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Article

The Diversity of Alien Plant Species in South Africa's National Botanical and Zoological Gardens

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Abstract: The management of biological invasions, which pose a growing threat to natural resources and human well-being, is critical for reducing associated negative impacts. As part of the process of developing a strategy for the management of biological invasions in the South African National Biodiversity Institute's (SANBI) gardens, we collated a list of alien plant species from 13 gardens as part of a situational analysis. We requested lists of alien plant species recorded in each of the SANBI's gardens. A total of 380 records included 225 alien plant species belonging to 73 families. A significant number of species were intentionally introduced through horticultural trade as ornamentals (49%; n = 225), while 20.9% were consumed as either food or medicine by humans. Plant life forms included woody and herbaceous plants, graminoids, succulents and ferns. Herbaceous (42.7%; n = 225) and woody plants (3.8%) were the dominant life forms. The Walter Sisulu National Botanical Garden had the highest number of alien species (88 species), followed by Kirstenbosch (61 species) and Pretoria (46 species) National Botanical Gardens, with herbaceous species constituting the largest number in all gardens (i.e., 47, 19, and 27 species, respectively). The number of species that we recorded that were listed in the National Environmental Management: Biodiversity Act (NEM: BA) (Act No. 10 of 2004): Alien and Invasive Species Regulations' categories were not notably different from the number of unlisted species (58.2% vs. 42.8%). The number of species listed in the different categories varied significantly across the different gardens, with a significantly higher number of unlisted species and of Category 1b species in the Walter Sisulu, Kirstenbosch and Pretoria National Botanical Gardens than in other gardens. That a significantly larger number of alien species originated from South America points to the need to improve biosecurity controls on existing relations. The results of this study provided a baseline database to help comparison between successive surveys in future.

Keywords: biodiversity conservation gardens; global change; introduction pathways

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1. Introduction

Botanical gardens represent the largest plant conservation network in the world [1], with diverse interconnected functions ranging from environmental education and scientific research to recreation [2,3]. Krishnan and Novy [4] reviewed different definitions of botanical gardens, and these definitions mainly emphasise the functions that gardens perform. For example, they were considered primarily as outdoor collections of labelled living plants in aesthetic landscapes, playing passive roles in their communities, as well as historical heritage sites. Presently, botanical gardens have evolved to include expanded programmes, such as the conservation of plant biodiversity, by serving as repositories of plant germplasm for the long-term preservation of species, scientific research, and creation of urban refuges for wildlife and humans [5]. In addition, Botanic Gardens Conservation International (BGCI) [6] defines botanical gardens as permanent institutions holding documented collections of living plants for the purposes of display and for education of the public. Although botanical gardens have focused strongly on plant conservation, a recent transition was noted whereby botanical gardens are valued as sentinel sites to identify pests and pathogen risks in biosecurity research for the early detection and eradication of alien pests, pathogens and plants' screening prior to authorisation of their release to horticultural markets [7–10].

According to BGCI, one of the typical characteristics of botanical gardens should be the ability for an "*Exchange of seed or other materials with other botanic gardens, arboreta or research institutions*". Consequently, botanical gardens have also been key in supporting economic botany during the 17th to 19th centuries, and this entailed the movement and introduction of new economically important plant species across the world [4]. Consistently, during the European expansion and exploration of Asia, South America and Africa, some European botanical gardens were engaged in economic botany and the cultivation of attractive plants [4,11]. The Europeans were actively involved in the collection and study, introduction and acclimatisation, cultivation, propagation and dissemination of newly discovered and tropical crops to colonial countries [4,12]. Similarly, botanical gardens play a major role in supporting the cultivation and distribution of alien plants that are used as ornamentals [12], with most of these alien species listed as the worst invasive species in the world, such as *Lantana camara* and *Acacia mearnsii* [8,13–15]. The World Resources Institute estimated that 150 million persons visited some 1500 botanical gardens around the world in 1989 [16]. Thus, it is also possible that with increased international tourist visitation to botanical gardens in the 17th and 18th centuries, alien species from different parts of the world were accidentally spread to different areas [1,17].

In South Africa, botanical gardens perform a range of diverse functions intertwined with the conservation of flora and fauna, in alignment with international conservation treaties (e.g., the Convention for Biological Diversity), research, environmental education, horticulture and nature-based tourism [2,18–20]. The 11 botanical gardens of the South African National Biodiversity Institute (SANBI) (i.e., Free State, Harold Porter, Karoo Desert, Hantam, Kirstenbosch, KwaZulu-Natal, Kwelera, Lowveld, Pretoria, Walter Sisulu, and Thohoyandou; see [21]) are classified as conservation gardens that, according to the BGCI's definition (see [2,3]), contain natural vegetation that is a national conservation priority (i.e., Critical Biodiversity Areas—CBAs) in addition to their cultivated collections [20–23].

A globally distinguishing attribute of the SANBI gardens is that they conserve representative biodiversity of seven of South Africa's nine biomes, except the Desert Biome and Indian Ocean Coastal Belt [18,21,22]. In addition, the Pretoria National Zoological Garden preserves a variety of animal species, both native and alien, for public display, and the Mokopane Biodiversity Conservation Centre has overlapping functions with both botanical gardens and zoological gardens [21]. South African National Botanical Gardens are associated with conservation priority biodiversity areas [21,23], and therefore warrant heightened protection from the escalating impacts of biological invasions.

To date, South Africa has recorded approximately 1880 alien species that have established within the country, some of which have become invasive (215 species, as indicated in Zengeya & Wilson [24]), and resulted in severe negative impacts on the recipient environment [23,24]. Biological invasions reduce biodiversity [25,26], which can threaten human well-being, especially for communities that rely on ecosystem goods and services in South Africa [26]. The impacts of biological invasions include the altering of habitat structures, hampering the proper functioning of ecosystems and limiting the availability of essential natural resources [26,27]. Subsequently, one of the strategic responses to the effective management of biological invasions in South Africa has entailed the development and enactment of legislative control via the National Environmental Management: Biodiversity Act (NEM: BA) (Act No. 10 of 2004) and the Alien and Invasive Species Regulations, hereafter called NEM:BA-A&IS Regulations [28], which are complemented by the updated 2021 NEM:BA-A&IS Regulations. It is required that SANBI must submit a report on the status of listed invasive species to the Minister of the Department of Forestry, Fisheries and the Environment (DFFE) every three years. Indeed, Zengeya and Wilson [24] pointed to the patchiness of species information as one of the main factors slowing the effective management of biological invasions in South Africa. The knowledge of alien species' records in the SANBI gardens constitutes critical indicators for monitoring biological invasions at the national level across South Africa [29,30], which may enhance the effective management of the impacts of such species in SANBI's gardens.

Despite the known and increasing negative impacts of biological invasions reported in the two national status reports produced thus far [24,26,30], the effective management of biological invasions in South Africa has been difficult because of several challenges. For instance, there is no overarching national management strategy for guiding different role players in safeguarding the national biodiversity and SANBI's national gardens from the negative impacts of biological invasions in South Africa. Above all, there is a paucity in the knowledge of the numbers of alien and invasive species, and their associated negative impacts are a nationwide problem that include SANBI's national gardens. Zengeya et al. [31] raised the issue of low reliability of current existing estimates of the numbers of species in different contexts. In addition, the lack of human capacity and limited resources hampers the success of containing the problem of biological invasions in different contexts, such as within local municipalities [32,33] and SANBI gardens. Although the NEM:BA-A&IS Regulations [28] emphasized the development of management plans for alien species occurring on state and private land, there has generally been limited compliance, partly due to the scarcity of scientific skills in invasion biology [29].

In view of the above arguments, the aims of this study were to: (1) document the diversity of alien and invasive plant species occurring in SANBI's gardens with the purpose of informing the development of a management strategy; and (2) classify different alien plant species recorded in different gardens based on continental origin, life form and their status as per the NEM:BA-A&IS regulations, to guide prioritisation in resources' allocation for management interventions. This is the first study to start screening and assessing the invasion risk for biodiversity conservation in South Africa's gardens (see a case study in China: Ni & Hulme [15]).

2. Methods and Materials

2.1. Study Area

The study was conducted in South Africa in 11 SANBI botanical gardens, 1 zoological garden and the Mokopane Biodiversity Conservation Centre, which are situated in 8 provinces and 7 South African biomes (Figure 1). The SANBI national botanical gardens are located in eight of South Africa's nine provinces, where there are unique vegetation types targeted for conservation (Table 1 [21]). These study sites were selected because they are all managed by SANBI and have a common function of biodiversity conservation.

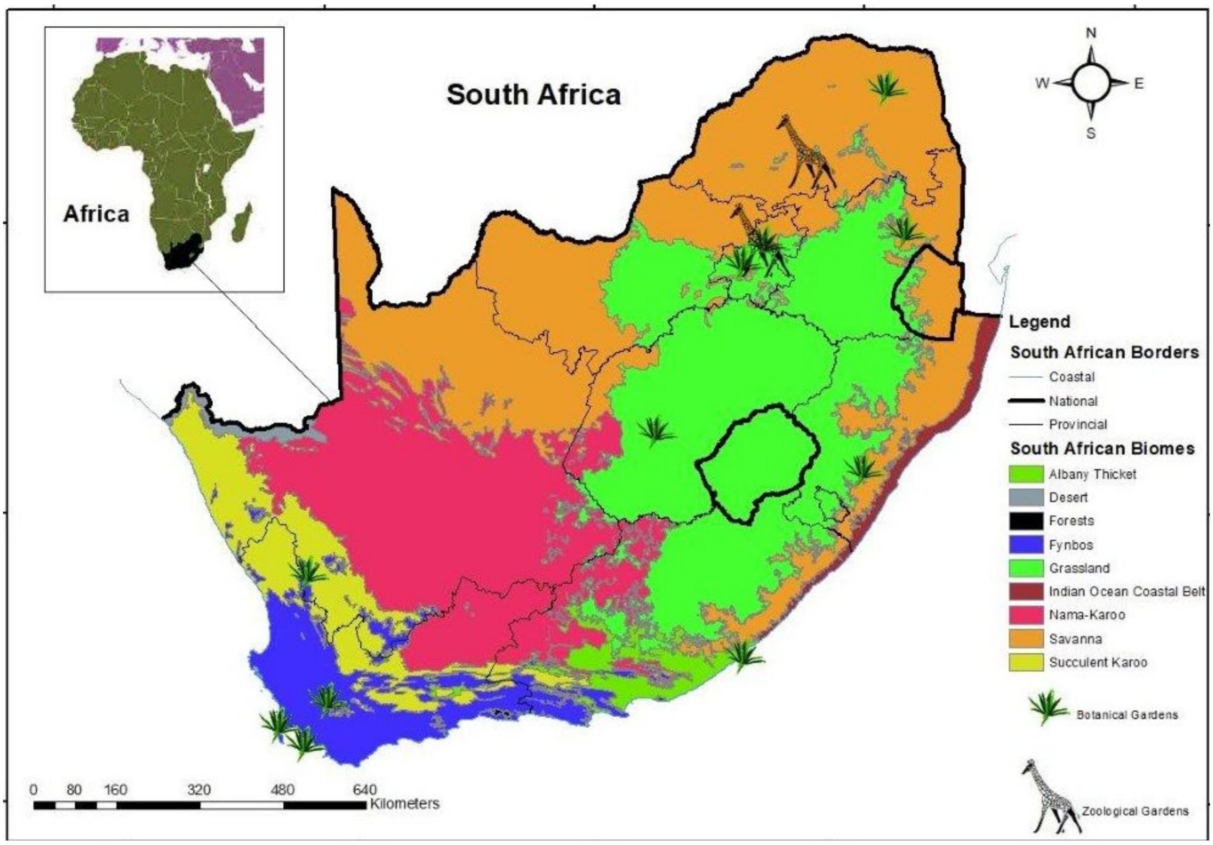

Figure 1. The locations of the SANBI botanical and zoological gardens overlayed on the national vegetation map of South Africa (i.e., vegetation layers from Mucina and Rutherford [22]).

2.2. Data Collection

The species data were obtained by requesting lists of alien species for each of the 13 SANBI gardens from the curators and garden estate managers.

Several key sources were used for plant species identification, including field guides by Bromilow [34,35] and Henderson [36], the Invasive Species South African Database [37] and herbarium specimen collections. Due to limited evidence, some species were identified only up to the genus level.

Species names were verified using the national resource: "The Status of Biological Invasions and their Management in South Africa" [24,26].

Following the criterion described in Mokotjomela et al. [33], plant species were classified by life form as follows: herbs, graminoids, succulents, woody for the shrubs and trees and ferns using the Botanical Database of Southern Africa (BODATSA) [38] and the Integrated Taxonomic Information System (Table A1, [39]). Pyšek et al. [40] showed that some species' traits, especially life form, stature and pollination syndrome, may provide a method of predicting impact, regardless of the habitat and geographical region invaded. In addition, the region of origin is critical for understanding and managing the pathway of introduction for alien species (see also [41]). The data collected for each species included the gardens and their provincial locations where the species was recorded in South Africa, the reason for introduction as a proxy for the pathway pattern, and the continental origin of each species. Since the native range of the species is important for climate matching with the recipient environment during invasion risk assessment [42], we made an assumption that the species were introduced directly to South Africa from their native continent. Inasmuch as the exact country of origin of each species was identified (after [12,33]), for this study we used the continental and/or broad region to classify the recorded species as specified in the Centre for Agriculture and Bioscience International (CABI) and Global Invasive Species Database. Species were also categorised following the NEM:BA-A&IS Regulations, 2021.

There are four categories—1a, 1b, 2, and 3—depending on what is permitted and the overall management goal [43,44], and the "Not listed species" (denoted by NL; 33; Tables 2 and A1).

Table 1. SANBI botanical and zoological gardens' features: area, the first date of current land use/proclaimed, biomes and preserved vegetation types.

National Botanical/Zoological Garden	Area (ha)	First Date of Current Land Use/Proclaimed	SA Province (Town)	Biome Represented (Bioregion) (Mucina & Rutherford, 2006)	Vegetation Types Represented (Mucina & Rutherford, 2006)
Free State NBG	67	1967	Free State Province (Bloemfontein)	Grassland (Dry Highveld Grassland) Azonal Vegetation (Alluvial Vegetation)	Gh 7 Winburg Grassy Shrubland Gh 8 Bloemfontein Karroid Shrubland Gh 5 Bloemfontein Dry Grassland AZa 5 Highveld Alluvial Vegetation
Hantam NBG	6230	2008	Northern Cape (Nieuwoudtville)	Succulent Karoo (Trans-Escarpment Succulent Karoo) Fynbos (Shale Renosterveld, and Granite and Dolerite Renosterveld)	FRd 1 Nieuwoudtville-Roggeveld Dolerite Renosterveld FRs 2 Nieuwoudtville Shale Renosterveld SKt 2 Hantam Karoo
Harold Porter NBG	201	1959	Western Cape (Betty's Bay)	Fynbos (Sand Fynbos, Western Strandveld and Sandstone Fynbos) Forest (Zonal & Intrazonal)	FFd 6 Hangklip Sand Fynbos FFs 11 Kogelberg Sandstone Fynbos FOz 1 Southern Afrotemperate Forest FS 7 Overberg Dune Strandveld Freshwater (rivers) Marine biodiversity
Karoo Desert NBG	154	1921	Western Cape (Worcester)	Succulent Karoo (Rainshadow Valley Karoo) Fynbos (Shale Fynbos and Shale Renosterveld)	FFh 4 Breede Shale Fynbos FRs 8 Breede Shale Renosterveld SKv 7 Robertson Karoo
Kirstenbosch NBG	199	1913	Western Cape (Cape Town)	Fynbos (Granite Fynbos, Sandstone Fynbos, and Shale Fynbos) Forest (Zonal and Intrazonal)	FFg 3 Peninsula Granite Fynbos FFh 5 Cape Winelands Shale Fynbos FFs 9 Peninsula Sandstone Fynbos FOz 1 Southern Afrotemperate Forest Freshwater (rivers)
KwaZulu-Natal NBG	48	1874/1969	KwaZulu-Natal (Pietermaritzburg)	Savanna (Sub-Escarpment Savanna)	SVs 4 Ngongoni Veld Freshwater (river)
Kwelera NBG	170	2014	Eastern Cape (East London)	Forest (Zonal and Intrazonal) Azonal Vegetation (Eastern Strandveld) Albany Thicket	AT 9 Albany Coastal Belt FOz 6 Southern Coastal Forest AZs 2 Albany Dune Strandveld AT 12Buffels Thicket Marine biodiversity
Lowveld NBG	164	1969	Mpumalanga (Nelspruit)	Savanna (Lowveld)	SVl 9 Legogote Sour Bushveld SVl 10 Pretoriuskop Sour Bushveld Freshwater (river)
Pretoria NBG	70	1958	Gauteng (Pretoria)	Savanna (Central Bushveld)	SVcb 6 Marikana Thornveld
Thohoyandou NBG	89	1986	Limpopo (Thohoyandou)	Savanna (Central Bushveld)	SVcb21 Soutpansberg Mountain Bushveld
Pretoria NZG	80	1899	Gauteng (Pretoria)	Savanna (Central Bushveld)	SVcb 6 Marikana Thornveld
Mokopane Biodiversity Conservation Centre	1398	1979	Limpopo (Mokopane)	Savanna (Central Bushveld)	SVcd 20 Makhado Sweet Bushveld SVcb 23 Polokwane Plateau Bushveld
Walter Sisulu NBG	276	1982	Gauteng (Roodepoort/Mogale City)	Savanna (Central Bushveld) Grassland (Mesic Highveld Grassland)	SVcb 9 Gold Reef Mountain Bushveld Gm 10 Egoli Granite Grassland Freshwater (river)

Table 2. Different categories of alien and invasive species following the NEM:BA-A&IS Regulations, 2021.

Category	NEM:BA-A&IS Description
Category 1(a)	Species that must be combatted and are targets for eradication
Category 1(b)	Species that are control targets and need a national management plan
Category 2	Species requiring a permit for restricted activities
Category 3	Species that are subject to exemptions
"Not Listed"	Unlisted species: Alien species that are not listed in the NEM:BA-A&IS Regulations but have been reported as present in natural or semi-natural ecosystems in South Africa or on offshore islands

Depending on the risk assessment outcome of each alien species in South Africa and their differential occurrence and impacts in different provinces (Kumschick et al. [42]), some species tend to have more than one listing category based on the context in which a risk assessment was carried out. To avoid allocating one species into more than one category, the most common category and/or where a species is a priority for management was considered to be the correct category in this study [33]. Additionally, the newly adopted risk assessment framework for South Africa classified species based on risk assessment for the whole country [42] instead of the contexts in each province as shown for different categories presented in the national status report and the national regulations [26].

2.3. Data Analyses

2.3.1. Species and Families

From the total records of alien species obtained from different gardens (Table 1), we identified the gardens that have the highest number of alien species, the dominant plant families and the most common species across the gardens. We also determined if there was an overlap among the gardens in the alien plant species that occur in each.

2.3.2. Species Classification: Continental Origin, Life Forms, and NEM:BA-A&IS Categories

To compare the numbers of alien species in different classification categories (i.e., life form, NEM:BA-A&IS Regulations' categories, species' continental origin and reason for plant species introduction (pathway)), species count data were analysed using a Generalised Linear Models (GLM), with a Poisson error distribution and log link in SPSS software, version 20. The counts of alien plant species were generated from total records obtained from different gardens, and they were specified as the dependent variable. Different species classification categories were treated as predictor variables.

3. Results

3.1. Identification of Alien Plant Species and Families

In total, there were 380 alien species records from in 13 SANBI gardens, representing 225 unique alien plant species belonging to 73 families. Different life forms included herbs (42.7%; n = 225), woody plants (37.8%), graminoids (10.7%), succulents (6.7%) and ferns (2.2%). The most common species, occurring in more than six gardens, were: *Solanum mauritianum* (11 gardens), *Lantana camara* (10), *Melia azedarach* (10) and *Acacia mearnsii*, *Jacaranda mimosifolia*, *Opuntia ficus-indica* and *Ricinus communis* (6 each). Among the reported plant species, a significant number (49%; n = 225) were introduced through horticultural trade as ornamental plant species (Wald χ^2 = 27.3; df = 6; p < 0.001), followed by plant species used for human consumption—medicine and food (Wald χ^2 = 5.2; df = 1; p = 0.023) being more dominant.

The most represented families in the records were Fabaceae (29 species) (mainly *Acacia*), Asteraceae (24 species), Poaceae (23 species), Solanaceae (14 species) (mainly *Solanum*), Myrtaceae (11 species) (mainly *Eucalyptus*) and Cactaceae (11 species) (mainly *Opuntia*).

Walter Sisulu NBG had the highest number of alien species records (88 species), followed by Kirstenbosch NBG (61 species) and Pretoria NBG (46 species) (Figure 2).

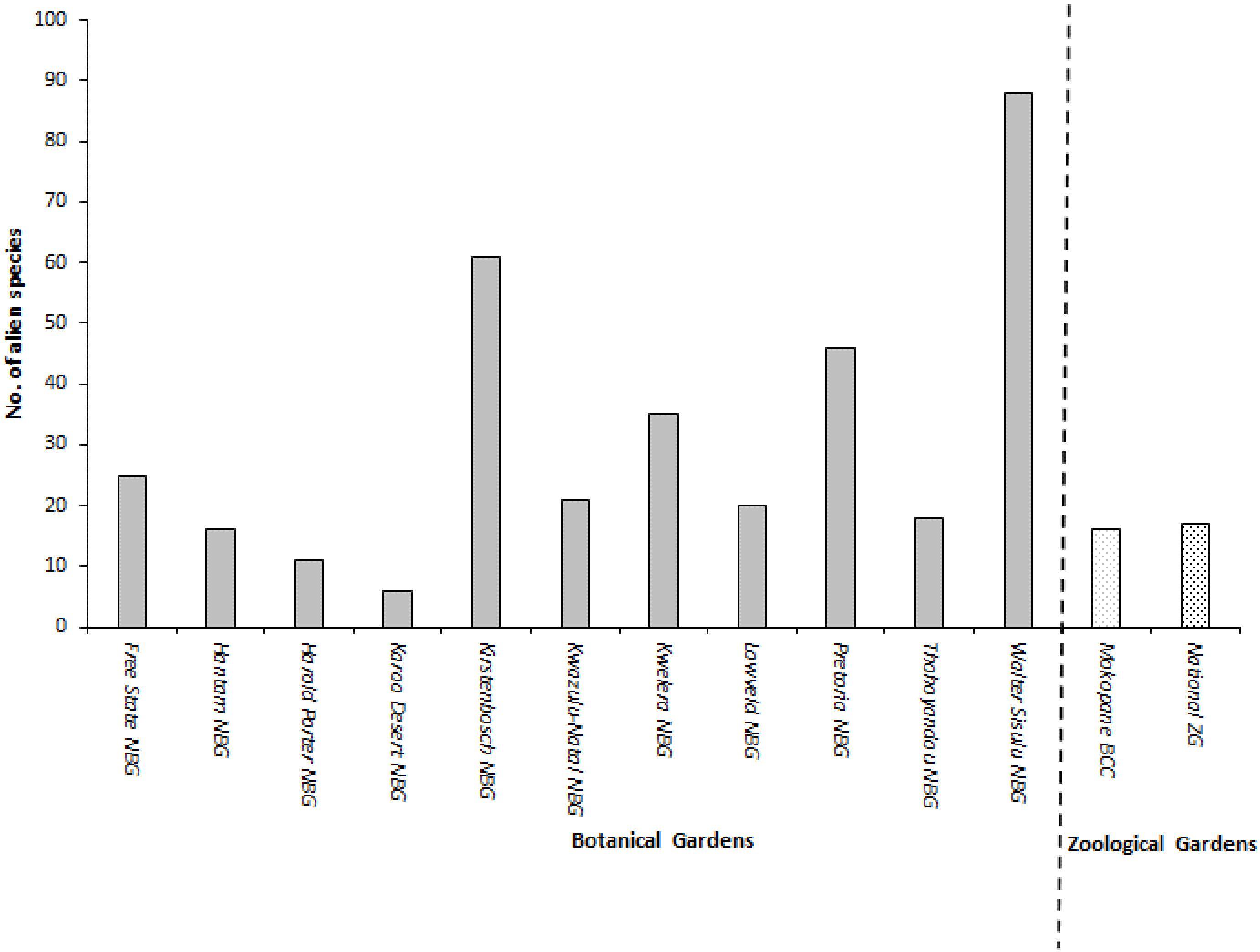

Figure 2. The number of alien plant species recorded in SANBI gardens.

3.2. Comparing Continental Origin of Different Alien Species, Life Forms and NEM:BA-A&IS Regulations' Categories

There was a statistically significant relationship between the number of alien species recorded across SANBI gardens and different continental regions of the world (Pearson $\chi^2 = 199.2$; df = 48; $p < 0.001$; Figure 3). Overall, most plant species were from the North and South Americas together (50 + 66 = 106 species). A significantly greater number of species were introduced from South America than from Asia (Wald $\chi^2 = 7.5$; df = 1; $p = 0.006$) and Australia (Wald $\chi^2 = 49.9$; df = 1; $p < 0.001$). However, the number of species from South America was not significantly different from the number of species from Europe (Wald $\chi^2 = 0.1$; df = 1; $p = 0.776$) and North America (Wald $\chi^2 = 1.0$; df = 1; $p = 0.326$).

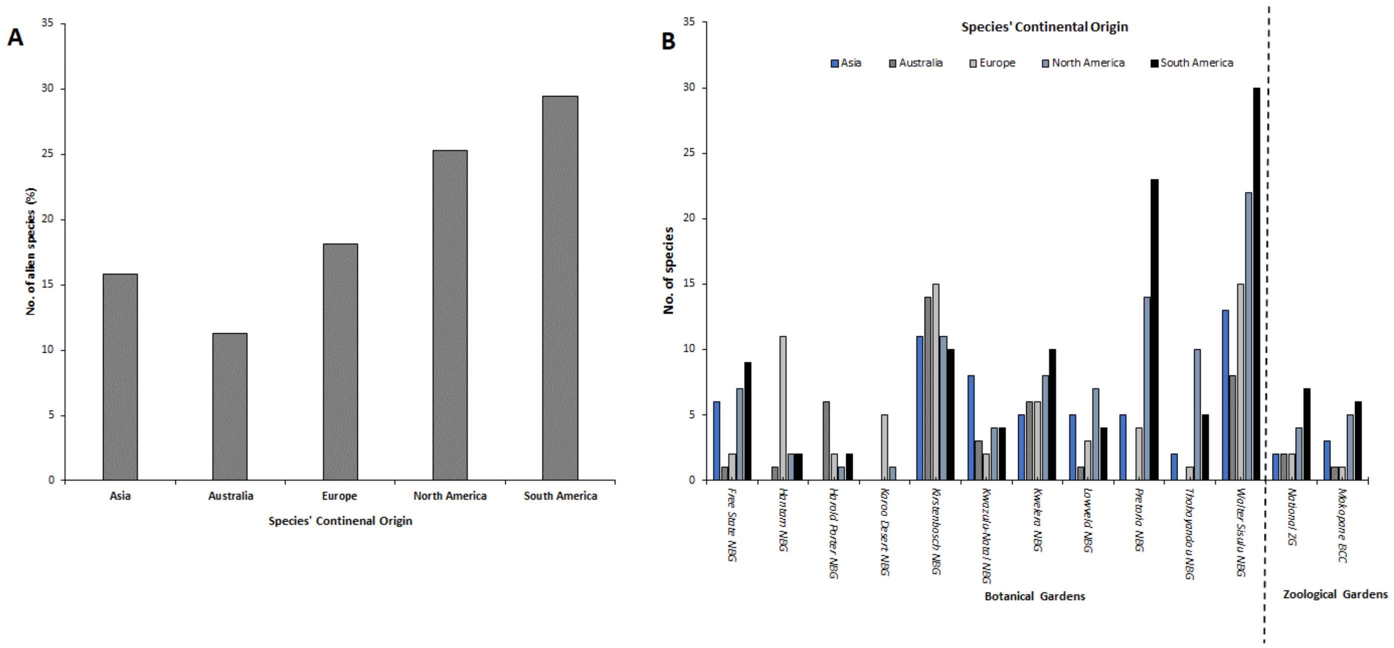

Figure 3. Number of records of different alien species from different continental space (%; $n = 380$; (**A**)) and their occurrence in different SANBI gardens (**B**).

There was a statistically significant relationship between the number of alien species recorded in SANBI gardens and life forms (Pearson $\chi^2 = 353.5$; df = 60; $p < 0.001$; Figure 4; Table A1). Herbaceous and woody alien species were dominant in the records. There was a significantly greater number of woody species than succulents (Wald $\chi^2 = 7.9$; df = 1; $p = 0.005$) and graminoids (Wald $\chi^2 = 3.8$; df = 1; $p = 0.052$). However, the number of woody species was not significantly different than the number of herbs (Wald $\chi^2 = 2.1$; df = 1; $p = 0.258$), and ferns (Wald $\chi^2 = 1.3$; df = 1; $p = 0.258$). It was noteworthy that the herbaceous species accounted for the largest number of species (i.e., 40 out of 88 species) in Walter Sisulu NBG (Figure 4; Table A1).

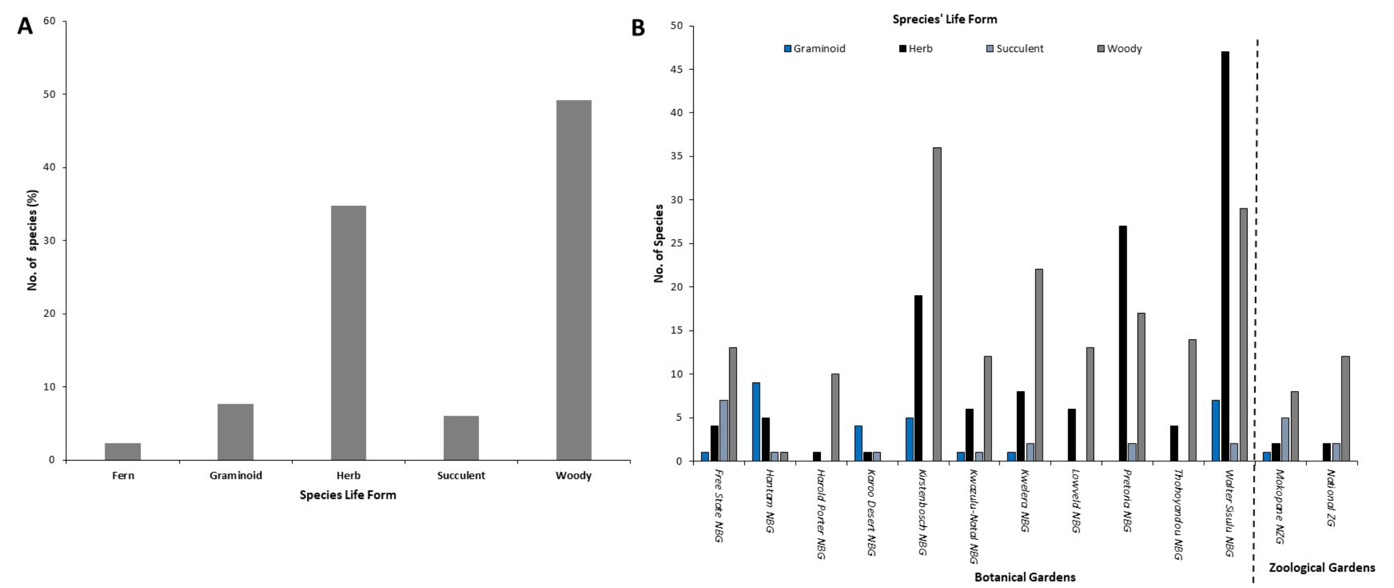

Figure 4. Number of records of different alien plant species in each life form (%; $n = 380$; (**A**)) and their occurrence in different SANBI gardens (**B**).

Finally, there were no statistically significant differences between the number of alien species listed in different NEM:BA-A&IS Regulations' categories and the number of unlisted species (χ^2 = 8.9; df = 4; p = 0.317: 58.2% vs 42.8%). We noted significant differences in the number of alien species representing each NEM:BA-A&IS Regulations' category in three gardens; namely, Walter Sisulu NBG, Kirstenbosch NBG and Pretoria NBG (Pearson χ^2 = 151.0; df = 48; p < 0.001; Figure 5). Walter Sisulu NBG had the highest number of unlisted (38 species) species and category 1b species (39), followed by Kirstenbosch NBG (32, 24) and Pretoria NBG (25, 18), respectively.

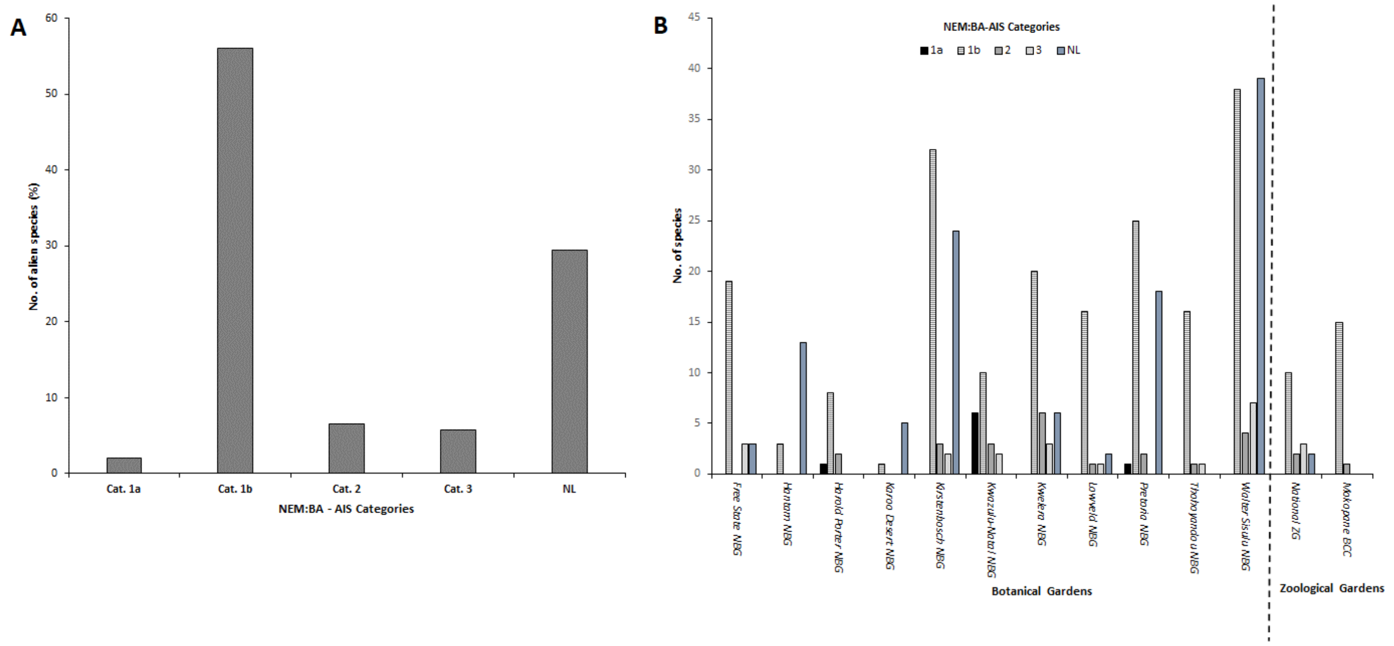

Figure 5. Numbers of alien species' records (%; n = 380) in different NEM:BA-AIS Regulations' categories for species (**A**) and their occurrence in different SANBI Gardens (**B**). Cat. = Category. Category 1a: Species that are targets for eradication. Category 1b: Species that are control targets and need a national management plan. Category 2: Species requiring a permit for restricted activities. Category 3: Species that are subject to exemptions. "Not Listed" (NL): Unlisted species: alien species that are not listed in the NEM:BA-A&IS Regulations but have been reported as present in natural or semi-natural ecosystems in South Africa or on offshore islands.

4. Discussions

We recorded a total of 225 alien plant species occurring in SANBI botanical gardens, and this can be partly attributed to deliberate introductions of species to these gardens for economic botany and ornamental and conservation research purposes [12,41,45]. Deliberate introduction of alien species for biosecurity screening in different parts of the world was previously reported [10,15,16,41], while the accidental introduction of some species as contaminants is common in many areas, including South Africa [12,46]. In the SANBI gardens, we found a large number of plant species (49%; n = 225) that were introduced through horticultural trade as ornamentals [intentional introductions, 41] in South Africa and that evidently escaped [34]. Unintentional introductions of alien species could also be accelerated by the fact that botanical gardens attract large numbers of visitors from different parts of the world performing different activities, including grilling meat with firewood from unknown sources [16], and this may account for the proportion of our records that had no specific known use (10.7 %, n = 225) in South Africa. We also suggest that, in part, the large diversity of alien plant species reported in this study is a likely result of their diverse uses [10,33,46] in the multi-racial South African society [46–48].

Other alien species are likely to have invaded the gardens by natural spread, such as through the dispersal of fleshy-fruited species by birds [48–51], roadways connecting the gardens with different potential alien propagule sources, such as urban home gardens [33,52,53] and river systems that traverse most of the gardens [20,54]. Indeed, van Kleunen et al. [12] have shown that horticultural alien species tend to have spread more than many other alien species, and that they naturalise much better, which is essential for invasion [55]. Apart from this, many SANBI gardens are situated near urbanised areas, thus making them vulnerable to high alien plant propagule pressure that promotes invasion [56]. The fragmentation of habitats, especially in urban areas, shifts the ecological balance away from native species and towards favouring the human-associated alien species [45,57]. However, since SANBI gardens are protected and experience low biophysical disturbance (e.g., [20,21]), they may have some natural resistance to invasion by alien species [58].

It has been shown that over 100 alien species have attained invasive status, with considerable direct and indirect negative impacts on the rich biotas of South Africa [59]. The fact that we recorded some of the most abundant and damaging alien woody plant species (i.e., *Lantana camara* and *Solanum mauritianum*; [26]) and *Melia azedarach* in the majority of the SANBI gardens (10–11) points to the possibility of undocumented impacts of these species. Above all, *L. camara* and *Acacia mearnsii* are among the worst alien invasive species in the world [13], and were recorded in some of the SANBI gardens. Additionally, the negative impacts of woody alien species (i.e., including trees and shrubs) have been documented [24,26], as well as their increasing numbers in South Africa [25,60]. In South Africa, the local biodiversity is threatened by, among others, the 141 Australian *Acacia* species (wattles), of which 13 are highly invasive and growing prolifically both in cultivation and outside [44,61]. While *M. azedarach* does not have major or severe known negative impacts in South Africa [24], we argue that its abundance suggests a possible effective long-distance dispersal mediated by local vertebrates which could compromise the dispersal of native species [62]. A plausible explanation of the finding is an absence of dedicated management plans (limited compliance) and limited capacity to implement control measures [20,33]. Since the impacts of alien species have not been investigated in SANBI gardens, this study provides bases for the urgent planning and prioritisation of efforts to manage the affected gardens.

Knowledge of the life forms and life cycles of different alien plant species and their native range can guide the prediction of invasion risk and support invasion scenario planning for management [40,63]. Our finding of a large number of herbaceous and woody species in the SANBI gardens is possibly due to the predominance of agricultural introductions for fodder in the neighbourhood farms, horticultural elements [46] and the use of graminoids for biofuel production in neighbouring farms [64]. Alien herbs and grasses are notorious in the farming sector, where they outcompete and reduce the numbers of palatable species in the pastures [65]. Nevertheless, there has been limited research on the negative impacts of herbs and grasses in South Africa [64], and specifically on the preserved vegetation in SANBI gardens as a unique land-use type (see [20]). We suggest that Walter Sisulu NBG may have the highest number of herbaceous species and other life forms because of high propagule pressure created by a water stream emerging from a catchment embedded in urbanised human settlements [66,67]. Although we could not distinguish between the intentional and unintentional species introductions, we also speculate that, in part, a high influx of international tourists in Gauteng (to Walter Sisulu & Pretoria NBGs) and the Western Cape (Kirstenbosch NBG) provinces, particularly from the Americas and Europe, are some of the unintentional sources of most species in this study. Above all, these gardens are located in the economic hubs of South Africa where there are numerous activities that facilitate alien species' spread [33], as well as a large local human population, as asserted in Pyšek et al. [68].

Biological invasions are reported to be one of the major drivers of ecological degradation in the grassland and fynbos biomes of South Africa [45,69,70], and, consistently, the gardens located in the fynbos and grassland biomes had a high number of alien species [20]. Most SANBI gardens have either wetlands or river systems, and indeed we recorded some of the species that have been specified as common in such environments by

Richardson et al. [45]. Although *Prosopis glandulosa* is common in arid areas [45], it was not reported as present in the arid Hantum and Karoo National Botanical Garden, possibly due to effective garden management in place. In general, we recorded many similar species to those identified in different main habitats by Richardson et al. [45], and even some alien plant species that were not known in the national regulations. Consequently, we assert that systematic sampling of alien species in SANBI gardens will be critical to improving the list we presented in this study.

While the abundance of the recorded species was not measured, the management of the existing populations is important to mitigate negative impacts. Listing the alien species in the national regulations facilitates understanding the species' impacts and their management needs [33,42,63], and thus prioritisation of limited resources. Alien species categorised as "1b" in the national regulations are targets for containment and, consequently, their occurrence in large numbers in SANBI gardens is possibly due to the absence of management actions. It is also possible that a large number (41.8%; n = 225) of the species were not listed in the national regulations due to limited capacity in performing the alien taxa risk assessment and profiling [see the framework, 42]. A large number of unlisted alien plant species corroborates the recent reports that there are many alien species that have not been documented [12,24,26,33,63], with actual numbers of invasive species increasing in South Africa [25]. In addition, this finding highlights the absence or limited scientific research needed to support the science-based management of biological invasions which could partly thwart management success in South Africa [33]. The results of this study are key to improving the development and implementation of integrated management plans to protect the integrity and sustainable conservation of the gardens' ecosystems from future impacts on botanical gardens as an important conservation strategy for the world's flora [2]. On the other hand, the horticultural plant propagations in botanical gardens can be pivotal for vegetation rehabilitation/restoration through reintroducing native species in degraded landscapes [2,4,70–72]).

5. Concluding Remarks

In this study, we have presented a list of alien and invasive plant species occurring in SANBI gardens located in different parts of South Africa, which may guide the safeguarding of biodiversity conservation gardens from the threats posed by biological invasions [2]. Indeed, compiling species lists and regular monitoring of high-risk sites, including the botanical gardens, can strengthen their management if public awareness campaigns are conducted timeously and the escape of various alien species from different points of introduction is reduced. We also recognise the complexity of the relationship between human socio-economic needs and alien species, and thus advocate for increased awareness of negative impacts as a potential strategy for mitigation. The findings in this study constitute progress toward reducing the reported uncertainty of the existing alien species data sets that restrict planning management of biological invasions in South Africa [63].

While this is the first study to collate this information, it is apparent that even the invasion status of unlisted species and potential negative impacts have not been investigated in SANBI gardens; a gap that Foxcroft et al. [32] identified as a major obstacle to effective science-based management of biological invasions in South Africa. The potentially impactful species populations will need to undergo clearing that is coupled with restoration using native plant species [72]. The finding that many plant species were not listed in the national regulations highlights the important knowledge gap in the negative impacts of the alien species in question and/or capacity constraints for compilation of the risk assessment. Further systematic surveys for alien and invasive species are required to improve the knowledge of invasion risk in biodiversity conservation gardens around the world. Considering the prominence of the role of botanical gardens in the dissemination of alien plants, the eight key research questions listed by van Kleunen et al. [12] should be explored in SANBI botanical gardens as a way of improving the current data sets and improving the management of negative impacts of the biological invasions in the preserved biodiversity as a natural asset in SANBI gardens.

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Appendix A

Table A1. List of alien plant taxa recorded in different SANBI botanical and zoological gardens (following SANBI 2016: BODATSA 2016, and it is: https://www.itis.gov/servlet/SingleRpt/SingleRpt#null, accessed on 15 February 2023). Each plant species was classified according to family, life form, NEM:BA-AIS Regulations' categories and invasion status defined by Blackburn et al. [73].

Family	Genus, Species and Lower Taxa	Life Form	NEM:BA-AIS Regs. Cat	Alien Status [73]
Adoxaceae	*Viburnum tinus* L.	Woody	NL	-
Alismataceae	*Sagittaria latifolia* Willd.	Herb	NL	Invasive
Amaranthaceae	*Amaranthus hybridus* L.	Herb	NL	Invasive
	Atriplex lindleyi F.Muell.	Herb	1b	Invasive
	Chenopodium album L.	Herb	NL	Invasive
	Dysphania sect. *botryoides* (L.) Mosyakin & Clemants	Herb	NL	-
	Salsola kali L.	Herb	1b	Invasive
Anacardiaceae	*Schinus molle* L.	Woody	NL	Invasive
Apiaceae	*Foeniculum vulgare* A.W.Hill	Herb	NL	Invasive
	Cyclospermum leptophyllum (Pers.)	Herb	NL	-
Apocynaceae	*Araujia sericifera* Brot.	Herb	1b	Invasive
	Thevetia peruviana (Pers.) K. Schum.	Woody	1b	Invasive
	Vinca major L.	Herb	1b	Invasive
Aristolochiaceae	*Aristolochia elegans* Mast.	Woody	1b	Invasive
Asparagaceae	*Agave americana* L. var. *americana*	Succulent	NL	Invasive
	Agave sisalana Perrine	Succulent	2	Invasive
	Furcraea foetida L.	Succulent	1a	Invasive
	Yucca sp.	Succulent	NL	-

Table A1. *Cont.*

Family	Genus, Species and Lower Taxa	Life Form	NEM:BA-AIS Regs. Cat	Alien Status [73]
Asteraceae	*Ageratum conyzoides* (Mill.) M.Sharma	Herb	1b	Invasive
	Ageratina adenophora (Spreng.) R.M.King & H.Rob.	Herb	1b	Invasive
	Bidens bipinnata L.	Herb	NL	Invasive
	Bidens pilosa L.	Herb	NL	Invasive
	Campuloclinium macrocephalum (Less.) DC.	Herb	1b	Invasive
	Chromolaena odorata (L.) R.M.King & H.Rob.	Herb	1b	Invasive
	Cirsium vulgare (Savi) Ten.	Herb	1b	Invasive
	Conyza sumatrensis (Retz.) E.Walker	Herb	NL	Invasive
	Cosmos bipinnatus Cav.	Herb	NL	Invasive
	Flaveria bidentis (L) Kuntze	Herb	1b	Invasive
	Galinsoga ciliata (Raf.) Blake	Herb	NL	-
	Hypochaeris microcephala (Sch.Bip.) Cabrera	Herb	NL	-
	Hypochaeris radicata L.	Herb	NL	Invasive
	Lactuca indica L.	Herb	NL	-
	Schkuhria pinnata (Lam.) Kuntze ex Thell.	Herb	NL	Invasive
	Sonchus oleraceus L.	Herb	NL	Invasive
	Sphagneticola trilobata (L.) Pruski	Herb	1b	Invasive
	Tagetes minuta L.	Herb	NL	Invasive
	Tithonia diversifolia (Hemsl.) A.Gray	Herb	1b	Invasive
	Tithonia rotundifolia S.F.Blake (Mill.)	Herb	1b	Invasive
	Zinnia peruviana L.	Herb	NL	Invasive
Basellaceae	*Anredera cordifolia* (Ten.) Steenis	Herb	1b	Invasive
Bignoniaceae	*Dolichandra unguis-cati* L. (A.Gentry)	Woody	1b	Invasive
	Jacaranda mimosifolia D.Don	Woody	1b	Invasive
	Tecoma stans (L.) Juss. ex Kunth	Woody	1b	Invasive
Boraginaceae	*Amsinckia menziesii* var. *retrorsa* (Lehm.) A.Nelson & J.F.Macbr.	Herb	NL	Invasive
	Echium plantagineum L.	Herb	1b	Invasive
	Heliotropium amplexicaule Vahl	Herb	NL	Invasive
	Heliotropium europaeum L.	Herb	NL	Invasive
Brassicaceae	*Brassica juncea* (L.) Czern.	Herb	NL	-
	Capsella bursa-pastoris (L.) Medik.	Herb	NL	Introduced but not naturalized
	Nasturtium officinale R.Br.	Herb	2	Invasive
	Raphanus raphanistrum L.	Herb	NL	Invasive
Cactaceae	*Cereus jamacaru* DC.	Succulent	1b	Invasive
	Cylindropuntia imbricata (Haw.) F.M.Knuth	Succulent	1b	Invasive
	Trichocereus spachianus(Lem.) Riccob	Succulent	1b	Invasive
	Opuntia aurantiaca Lindl.	Succulent	1b	Invasive
	Opuntia engelmannii Salm-Dyck ex Engelm.	Succulent	1b	Invasive
	Opuntia ficus-indica (L.) Mill.	Succulent	1b	Invasive
	Opuntia leucotricha DC.	Succulent	1b	Invasive
	Opuntia microdasys (Lehm.) Pfeiff.	Succulent	1b	Invasive
	Opuntia pubescens J.C.Wendl. ex Pfeiff.	Succulent	1a	Introduced but not naturalized

Table A1. *Cont.*

Family	Genus, Species and Lower Taxa	Life Form	NEM:BA-AIS Regs. Cat	Alien Status [73]
Cannabaceae	*Celtis australis* L.	Woody	3	Introduced but not naturalized
Cannaceae	*Canna indica* L.	Herb	1b	Invasive
Caprifoliaceae	*Centranthus ruber* (L.) DC.	Herb	1b	Invasive
	Lonicera japonica Thunb.'Halliana'	Woody	3	Invasive
Caryophyllaceae	*Silene gallica* L.	Herb	NL	-
Cistaceae	*Cistus ladanifer* L.	Woody	NL	Invasive
Commelinaceae	*Tradescantia fluminensis* Vell.	Herb	1b	Invasive
Convolvulaceae	*Convolvulus arvensis* L.	Herb	1b	Introduced but not naturalized
	Cuscuta campestris Yunck.	Herb	1b	Invasive
	Ipomoea purpurea (L.) Roth	Herb	1b	Invasive
Crassulaceae	*Bryophyllum delagoense* (Eckl. & Zeyh.) Schinz	Succulent	1b	Invasive
Cucurbitaceae	*Diplocyclos palmatus* L.	Woody	1a	Invasive
Cyatheaceae	*Sphaeropteris excelsa* (Endl.) R.M.Tryon	Fern	NL	Invasive
Cyperaceae	*Cyperus eragrostis* Lam.	Graminoids	NL	-
Euphorbiaceae	*Euphorbia heterophylla* L.	Herb	NL	-
	Euphorbia peplus L.	Herb	NL	-
	Homalanthus populifolius Graham.	Woody	1b	Invasive
	Mercurialis annua L.	Herb	NL	-
	Ricinus communis L.	Woody	2	Invasive
Fabaceae	*Acacia cyclops* A.Cunn. ex G.Don	Woody	1b	Invasive
	Acacia dealbata Link	Woody	2	Invasive
	Acacia elata A.Cunn. ex Benth.	Woody	1b	Invasive
	Acacia longifolia (Andrews) Willd.	Woody	1b	Invasive
	Acacia mearnsii De Wild.	Woody	2	Invasive
	Acacia melanoxylon R.Br.	Woody	2	Invasive
	Acacia podalyriifolia A.Cunn. ex G.Don	Woody	1b	Invasive
	Acacia saligna (Labill.) H.L.Wendl.	Woody	1b	Invasive
	Caesalpinia decapetala (Roth) Alston	Woody	1b	Invasive
	Caesalpinia gilliesii Wall. ex. Hook.	Woody	1b	Invasive
	Crotalaria agatiflora Schweinf.	Woody	1b	Invasive
	Cytisus palmensis (Christ) Hutch.	Woody	NL	-
	Desmodium sp.	Woody	NL	-
	Gleditsia triacanthos L.	Woody	1b	Invasive
	Medicago lupulina L.	Herb	NL	-
	Medicago polymorpha L. var. *brevispina* (Benth.) Heyn	Herb	NL	-
	Paraserianthes lophantha (Willd.) I.C.Nielsen	Woody	1b	Invasive
	Prosopis glandulosa var. *torreyana* (L.D.Benson) M.C.Johnst.	Woody	1b	Invasive
	Robinia pseudoacacia L.	Woody	1b	Invasive
	Senna bicapsularis (L.) Roxb.	Woody	1b	Invasive
	Senna septemtrionalis (Viv.) H.S.Irwin & Barneby	Woody	1b	Invasive
	Senna sp.	Woody	1b	-
	Sesbania bispinosa (Jacq.) W.Wight	Woody	NL	-

Table A1. *Cont.*

Family	Genus, Species and Lower Taxa	Life Form	NEM:BA-AIS Regs. Cat	Alien Status [73]
Fabaceae	*Sesbania punicea* (Cav.) Benth.	Woody	1b	Invasive
	Spartium junceum L.	Woody	1b	Invasive
	Tipuana tipu (Benth.) Kuntze	Woody	3	Invasive
	Vicia atropurpurea L.	Herb	NL	-
	Vicia sativa L.	Herb	NL	-
Fagaceae	*Quercus robur* L.	Woody	NL	Invasive
Hypericaceae	*Hypericum canariense* L.	Woody	NL	-
Iridaceae	*Iris pseudacorus* L.	Herb	1a	Invasive
	Sisyrynchium sp.	Herb	NL	-
Juncaceae	*Juncus bufonius* L. aggregate	Herb	NL	-
Lamiaceae	*Salvia tiliifolia* Vahl.	Herb	1b	Invasive
Lauraceae	*Cinnamomum camphora* (L.) J.Presl	Woody	1b	Invasive
Liliaceae	*Lilium formosanum* Wallace	Herb	1a	Invasive
Malvaceae	*Hibiscus trionum* L.	Herb	NL	Invasive
Meliaceae	*Melia azedarach* L.	Woody	1b	Invasive
Moraceae	*Morus alba* L.	Woody	3	Invasive
	Morus nigra L.	Woody	NL	-
Myrtaceae	*Eucalyptus camaldulensis* Dehnh.	Woody	1b	Invasive
	Eucalyptus grandis W.Hill ex Maiden	Woody	1b	Invasive
	Eucalyptus paniculata Sm.	Woody	NL	Introduced but not naturalized
	Eucalyptus saligna Sm.	Woody	NL	-
	Leptospermum laevigatum (Gaertn.) F.Muell.	Woody	1b	Invasive
	Callistemon rigidus R.Br..	Woody	1b	Invasive
	Metrosideros excelsa Sol. ex Gaertn.	Woody	1a	Invasive
	Myrtus communis L.	Woody	NL	-
	Psidium guajava L.	Woody	2	Invasive
	Syzygium paniculatum Gaertn.	Woody	NL	Invasive
Nyctaginaceae	*Mirabilis jalapa* L.	Herb	1b	Invasive
Nymphaeaceae	*Nymphaea mexicana* Zucc	Herb	1b	Invasive
Oleaceae	*Ligustrum japonicum* Thun.	Woody	1b	Invasive
	Ligustrum lucidum W.T. Aiton	Woody	1b	Invasive
	Ligustrum vulgare L.	Woody	1b	Invasive
	Syringa vulgaris L.	Woody	NL	-
Onagraceae	*Oenothera rosea* L'Herit. ex Aiton	Herb	NL	Invasive
	Oenothera stricta Ledeb. ex Link	Herb	NL	Invasive
	Oenothera tetraptera Cav.	Herb	NL	Introduced but not naturalized
Oxalidaceae	*Oxalis corniculata* L.	Herb	NL	Invasive
	Oxalis latifolia Kunth	Herb	NL	Invasive
Papaveraceae	*Argemone ochroleuca* Sweet	Herb	1b	Invasive
	Fumaria muralis Sond. ex Koch	Herb	NL	Introduced but not naturalized
	Papaver rhoeas L.	Herb	NL	Invasive

Table A1. *Cont.*

Family	Genus, Species and Lower Taxa	Life Form	NEM:BA-AIS Regs. Cat	Alien Status [73]
Passifloraceae	*Passiflora caerulea* L.	Herb	1b	Invasive
	Passiflora edulis Sims.	Herb	2	Invasive
	Passiflora ligularis Juss.	Herb	NL	-
	Passiflora subpeltata Ortega.	Herb	1b	Invasive
Phytolaccaceae	*Phytolacca americana* L.	Herb	1b	Invasive
	Phytolacca dioica L.	Woody	3	Invasive
	Phytolacca octandra L.	Herb	1b	Invasive
Pinaceae	*Pinus patula* Schiede ex Schltdl. & Cham.	Woody	2	Invasive
	Pinus pinaster Aiton	Woody	1b	Invasive
Pittosporaceae	*Pittosporum undulatum* Vent.	Woody	1b	Invasive
Plantaginaceae	*Plantago lanceolata* L.	Herb	NL	Invasive
	Plantago major L.	Herb	NL	Invasive
Poaceae	*Arundo donax* L. 1753	Graminoids	1b	Invasive
	Avena barbata Pott ex Link	Graminoids	NL	Introduced but not naturalized
	Avena fatua L.	Graminoids	NL	Invasive
	Brachypodium distachyon (L.) P.Beauv.	Graminoids	NL	-
	Briza maxima L.	Graminoids	NL	Introduced but not naturalized
	Bromus diandrus Roth	Graminoids	NL	Introduced but not naturalized
	Bromus pectinatus Thunb.	Graminoids	NL	Introduced but not naturalized
	Bromus rigidus Roth.	Graminoids	NL	-
	Calamagrostis acutiflora (Schrad.) Rchb.	Graminoids	NL	NA
	Cortaderia jubata (Lemoine) Stapf.	Graminoids	1b	-
	Digitaria debilis (Desf.) Willd.	Graminoids	NL	-
	Eragrostis mexicana (Hornem.) Link	Graminoids	NL	-
	Hordeum murinum L.	Graminoids	NL	Invasive
	Imperata cylindrica (L.) Raeusch	Graminoids	NL	-
	Lolium rigidum Gaudin	Graminoids	NL	Introduced
	Nassella trichotoma (Nees) Hack. ex Arechav.	Graminoids	1b	invasive
	Paspalum dilatatum Poir.	Graminoids	NL	Invasive
	Paspalum urvillei Steud.	Graminoids	NL	Invasive
	Pennisetum clandestinum Hochst. ex Chiov.	Graminoids	1b	Invasive
	Pennisetum setaceum (Forssk.) Chiov.	Graminoids	1b	Invasive
	Pennisetum villosum R.Br. ex Fresen.	Graminoids	1b	-
	Phalaris minor Retz. (1783)	Graminoids	NL	-
	Stipa capensis Thunb.	Graminoids	NL	Introduced
	Vulpia myuros (L.) C.C. Gmel.	Graminoids	NL	-
Pontederiaceae	*Pontederia crassipes* (Mart.) Solms	Herb	1b	Invasive
Polypodiaceae	*Nephrolepis cordifolia* L.	Fern	1b	Invasive
	Nephrolepis exaltata (L.) Schott	Fern	1b	Invasive

Table A1. *Cont.*

Family	Genus, Species and Lower Taxa	Life Form	NEM:BA-AIS Regs. Cat	Alien Status [73]
Primulaceae	*Ardisia crenata* Sims	Woody	1b	Invasive
	Lysimachia arvensis L.	Herb	NL	Introduced but not naturalized
Pteridaceae	*Adiantum raddianum* Presl	Fern	NL	Introduced but not naturalized
Rosaceae	*Cotoneaster franchetii* Bois	Woody	1b	Invasive
	Cotoneaster pannosus Franch.	Woody	1b	Invasive
	Potentilla indica (Jacks.) Focke	Herb	NL	Invasive
	Prunus persica (L.) Batsch	Woody	NL	Invasive
	Pyracantha angustifolia (Franch.) C.K.Schneid.	Woody	1b	Invasive
	Pyracantha coccinea M.Roem.	Woody	1b	Invasive
	Rosa rubiginosa L.	Woody	1b	Invasive
	Rubus cuneifolius Pursh.	Woody	1b	Invasive
	Rubus fruticosus Lour.	Woody	2	Invasive
	Rubus odoratus L.	Woody	NL	-
Rubiaceae	*Richardia brasiliensis* Gomes	Herb	NL	Invasive
Salicaceae	*Populus canescens (Aiton) Sm.*	Woody	2	Invasive
Salviniaceae	*Azolla filiculoides* Lam.	Fern	1b	Invasive
Sapindaceae	*Cardiospermum grandiflorum* Swartz	Woody	1b	Invasive
Scrophulariaceae	*Verbascum chaixii* Vill.	Herb	NL	-
Simaroubaceae	*Ailanthus altissima* (Mill.) Swingle	Woody	1b	Invasive
Solanaceae	*Cestrum aurantiacum* Lindl.	Woody	1b	Invasive
	Cestrum laevigatum Schltdl.	Woody	1b	Invasive
	Cestrum parqui L'Her.	Woody	1b	Invasive
	Datura ferox L.	Herb	1b	Invasive
	Datura innoxia Mill.	Herb	1b	Invasive
	Datura stramonium L.	Herb	1b	Invasive
	Physalis angulata L.	Herb	NL	Introduced but not naturalized
	Physalis peruviana L.	Herb	NL	Invasive
	Physalis viscosa L.	Herb	NL	Invasive
	Solanum elaeagnifolium Cav.	Woody	1b	Invasive
	Solanum mauritianum Scop.	Woody	1b	Invasive
	Solanum nigrum L.	Herb	NL	-
	Solanum pseudocapsicum L.	Herb	1b	Invasive
	Solanum seaforthianum Andrews	Woody	1b	Invasive
	Solanum sisymbriifolium Lam.	Herb	1b	Invasive
Tropaeolaceae	*Tropaeolum majus* L.	Herb	NL	Invasive
	Tropaeolum speciosum Poepp. & Endl.	Herb	3	NA
Verbenaceae	*Lantana camara* L.	Woody	1b	Invasive
	Phyla nodiflora (L.) Greene	Herb	NL	-
	Verbena aristigera S.Moore	Herb	NL	-
	Verbena bonariensis L.	Herb	1b	Invasive
Zingiberaceae	*Hedychium coronarium* J.Koenig.	Herb	1b	Invasive
	Hedychium flavescens Carey ex Roscoe.	Herb	1b	Invasive

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