Queensland – QLD; South Australia – SA; Tasmania – TAS; Victoria – VIC; and Western Australia – WA) and two main territories (the Australian Capital Territory – ACT; and the Northern Territory – NT), hereafter referred to as 'states' for simplicity. Australia's plant censuses, including information on whether a species is native or introduced, have been developed at a jurisdictional level by government environment departments, therefore there are currently eight independent plant censuses at the state level. In addition, there are plant censuses for the external territories, which are offshore islands under Australian sovereignty. At the national level, there is one existing plant census for vascular plants that provides information for the whole of Australia, the Australian Plant Census (APC) (Australian Plant Census 2022), endorsed by the Council of Heads of Australasian Herbaria (CHAH). The APC provides authoritative data for names and published taxon concepts for native and naturalised taxa in Australia. Despite being federally managed, the APC provides information on a state-by-state basis, without combining the information into a national status.

In addition, the Global Register of Introduced and Invasive Species (GRIIS) v1.9 was recently published for Australia (Randall et al. 2022), classifying, among taxa from other kingdoms, the alien flora of Australia into introduced and invasive. However, the criteria for species' inclusion and status are based on impact (Pagad et al. 2018).

In summary, different data sources (ten in total) following different criteria resulted in inconsistencies at the Australian national level (Martín-Forés et al. 2023a, b). Similarly, weed lists and management strategies developed at the state level might become inefficient and ineffective if not shared with adjacent states. For example, certain species of brome grass (*Bromus* sp.) are naturalised in most of Australia, and identified as posing harmful impacts; despite this, adjacent states adopting different classification schemes may follow different control strategies, constituting a clear example of ineffective management at the national scale. To overcome mismatches caused by jurisdictional boundaries and enable efficient management and biosecurity of biological invasions by the Australian federal government, a consensus on clearer definitions, concepts and classifications across Australia is much needed.

To harmonise the different criteria followed by independent jurisdictions, here we: i) propose an adapted workflow to refer to plant invasions in Australia, resulting from the combination of all different frameworks used in the data sources; ii) cross-reference the information between different data sources at the state level and combine it at the national level to identify mismatches at both scales, iii) propose a prioritisation procedure to address mismatches at the state and national level in order to harmonise contrasting invasion statuses, iv) provide up-to-date information on the alien flora in Australia.

We developed harmonisation steps as an integration exercise to develop a much-needed automated system able to cross-reference and integrate all the existing datasets across Australia. We only combined information and did not coin any new terms, nor did we reclassify any taxon from its status as recorded in Australian plant censuses. As a result, we recently published the Alien Flora of Australia (AFA) (Martín-Forés et al. 2023a, b), a unified and standardised dataset including invasion status for the Australian flora at the national scale. We hope that both the harmonised workflow proposed here, and the standardised dataset we have created in parallel, will provide a strong evidence-base for planning and informing actions for prevention and to mitigate risks at the Australian national scale. Similarly, this integration exercise can be adapted and extrapolated to any other federally managed country to help bridge the gap between federal and state biosecurity initiatives.

Methodology

The terminology used in Australian plant censuses

Regarding taxonomic differences across Australian plant censuses, we followed the taxonomy and nomenclature adopted by the APC (Australian Plant Census 2022) when taxonomic resolution was needed (see Martín-Forés et al. 2023a, b for details). The APC provides authoritative data for names and published taxon concepts for native and naturalised vascular flora in Australia and is the most recognised authority for the Australian vascular flora at the national level. The APC is one of the taxonomic resources of the Australian National Species List (auNSL; https://biodiversity.org.au/nsl/) and is endorsed by the Council of Heads of Australasian Herbaria (CHAH).

The APC displays information on taxon distribution and invasion status for vascular flora contributed by different jurisdictions. It is mostly based on the terminology used by Blackburn et al. (2011) (Fig. 1c) and it classifies taxa as native, naturalised, or with uncertain origin. It follows a system of Boolean flags displayed in a consecutive way for each state and main territory. Therefore, in some instances, more than one status is displayed for a taxon in each territory. For example, a taxon recorded in one state as 'native and naturalised and uncertain origin' is a taxon native to that state, naturalised in other areas within the same state where it was not originally considered native, and appearing in other areas where there is no consensus on its 'nativeness'. Deliberately introduced alien species for gardening and ornamental purposes that have not established outside of cultivation are not listed on the APC and therefore not considered in our workflow and not reported here.

The Australian GRIIS (Randall et al. 2022) follows the impact-based definition of 'invasive' (Fig. 1b), therefore classifying alien species as introduced or invasive to Australia, without providing specific information for states and territories. This definition of 'invasive' is based on expert consultation regarding evidence of negative impacts caused by species that are known to be an agent of change and threaten biodiversity (Pagad et al. 2015, 2018). Thus, 'invasive' on GRIIS should not include native species within the country (although see native-alien category in Pagad et al. (2018)).

Regarding plant censuses at the state level, we obtained them from the Australian Capital Territory (Lepschi et al. 2019), the Northern Territory (Northern Territory Herbarium 2015), New South Wales (PlantNET 2022), Queensland (Laidlaw 2022), South Australia (Department for Environment and Water 2022), Tasmania (de Salas and Baker 2022), Victoria (VicFlora 2023) and Western Australia (Western Australian Herbarium 2022). Plant censuses from different states use different terms to refer to alien species and differ in the extent to which they categorise species according to impact or barriers overcome (Suppl. material 1: table S1).

Terminology integration

We use the concept of the introduction-naturalisation-invasion continuum in the harmonised workflow presented here. Therefore, we kept and selected terms based on an adaptation from the Blackburn et al. (2011) framework. We made this decision because we wanted to follow a standard terminology that was not impact-based, and Blackburn et al.'s (2011) framework is the most recognised internationally, and the most directly comparable with the terminology employed in the APC. Impact of alien taxa should be assessed following specific guidelines (Hawkins et al. 2015; Bacher et al. 2018); thus, to acknowledge that the GRIIS' definition of 'invasive' explicitly incorporates negative impacts, we replaced the 'invasive' records on the Australian GRIIS (Randall et al. 2022) with 'harmful invasive', according to the definitions presented by Essl et al. (2020).

Hence, we proposed an adapted workflow (Fig. 2), by which information about presence (present/extinct), origin (native/introduced/uncertain) and invasion status along the continuum (casual/naturalised/invasive) are provided in a combined manner for all data sources. Accordingly, we use 'introduced' where information on an alien taxon status along the continuum had not been provided in a given Australian data source (therefore it can refer to casual aliens or in cases where no information on naturalisation is available, e.g., in the case of binary censuses like the South Australian one). In the harmonised workflow presented here, we did not include 'casual' or 'invasive', because most of the censuses lacked detailed information on the spread and dispersal within the introduced range. In addition, for native taxa that are also recorded as naturalised or doubtfully naturalised within the same jurisdiction, we used 'native colonising' and 'native potentially colonising' acknowledging a mere reflection of dispersal but not impact. Finally, for taxa no longer present in a given state we used 'presumed extinct' for native taxa and 'formerly introduced' for alien taxa (Fig. 2). Our proposed workflow therefore includes the following terms: native (also native potentially colonising and native colonising), introduced (also doubtfully or formerly),

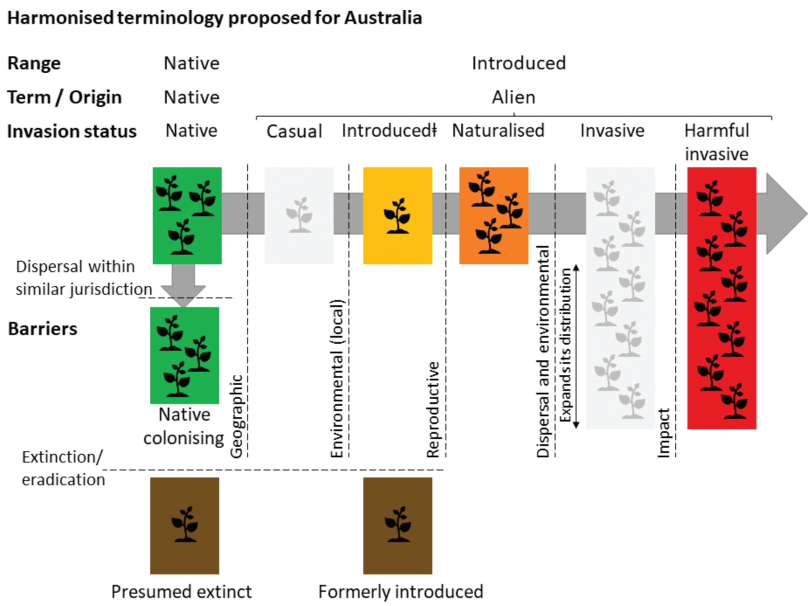

Figure 2. Harmonised workflow to unify terminology on biological invasions across Australian data sources. The unified terminology is based on Blackburn et al. (2011) but incorporating the notion of impact to account for the species recorded as invasive in the Australian Global Register for Introduced and Invasive Species (GRIIS) following the IUCN's guidelines. The term 'introduced' marked with ǂ in our proposed workflow does not refer strictly to 'casual' alien species but has been used instead when information on naturalisation was not available in a specific census. The terms 'casual' and 'invasive' appear in grey as there is currently not available information across the Australian data sources to categorise species within these categories.

naturalised (also doubtfully or formerly), harmful invasive, presumed extinct, and uncertain origin. Certain categories (e.g. doubtfully naturalised, formerly naturalised) specified on the APC, and therefore appearing in this workflow and the Alien Flora of Australia (AFA), do not have a direct translation into other frameworks (e.g., impact-based ones and Darwin Core). For this reason, and to accommodate Australian states like Victoria, where its census follows the Darwin Core standard, we provide equivalences to Darwin Core for the harmonised terminologies used here. We have provided a glossary with specific meanings for each term at both scales and according to different sources of vocabulary for invasion ecology (Table 1).

Identification of mismatches on invasion status

We used the workflow, and developed an associated script, to create a unified and standardised dataset of alien flora in Australia, the Alien Flora of Australia (AFA) (Martín-Forés et al. 2023a, b). The script is available on github (https://github.com/MartinFores/AFA) and Figshare (doi: 10.6084/m9.figshare.23513478). The script curates all the data sources and converts the terms used in each of them to the ones we proposed in the harmonised workflow explained above. Subsequently, the script detects mismatches at the jurisdictional level by comparing the information on invasion status recorded for each taxon on each of the plant censuses and the taxonomic distribution and invasion status provided on the APC for each of the states. The result of the comparison between the state plant censuses and the distribution information recorded on the APC is displayed in the state-by-state datasets comprising the AFA.

Table 1. Glossary of harmonised terminology to be used in the Alien Flora of Australia (AFA). The terms are adapted from Blackburn et al. (2011), with equivalent terms used by Darwin Core, the Australian Plant Census (APC) and the Australian Global Register of Introduced and Invasive Species (GRIIS).

		Term used in the AFA	Darwin Core establishment means [11]	Darwin Core [10] degree of establishment [12]	APC	GRIIS	Definition at the state level	Definition at the national level	Number of records nationally
	Native (any)	Native	Native	Native	Native	N/A	Native to a given Australian state without being naturalised in other areas of such state	Native to at least one Australian state regardless of being introduced or naturalised into other states	26,692
		Native potentially colonising	Native	Native	Native and doubtfully naturalised	Native-alien	Native to a given Australian state being potentially naturalised in other areas of such state	NA	0
		Native colonising	Native	Native	Native and naturalised	Native-alien	Native to a given Australian state although being also naturalised in other areas of such state	Native to at least one Australian state in which it is also naturalised regardless of being introduced or naturalised into other states	104
Alien	Introduced (any)	Introduced	Introduced	-Casual-Introduced (Not enough information)	NA	Alien	Species that is an alien and is recorded as introduced into a given state. [7,8]	Species that is not native to any Australian state and is introduced in at least one state. There is not specific information of its naturalisation in the combined data sources, therefore it is not possible to know.	18
		Doubtfully introduced	NA (we assumed it would still be introduced as casual)	NA	NA	NA	Species for which it is uncertain if it is introduced in a given state.	NA	0
		Formerly naturalised	NA (we assumed it would still be introduced in a casual form)	NA	Formerly naturalised	Alien	Species that was known to have been introduced in the past into a given state. Although it could be presumed to have been eradicated, it would most likely still be a casual alien.	Species that is not native to any Australian state and neither introduced or naturalised nor doubtfully introduced and doubtfully naturalised in any other state. It could be presumed to have been eradicated although it is likely to still be a casual alien (there are currently 44 species under this category at national scale).	40
	Naturalised (any)	Naturalised	Introduced	-Reproducing -Established	Naturalised	Alien	Fraction of introduced species that have been able to form unassisted self-sustaining populations [7,8]. The only species that was recorded as 'reproducing' [12] in one of the states has been grouped under this category	Species that is not native to any Australian state and is naturalised in at least one state.	3,026
		Doubtfully naturalised	Introduced	NA (unofficially referred to as adventive)	Doubtfully naturalised	Alien	Species that despite being introduced, it is unknown if it can form self-sustaining populations. In other sources, sometimes referred to as adventive.	Species that is not native to any Australian state and is doubtfully naturalised in at least one state, without being known to be naturalised in any state.	326

		Term used in the AFA	Darwin Core establishment means [11]	Darwin Core [10] degree of establishment [12]	APC	GRIIS	Definition at the state level	Definition at the national level	Number of records nationally
Alien	Invasive (any)	Invasive	Introduced	-Colonising -Invasive -Widespreadinvasive	NA	Alien	Naturalised species that have dispersed and spread in the invaded range at a significant distance from the introduction point, regardless of its impact within the invaded community [7,8,12].		NA
		Harmful invasive	Introduced	NA	NA	Invasive	Invasive alien species that is known to have a negative impact within the invaded range and/or to pose a threat to native biodiversity [7]. In GRIIS referred to as invasive [32–34].		77
	Uncertain	Uncertain origin	Uncertain	NA	Uncertain origin	Cryptogenic Uncertain	Species for which its origin is not known to be native or introduced to a given state	Species of unknown origin that occurs in at least one state.	11
	Other categories	Presumed extinct	NA	NA		NA	Species that was native to a given Australian state although is now presumed to be extinct	Species that is now presumed to be extinct in at least one Australian state and is not recorded to be present in any other form any other Australian state.	21
		Formerly introduced	NA	NA		N/A	Species that was known to have been introduced in the past into a given state, but there is no longer present. It could be presumed extinct or have been eradicated.	Species alien to Australia that has now been eradicated or is extinct in at least one Australian state and is not recorded to be present in any other Australian state.	1

In a subsequent step, the script combines the information provided at the state level into a national invasion status and compares it with that provided in GRIIS. The script then detects mismatches at the national level and subsequently address them by combining contrasting statuses into a unified national status (see next sections for details); see Martín-Forés et al. 2023a,b for details on the script designed to detect mismatches in invasion status at the state and territory levels in Australia.

Prioritisation procedure to unify invasion status at the Australian state level

We developed a prioritisation procedure to address mismatches on invasion status at the state level in Australia. When a species was not listed on the APC or was recorded on the APC as not present in a given state, we kept the invasion status recorded in the state plant census. For species that appeared in both state and APC sources but these sources displayed a mismatch in the invasion status, we developed a prioritisation procedure following the precautionary principle. Our system prioritises, for each taxon in each state, the recorded invasion status that has advanced the furthest along the invasion continuum. Naturalised, followed by doubtfully naturalised, are prioritised over introduced, formerly naturalised, doubtfully introduced and formerly introduced. Any invasion status recorded within an alien category for a taxon is prioritised over uncertain origin, and those over native statuses, which include, in order of priority, native colonising, native potentially colonising, native, and finally presumed extinct (Fig. 3). In all component datasets developed at the state level as part of the AFA, we incorporated a new column with the unified status for each taxon in each state (See Martín-Forés et al. 2023a, b to access all the standardised regional datasets for all Australian states).

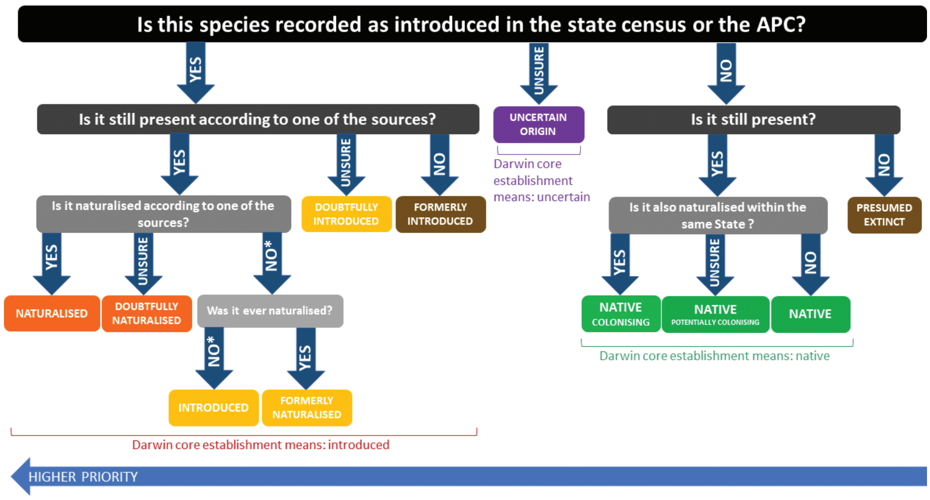

Figure 3. Prioritisation procedure to assign the most conservative invasion status for a given species in a given Australian state after comparing the records in the corresponding state census and in the Australian Plant Census (APC). The status 'naturalised' refers to introduced species that form unassisted self-sustaining populations. *Indicates that in some cases there is not enough information in the state censuses to respond to these questions; therefore, we have assumed that the answer would be no. Darwin Core equivalences with regards to establishment means (native, introduced and uncertain) are also included.

Prioritisation procedure to combine invasion statuses at the Australian national level

The prioritisation procedure used to assign national status differed from the one used at state level (above) as follows: if a taxon was native to at least one state, it was considered native to Australia (Fig. 4). If it was not 'native' to any state, but native colonising (or native potentially colonising), it was considered native colonising at the national scale; and if it was not native in any possible form to any state but recorded with uncertain origin in at least one state, we kept 'uncertain origin'. If the taxon had not been recorded as native or having uncertain origin in any of the states, then the recorded invasion status that had advanced the furthest along the continuum was prioritised as a precautionary measure for addressing potential invasion. Only if the species was not present in any state was it then recorded as presumed extinct at the national scale (Fig. 4).

For the species that were alien (in any form) to Australia at the national scale according to our workflow and that appeared recorded as 'invasive' according to GRIIS, we changed their invasion status to 'harmful invasive' at the national scale, because GRIIS classification is impact-based. When other mismatches were identified (e.g., species that are native to at least one Australian state but appeared recorded as introduced or invasive (i.e. harmful invasive) in GRIIS), we kept the information obtained via our script.

Results

The Australian native and alien flora in numbers

According to the AFA, at the national level, there are 30,527 vascular flora species in Australia, including native species and alien species that are established outside of cultivation. However, because some of these species are only present in

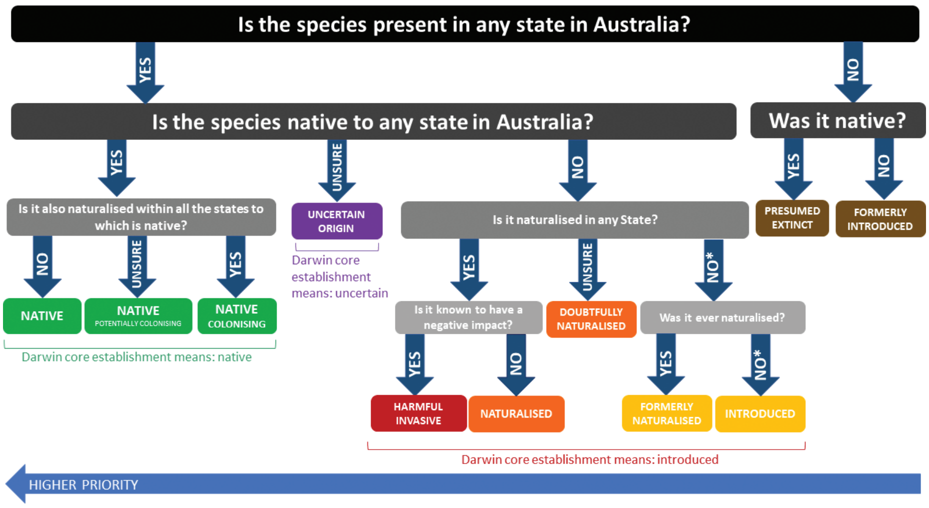

Figure 4. Prioritisation procedure to assign the national status for a given species after merging the most conservative statuses across all the Australian states. The status 'naturalised' refers to introduced species that form unassisted self-sustaining populations. The status 'harmful invasive' was only assigned for the species that, being introduced at the national level, appeared recorded as invasive in the Australian GRIIS. *Indicates that in some cases there is not enough information in the state censuses to respond to these questions, therefore we have assumed that the answer would be no. Darwin Core equivalences with regards to establishment means (native, introduced and uncertain) are also included.

external territories and nine species did not have any distribution information, there are currently a total of 30,287 species listed, from which 3,487 records correspond to alien species that have not been deliberately introduced for gardening and ornamental purposes (11.4% of the total number of species). From these alien species, 58 species are recorded as introduced (not known to have formed self-sustaining populations to date), 3,352 species are recorded as naturalised (able to form self-sustaining populations) and 77 as harmful invasive (which accounts for 2.2% of the total of alien plants reported here). As mentioned above, there is not enough information in the combined data sources to classify Australian taxa as 'casual' or 'invasive' *per se* (sensu Blackburn et al. 2011). There are currently 11 species whose origin is uncertain at the national scale, while 21 species were native and have become extinct (presumed extinct) or were introduced and are presumed to have been extinct or eradicated (formerly introduced) (Table 2; Suppl. material 1: fig. S1).

The number of alien species across Australian states ranged from 564 in the Northern Territory to more than 1,900 in each of New South Wales, Queensland and Victoria. However, the percentage of alien species across Australian states, ranged from 10% in the Northern Territory and Western Australia to over 38% in the Australian Capital Territory (Table 2; Suppl. material 1: fig. S1). Within the alien species in each state, the percentage of harmful invasive species for which there is evidence of negative impact according to GRIIS, ranged from 2% in Tasmania to 4.4% in the Northern Territory (Table 2; Suppl. material 1: fig. S1). Beyond state and federal use, these data can also be used to report on the global status of Australian biodiversity and to provide indicators of biological invasions.

Table 2. Summary showing the number of species within each group (i.e. native, alien, uncertain origin and other categories), and percentage where indicated, regarding invasion status at national and state scales. Alien species at national scale are those for which origin is not Australian, whereas at the state level, alien species refer to those that could be native to other Australian territories. For alien species, the invasion status (e.g. introduced, naturalised and harmful invasive) has also been specified when known. To facilitate understanding, native (any) includes native, native colonising and native potentially colonising; naturalised (any) includes naturalised and doubtfully naturalised; introduced (any) includes introduced, doubtfully introduced, and formerly naturalised, assuming that, most likely, there is still an introduced individual of such species; other categories include species that are presumed extinct and species that were formerly introduced; harmful invasive refers to alien species known to have a negative impact in the native biota. States and main territories have been abbreviated (the Australian Capital Territory, ACT; New South Wales, NSW; the Northern Territory, NT; Queensland, QLD; South Australia, SA; Tasmania, TAS; Victoria, VIC; Western Australia, WA).

Scale	Region	Total	Native total	Alien total (% of total)	Uncertain origin	Other categories	Alien species		
							Introduced	Naturalised	Harmful invasive (% of alien)
National*	Australia	30,557	26,796	3,487 (11.4)	11	22	58	3,352	77 (2.2)
Main territory	ACT	2,034	1,245	785 (38.6)	4	0	120	643	22 (2.8)
State	NSW	9,248	7,296	1,952 (21.1)	0	0	114	1,777	61 (3.1)
Main territory	NT	5,600	5,032	564 (10.1)	4	0	63	476	25 (4.4)
State	QLD	11,812	9,904	1,904 (16.1)	0	4	76	1,769	59 (3.1)
State	SA	5,686	3,940	1,739 (30.6)	3	4	203	1,487	49 (2.8)
State	TAS	3,167	2,181	970 (30.6)	2	14	105	847	18 (1.9)
State	VIC	6,018	3,932	1,989 (33.1)	80	17	121	1,819	49 (2.5)
State	WA	15,001	13,484	1,505 (10)	0	12	1	1,504	51 (3.3)

*There are 29 species that are included in the database because of appearing on the Australian Plant Census (APC) but they are not recorded in any state or external territory. There are also 211 species that are included in the database but only appear in external territories.

Mismatches across Australian alien flora data sources

To report the mismatches here, we grouped invasion status into higher classes. As such, native (any) includes all native, native potentially colonising and native colonising taxa; while alien (any) includes all introduced species regardless of their invasion status; introduced (any) includes all doubtfully introduced, introduced, and formerly naturalised taxa; and naturalised (any) includes all doubtfully naturalised and naturalised taxa. Subsequently, we grouped the mismatches into several classes as follow: mismatches within groups, across alien groups (when they differ in the invasion status or the degree of establishment reported), and across different groups (native vs. alien).

We also identified mismatches related to either taxa presence or origin uncertainty. Finally, the category 'other mismatches' referred to taxa that were either not listed or were an excluded taxon on the APC, taxa recorded as not present in a given state or lacking information about invasion status, and taxa that were pro-parte or pro-parte misapplied and therefore no accurate equivalence of taxonomy and status could be assigned (Fig. 5).

The degree of mismatches at the national scale between the data obtained by our script integrating unified statuses across Australian states and GRIIS showed that, for all alien species, only four had similar statuses recorded in both data sources. This is due to most of the mismatches found (64%) taking place across alien groups (i.e., GRIIS does not include records stating naturalised, therefore over 2,000 species that are naturalised in the AFA appear recorded as introduced in GRIIS). Also, around 30% of the mismatches were due to certain species not being listed on GRIIS. There were 66 species (2% of the national mismatches) that were recorded as introduced according to GRIIS despite being native to at least one Australian state (see Suppl. material 1: tables S2, S3 for details). The case of *Phragmites australis* (Cav.) Trin.

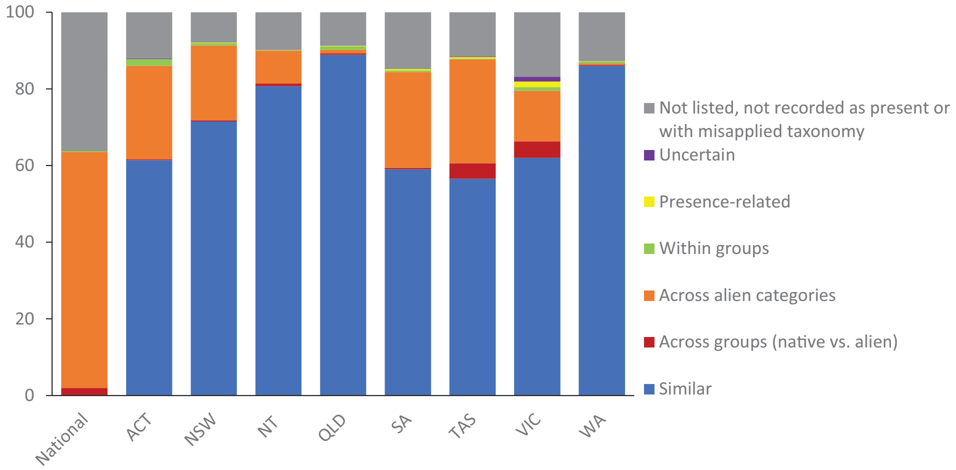

Figure 5. Percentage of similarity and mismatch between the national and the state scales. States and main territories have been abbreviated (the Australian Capital Territory, ACT; New South Wales, NSW; the Northern Territory, NT; Queensland, QLD; South Australia, SA; Tasmania, TAS; Victoria, VIC; Western Australia, WA). Records were grouped in seven categories of mismatch. Similar: no mismatch between data sources. Across groups: mismatches across groups (native vs. alien); Across alien categories: mismatches across alien groups that differ in the invasion status or the degree of establishment reported; Within groups: mismatches within groups (e.g. naturalised vs. doubtfully naturalised); Presence-related: mismatches because of the taxon not present in one of the data sources; Uncertain-related: mismatches because a taxon has uncertain origin in one of the data sources; Not listed, not recorded as present or with misapplied taxonomy refers to mismatches when that is the case in one of the data sources.

Ex Steud. was especially curious as it is native to all Australian states except Western Australia but appeared recorded as invasive (harmful invasive) on GRIIS v1.9.

At the state scale, the mismatches detected ranged from 10% in Queensland to over 40% for South Australia (Fig. 5; Suppl. material 1: table S2). The fact that Queensland had less mismatches is most likely due to the Queensland Herbarium using the same terminology as the APC and therefore species falling within similar categories. By contrast, the highest percentage was detected in South Australia, a state that did not provide precise information about the position along the continuum, and therefore most species could only be assigned to 'introduced'. However, the highest number of severe mismatches (i.e. those across native and alien groups) were detected in Victoria and Tasmania, with 281 and 115 mismatches falling in this category (Fig. 5; Suppl. material 1: table S2).

Discussion

There are currently more than 13,000 vascular plant species naturalised outside their native range in the world (van Kleunen et al. 2015, 2019). While the number of high-quality, freely accessible online databases for alien flora at regional scales have increased in recent decades, their ultimate value for management actions depends on the feasibility of integrating the information they contain at larger spatial scales (Luo et al. 2011; Latombe et al. 2017). Integration is especially important when the data sources follow different criteria and has been previously proposed by merging global databases (Seebens et al. 2020).

We have created the first harmonised workflow and standardised dataset on alien flora in Australia, to assess the inconsistencies among current data sources, and to provide an updated state-of-the-art checklist of non-deliberate plant invasions across Australia. Having a free, easy-to-update Alien Flora of Australia (AFA) standardised dataset at the national scale that combines all up-to-date Australian state and national vascular plant censuses, offers a valuable research infrastructure. This national infrastructure creates cost-effective new opportunities to study biological invasions at the continental scale at a speed and performance appropriate for a broad range of stakeholders ranging from state and national government entities in Australia, both the national and international scientific community, to biosecurity committees, land managers, and society in general.

We would like to clarify that this integration exercise provides a reflection of the diverse information existing in Australia. We have developed tools to be able to combine contrasting information, but we have not classified taxa differently to those in the original records on Australian plant censuses. From our point of view, mismatches on invasion statuses within alien groups (e.g. naturalised vs. doubtfully naturalised) are unlikely to be very problematic for management purposes. Nevertheless, mismatches across groups (e.g. introduced vs. naturalised) fail to provide accurate information along the invasion continuum, thereby hampering development of biosecurity strategies and prioritisation for invasion management or eradication. Finally, mismatches across different groups (e.g. native vs. naturalised) provide contradictory information and pose the highest risk to management and conservation because an alien species could be considered as native and managed as such or vice versa.

Due to the high percentage of mismatches detected regarding terminology and classification, we encourage Australian herbaria to adopt a unified scheme in the way they provide information in the state plant censuses. Ideally, the scheme they adopt should provide information on the stage of the plant taxon along the introduction-naturalisation-invasion continuum based on overcoming ecological barriers. We recommend herbaria to follow Blackburn et al. (2011) when classifying plant taxa because it splits the classification along the continuum in easily recognisable stages. Schemes with intermediate stages such as Darwin Core can be risky to implement, due to the time lag existing between a species moving along consecutive phases of the "continuum" and human detection (e.g. a plant could have been detected as reproducing when it is already naturalised). Too many intermediate phases in the "continuum" can jeopardise the certainty of a taxon being correctly classified in one stage but not in the next one (Essl et al. 2011; Rouget et al. 2016).

We also advise limiting the use of the term 'invasive' to refer to naturalised species that spread and reproduce at multiple sites (e.g. Blackburn et al. 2011; Fig. 1c) and use instead 'harmful invasive' to refer to invasive taxa with negative impacts (Essl et al. 2020). We understand the terminology proposed here differs from international regulations such as CBD or IUCN; hence, we invite international bodies to realign their terminology by replacing the term 'invasive' with 'harmful invasive' when harmful impact is implied. In line with this, if impact status was required to be reported for a given application, complementary steps in future could include assessing the environmental and socioeconomic impacts of alien taxa following the EICAT (Environmental impact classification for alien taxa; Hawkins et al. 2015) and SEICAT (Socio-economic impact classification of alien taxa; Bacher et al. 2018) frameworks, respectively. These frameworks have been adopted by the IUCN to rank introduced species by the magnitude of their potential impacts (Wallingford et al. 2020) and could be used to inform and address impact in Australia (see Box 1 for further discussion regarding the use of 'invasive').

At the end of the present study, we engaged with GRIIS to discuss potential causes and consequences of mismatches in the respective databases. We shared our dataset and findings so that the species lists reported in the Suppl. material 1 could be assessed prior to the release of the new GRIIS version. In the upcoming GRIIS

Box 1. Further discussion on the definition and use of the term 'invasive'.

Invasion frameworks such as Blackburn's (Blackburn et al. 2011), where the definition of invasive is proposed from a perspective of the barriers that a species has overcome, are more of a theoretical concept. However, application of this approach can pose practical difficulties in determining when a naturalised species has reached 'a significant distance' away from the introduction point to be considered invasive.

By contrast, frameworks such as IUCN and CBD, do not illustrate the barriers overcome by alien species and classify them as 'invasive' when impact is evident.

In this sense, we would like to highlight that not all naturalised and invasive species *sensu* Blackburn et al. (2011) have harmful impacts. There are invasive species for which there is no evidence to consider them harmful. Indeed, an alternative framework to the EICAT (Environmental impact classification for alien taxa; Hawkins et al. 2015), namely EICAT+ (Vimercati et al. 2022) has been created in order to assess beneficial impacts of alien taxa.

It is not our intention to discourage the use of 'invasive'; on the contrary, we use the term here to refer to the spread and dispersal of alien taxa within the introduced range, as proposed by Blackburn et al. (2011). However, as there is currently no information regarding spread available on the Australian censuses, we could not classify the species as simply 'invasive'. Due to this limitation, we changed the terminology to 'harmful invasive' as suggested by Essl et al. (2020), to consider for both frameworks, Blackburn's and the IUCN's.

Perhaps 'harmful alien' would be a more accurate term than 'harmful invasive', to avoid any automatic association between species impact and invasiveness, as it is known that small casual populations can still exert a negative impact. The question of impact (negative or positive) could therefore be scored on its own axis, independently from population size and spread.

We hope that the mismatches in definitions and records of invasion status for vascular plants highlighted here help in reaching a consensus in the terminology used both within the scientific community and by policy makers. Towards this end, after the new version of GRIIS is released and after conducting a workshop with relevant Australian authorities in invasion and biosecurity, we would review our own terminology used in the Alien Flora of Australia (AFA; Martín-Forés et al. 2023a,b) and provide new details on any consensus reached in the metadata.

version (to be released soon), a classification category labelled 'native-alien' will be included to refer to species native to a certain area but naturalised somewhere else. Species classified as 'native-alien' could therefore be simultaneously tagged as harmful invasive to refer to impact in the areas in which are introduced. Classification for certain species appearing on GRIIS v1.9 will therefore be modified in the new GRIIS version. In this sense, we will keep combining efforts and collaborating with GRIIS to deliver harmonised information across Australia. As part of this, once the new GRIIS is publicly available, we will adapt our script and publish an updated version of the AFA dataset. Hence, we encourage users to check for updates on Figshare (Martín-Forés et al. 2023b; doi: 10.6084/m9.figshare.23513478) and always use the latest available versions of the script and dataset.

Implications and applications of the AFA

One of the strengths of the AFA, is that the information for each plant species is easily comparable among all Australian states and at the national scale, with new opportunities arising from its use. While the division between federal and state levels makes sense in terms of local adaptability and expertise, effective communication and collaboration between the two policy levels are crucial. National strategies and policies can help ensure a coordinated and cohesive approach to invasive species management, addressing both local and broader concerns. At the same time, a decentralised system allows for adaptability and the opportunity for state agencies to create additional regulations and trigger rapid responses to emerging or pressing threats. In this sense, this harmonised dataset at the national scale is robust, as it allows developing federal strategies whilst simultaneously maintaining the information relevant for each jurisdiction.

As a result of the division in biosecurity legislation between federal and state levels, there are complicated cases of species being native to certain areas of Australia but introduced in others where they cause known negative impact and are therefore listed as weeds. For example, *Pittosporum undulatum*, or sweet pittosporum, is native to coastal areas of southern Queensland, New South Wales and certain regions of Victoria. However, it is a declared weed in South Australia, and listed as a common environmental weed in Tasmania and Western Australia. Due to expansion in its area of distribution, *P. undulatum* has been labelled as an environmental weed outside its natural range in Victoria and New South Wales, which gave rise to debate due to potential undesired associated effects (Howell 2003). Cases like this can benefit from overarching federal legislation and coordinated efforts among state agencies to ensure successful outcomes in every jurisdiction. A more notorious example is the case of *Bromus diandrus*, species original to Mediterranean Europe which is naturalised in all Australian states (doubtfully naturalised in the Northern Territory). *Bromus diandrus* poses a serious concern as a widespread grass weed having a detrimental impact on crop yield in Western Australia, where it is a declared weed being managed. South Australia, the adjacent state, shares a Mediterranean-type climate with Western Australia. Despite *B. diandrus* also being naturalised in South Australia, the species has not been declared as a weed in this state. This could potentially contribute to further dispersion into Western Australia, therefore hindering management efforts currently taking place in Western Australia. Cases like brome grass (*Bromus* sp.) that have successfully naturalised in almost the totality of continental Australia could benefit from a unified national strategy.

To date, only 32 plant species that are likely to become harmful invaders have been incorporated into the Weeds of National Significance (WoNS) (Thorp and Lynch 2000). Once an alien plant species is declared as a WoNS, a national management plan outlining strategies for controlling and managing its spread is developed, typically involving federal and state governments and local authorities. Therefore, to date, National Environmental Biosecurity Response Agreements (NEBRA 2021) have only been developed for these 32 WoNS. We hope that the AFA resulting from this integration exercise assists predicting invasions trends and identifying alien plant species introduced to Australia that are already naturalised in several states. For example, there are 77 alien species that are recorded as naturalised in all Australian states (see Suppl. material 1: table S4); of which, only *Lycium ferocissimum* Miers is currently considered a WoNS and is included on GRIIS as a harmful invasive. Even though distribution across several states can be a result of multiple introduction events (Koontz et al. 2018), we could expect a species that is already naturalised across multiple regions in Australia to potentially become problematic. Species that are already recorded as naturalised in several states and that are known to have had negative impacts in other areas worldwide should be rapidly assessed for inclusion in both GRIIS and WoNS.

In a similar manner, alien plant species that are currently doubtfully introduced or introduced in only one state, could be the target of eradication efforts (Rejmánek and Pitcairn 2002), with funding allocated to the relevant state, to prevent further naturalisation and potential expansion into other Australian states.

Native plant species that are naturalised in other areas within the state to which they are native (i.e., recorded in the AFA at national scale as native colonising or native potentially colonising), could be associated with effects not only within their own region of origin but also in other states in which they might appear as introduced or naturalised. These range-expanding native species require specific attention (Essl et al. 2019). There are currently 103 species in the category of native colonising; from these, 41 species are also introduced or naturalised in other Australian states (see Suppl. material 1: table S5 for details). This information should be an important consideration for land managers, and when designing conservation strategies. Monitoring those 41 species could also be implemented as part of internal biosecurity procedures in Australia to ensure that these species, despite being native, do not pose any harm to other Australian biodiversity (Wallingford et al. 2020) or international invasion risks if material is exported. It would be especially useful to monitor and model trends for those species under climate change (Hulme 2017). For those species expected to shift ranges under increasing temperatures or rainfall redistribution, this information would be crucial to apply pre-emptive management procedures. In a similar manner, the AFA can help identifying potential native species for which their spread into new areas through climate tracking may not be undesirable if it prevents them from being at risk of extinction.

In closing, we highlight that the information provided here on plant invasions in Australia can be easily updated in the future with upcoming releases of the APC and state censuses. The script we created to develop the AFA (Martín-Forés et al. 2023a, b; https://github.com/MartinFores/AFA) can be used at any time to automatise this process in the future. Such updates may be especially useful when combined with occurrence data in order to monitor alien flora across Australia under global change, as certain alien taxa are predicted to expand (Dullinger et al.

2017) or contract (Pouteau et al. 2021) their distribution ranges, whereas others can shift their distribution to track optimal environmental conditions in contiguous states.

Our script and approach can be adapted and applied to similar situations in other federally managed countries in which idiosyncrasies in the classification of alien species arise among jurisdictions. To do so, the appropriate data curation steps would need to be adapted to the way information is displayed in each of the data sources of a given country. Taxonomy matching could be easily done via the Global Biodiversity Information Facility (GBIF) taxonomic backbone and World Flora Online, with both options currently included within our script. Afterwards, prioritisation procedures can be implemented with the same functions we created.

Acknowledgements

We acknowledge the TERN Ecosystem Surveillance as well as support by the Australian Government through the National Collaborative Research Infrastructure Strategy. We thank Dr Kerry Gibbons and Dr Hannah McPherson from the Royal Botanic Gardens for providing the 2022 plant census of NSW, and Julia Percy-Bower and Cheryl Parker from the Western Australian Herbarium for collating the alien census of WA from FloraBase and sharing it with us. We are grateful as well for the help provided by Anne Fuchs and Julia Inez Bignall regarding the boolean flags in the APC dataset, and for insight in the application of the Darwin Core vocabulary in VicFlora provided by Niels Klazenga. We also thank Louis Elliott, Gillian Brown, and Ben Richardson for valuable conversations about the censuses of the Northern Territory, Queensland and Western Australia, respectively. We also acknowledge the Herbarium Information Systems Committee (HISCOM) for valuable feedback to improve the standardisation process to create the Alien Flora of Australia (AFA) dataset. We would like to thank Cameron Slatyer from CSIRO and the Atlas of Living Australia, and Shyama Pagad, Deputy Chair-Information. IUCN SSC Invasive Species Specialist Group (ISSG) and point of contact for the Australian GRIIS for supportive communication with us during the process. Likewise, I am very grateful for insightful conversations on the topic with Philip Hulme, Phill Cassey, John Virtue and Andrew Lowe. Finally, we would like to acknowledge two anonymous reviewers and Dr Maud Bernard-Verdier, Editor of Neobiota for their valuable suggestions that have considerably improved this paper.

Additional information

Conflict of interest

The authors have declared that no competing interests exist.

Ethical statement

No ethical statement was reported.

Funding

We acknowledge the TERN Ecosystem Surveillance as well as support by the Australian Government through the National Collaborative Research Infrastructure Strategy. AP funded by ANID/BASAL FB210006.

Author contributions

I.M.F conceived the idea; I.M.F and D.L. contacted the corresponding state authorities to obtain up-to-date censuses and clarify classifications in each state and discussed the validation with the HIS-COM members; I.M.F. analysed the trends from the Alien Flora of Australia (AFA) dataset; I.M.F. led the writing of the manuscript. All coauthors provided insightful advice, valuable feedback on the manuscript and agreed to submit the final version of the manuscript.

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Data availability

The data underpinning the analysis reported in this paper are deposited in the Figshare Data Repository at doi: 10.6084/m9.figshare.23513478. Similarly, the R scripts underpinning the analysis reported in this paper are deposited on GitHub at https://github.com/MartinFores/AFA.

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Supplementary material 1

Supplementary information

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Data type: docx

Explanation note: **fig. S1.** Summary of the records of the alien flora of Australia (AFA) at both the national and state scales with regards to (top) origin (native, alien, uncertain or other categories), and (bottom) within the alien flora, grouped by invasion status (introduced, naturalised and harmful invasive). **table S1.** Terms, codes, and conversion procedure followed to harmonised terminology on invasions statuses across Australian states to make them comparable. **table S2.** Mismatches of the status assigned to species between different sources at the national scale (Alien Flora of Australia, AFA, vs. Global Register of Introduced and Invasive Species, GRIIS) and state scale. **table S3.** Scientific name according to the Australian Plant Census (APC) of the species that are introduced according to the Global Register of Introduced and Invasive Species (GRIIS) despite being native to at least one Australian state according to the Alien Flora of Australia (AFA). **table S4.** Scientific name according to the Australian Plant Census (APC) of the alien species not originally from Australia that are naturalised in all Australian states. **table S5.** Scientific name of the native colonising (i.e. those also naturalised in other areas of the state to which they are native).

Link: https://doi.org/10.3897/neobiota.92.113013.suppl1