Chapter 19
Invasive Alien Species in the *Campos Sulinos*: Current Status and Future Trends

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19.1 General Background of Biological Invasions

In previous centuries, species introductions into new regions were widely celebrated by societies, as they were "enriching" the flora and fauna mainly to improve domestic stock and supply additional food (Simberloff and Rejmánek 2011). Through this process, humans connected regions that were naturally separated by *geographical barriers* and began to alter the limits of species distributions. As contemporary

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anthropic actions have escalated, the extent and frequency of species transfer around the world have been increasing, expanding the distributional range of organisms at accelerated rates (Mack et al. 2000; Seebens et al. 2017). As a result, we often observe species outside of their *native range* coexisting with local biodiversity. However, some species introductions were also unintentional, and many concerns related to changes in natural species distributions came out in the last century. Researchers have tried to gain an insight into processes and consequences of biological invasions across environments by assessing: (i) which species invade; (ii) which habitats are invaded; (iii) what are the impacts of invasions, and (iv) how we can manage them. In this chapter, we aim to answer these questions by focusing on the *Campos Sulinos* region. We (1) briefly provide background on the topic of biological invasions, by introducing the main concepts, the idea of invasion stages, and the classical hypothesis involved; (2) show invasion patterns, highlighting the invaded areas and the most important invasive alien species (IAS) in the *Campos Sulinos*; (3) present the main drivers and impacts of invasion, and (4) introduce the challenging management strategies. Finally, (5) we come up with a brief reflection about the future of the invasions in the ongoing global change scenario and some recommendations to keep moving forward in IAS management.

The invasion process begins with the *transport* of a species from its historical biogeographic distribution (i.e., *native range*) to a new ecosystem, carried on a human-assisted *vector* along a *route* (i.e., *invasion pathway*). This transport could be intentional, when there is a specific intentional purpose (e.g., cultivated plants or domestic animals), or unintentional, as the by-product of the movement of other goods (e.g., contaminated crops seeds or ballast water). The organisms, which survived the transport, are *introduced* to a region beyond their native range (i.e., *alien species*), can *establish* in the wild by forming viable self-standing populations (i.e., *naturalized species*), and may *spread* substantially from their point of introduction, becoming *invasive alien species* (Fig. 19.1; Box 19.1; Richardson et al. 2000; Richardson and Pyšek 2006; Blackburn et al. 2011).

The invasion process can be divided into sequential stages (i.e., transport, introduction, establishment, and spread) which differ in the nature of the barriers imposed (i.e., geography, captivity or cultivation, survival, reproduction, and dispersal), and therefore the mechanisms required to overcome them (Fig. 19.1; Richardson and Pyšek 2006; Blackburn et al. 2011). According to the *Tens rule hypothesis* (see Box 19.2), approximately 10% of the introduced species successfully take consecutive steps of the invasion process (Williamson and Brown 1986; Williamson and Fitter 1996). Thus, not all alien species will survive and reproduce in a new ecosystem, and not all naturalized species are capable of dispersing large areas and becoming invasive. Which alien species are potential invaders and which ecosystems are more invasible have been the main challenging questions in biological invasion research (Rejmánek 1995).

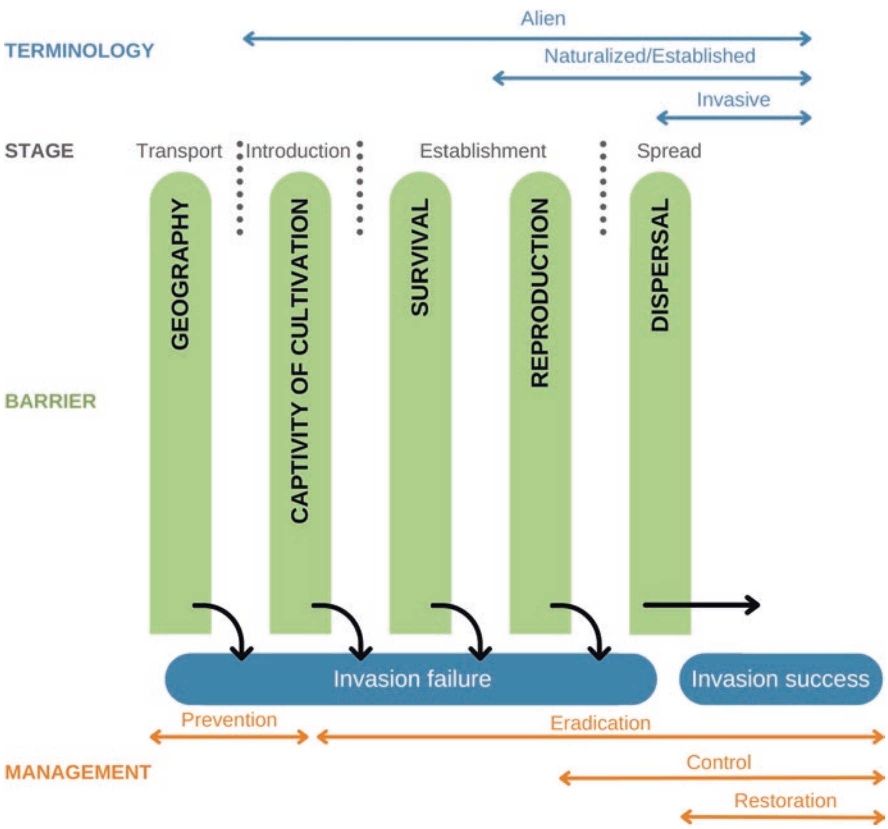

Fig. 19.1 Framework of biological invasions, with indication of barriers and management actions according to the stage of the invasion process and definition of terms used for alien species. (Modified from Richardson et al. 2000 and Blackburn et al. 2011)

According to the National Invasive Alien Species Database (http://bd.institutohorus.org.br) for Brazil, created and managed by the Horus Institute for Environmental Conservation and Development, there are 481 invasive alien species (IAS) in Brazil, of which 267 (55.5%) are animals, 209 (43.5%) are plants, and five species belong to other Kingdoms. Studies that have analyzed this database found the south and the southeastern of Brazil are most invaded regions (Dechoum et al. 2021). Particularly in the *Campos Sulinos*, the attention regarding alien species occurrence has been increasing in the last years. For instance, the three southern states (Rio Grande do Sul, Santa Catarina, and Paraná) have taken a great step with the publication of official lists of IAS. The first state to publish such a list was Paraná in 2007, which has been updated twice, and in 2015 included 71 species of plants and 140 of animals (Portaria IAP 59/2015). The official list of Santa Catarina

Box 19.1:
Glossary with key concepts used in research on biological invasion, or ecological concepts adapted for the context of biological invasion

CONCEPT	DEFINITION	REFERENCES
Alien range (syn. non-native, exotic, or introduced range)	The distribution area to which a species was transported due to human actions, and did not naturally occur before	[2]
Alien species (syn. non-native, exotic, introduced species)	Those whose presence in a region is due to human actions that enabled them to overcome biogeographical barriers	[2]
Biological invasions (syn. bioinvasions, biotic invasions, species invasions)	The processes involved in determining: (i) the transport of organisms through human activity to areas outside their native range and (ii) the fate of such organisms in their new ranges (survival, establishment, reproduction, dispersion, spread, impact)	[2]
Biotic resistance	The ability of resident species to limit the establishment, survival and/or spread of alien species	[2]
Control	A management action that aims the suppression of an invasive alien species within a defined geographic area	[3]
Eradication	A management action that aims the extirpation of the entire population of an invasive alien species within a designated management unit	[2;3]
Establishment	Stage of the invasion process whereby an alien species forms self-sustaining populations over multiple generations without (or despite) human intervention	[3]
Impact	The environmental and/or socioeconomic changes that invasive species cause in the recipient ecosystems	[2]
Introduction	Stage of the invasion process regarding the movement of a species, intentionally or unintentionally, due to human activity, from an area where it is native to a region outside that range	[2]
Invasibility	The properties of a community, habitat or ecosystem that determine its inherent vulnerability to invasion	[2]
Invasive species	Alien species that sustain self-replacing populations over several life cycles, produce reproductive offspring, often in large numbers at considerable distances from the parent and/or site of introduction, and have the potential to spread over long distances	[2]
Invasiveness	The features of an alien species (e.g. life-history traits) that define its capacity to invade (i.e. to overcome the barriers of the invasion process)	[2]
Management	Activities undertaken to prevent, eradicate or control invasive alien species	[3]
Native range	The distribution area to which a species occurrence is due to its evolution history and natural dispersal	[1]
Native species (syn. indigenous species)	Species whose presence in a region is due to its evolution history and natural dispersal	[2]
Naturalized species (syn. established)	Alien species that sustain self-replacing populations for several life cycles or a given period of time (10 years is advocated for plants) without (or dispite) the direct intervention of humans	[2]
Pathway	A combination of processes and opportunities that result in the human-mediated movement of alien taxa from one area to another	[2;3]
Propagule pressure (syn. introduction effort)	Composite measure consisting of the number of individuals released in a region, resulting from the number of individuals introduced in an introduction event (i.e. propagule size) and the frequency of introduction events (i.e. propagule number)	[4]
Spread (syn. expansion)	The process whereby a naturalized species expands into new areas (usually new regions, rather than local-scale movements) owing to natural or human-mediated dispersal	[2]
Vector	A broadly defined phenomenon involving dispersal mechanisms that can be both non-human mediated (wind, water, birds, mammals, amphibians, etc.) and human mediated	[2]

[1] Blackburn et al. (2011) A proposed unified framework for biological invasions. Trends in ecology & evolution, 26(7), 333-339. [2] Richardson et al. (2011) A compendium of essential concepts and terminology in invasion ecology. Fifty years of invasion ecology: the legacy of Charles Elton, 1, 409-420. [3] Simberloff & Rejmánek (2011) Encyclopedia of Biological Invasions, 1st ed. University of California Press [4] Lockwood et al. (2005) The role of propagule pressure in explaining species invasions. Trends in ecology & evolution, 20(5), 223-228.

Box 19.2:
Principal hypotheses used to explain biological invasions

HYPOTHESIS	DESCRIPTION	KEY REFERENCES
Biotic resistance (syn. diversity-invasibility hypothesis)	An ecosystem with high biodiversity is more resistant against alien species than an ecosystem with lower biodiversity	Elton (1958); Levine & D'Antonio (1999)
Darwin´s naturalization	Alien species that are phylogenetically distantly related to resident species are more likely to be successful than those closely related	Daehler (2001); Darwin (1859)
Disturbance	The invasion success increases in higher disturbed ecosystems	Elton (1958); Hobbs & Huenneke (1992)
Enemy release	The absence of natural enemies (e.g. competitors and predators) in the alien range increase invasion success	Keane & Crawley (2002)
Evolution of increased competitive ability	After having been released from natural enemies, alien species will allocate more energy in growth and/or reproduction, which makes them more competitive	Blossey & Nötzgold (1995)
Fluctuating resource	Pulses of resources, due to an increase in supply or to a decrease in use, enhance the invasibility of communities	Davis et al. (2000)
Limiting similarity	Successful invaders are functionally distinct from species in the recipient community	MacArthur & Levins (1967)
Novel weapons	Alien species have competitive advantage against native species because they possess traits (e.g. biochemical compounds) that are new to the recipient community	Callaway & Ridenour (2004)
Propagule pressure	A high propagule pressure of alien species (i.e. high supply and frequency of introductions) increase invasion success	Lockwood, Cassey & Blackburn (2005)
Tens rule	Approximately 10% of species successfully take consecutive steps of the invasion process	Williamson & Brown (1986)

was published in 2010, revised in 2012, and has cataloged 99 IAS (Resolução CONSEMA 08/2012). Rio Grande do Sul published the official list in 2013 and included 79 species (Portaria SEMA 079/2013). However, there is a lack of studies integrating the information for the *Campos Sulinos* as a whole region and sharing the progress, challenges, and difficulties of IAS management across the three states. The dramatic loss of natural grasslands in the region (Baeza et al. 2022), and the current threats to the remaining areas due to biological invasions, make it essential to continue moving forward for improving management actions.

The success of invasion results from the combination of three main components: (i) the introduction effort (i.e., *propagule pressure*), (ii) the capacity of a species to invade (i.e., *invasiveness*), (iii) and the susceptibility of the recipient community to be invaded (i.e., *invasibility*; Richardson and Pyšek 2006). Although it is difficult to generalize, there are some characteristics that have been associated with invasiveness across different taxa, such as high genotypic and phenotypic plasticity, rapid growth, high and early fecundity, and fertility (Baker 1965; Rejmánek and Richardson 1996). For instance, the invasiveness of *Eragrostis plana*, one of the most abundant invasive alien grasses in Rio Grande do Sul (Guido et al. 2016), has been associated with the high production of seeds that germinate faster than natives

(Guido et al. 2017), a great competitive ability (Guido et al. 2019), resistance to adverse conditions (Guido et al. 2016), and livestock avoidance (Bremm et al. 2016). However, which traits favor invasion depend on the difficulties the species must overcome in the alien range, and therefore, the study of community invasibility is also necessary for understanding the process.

Several hypotheses have been proposed to explain the complex relationship between the invaders and the *recipient community* to explain the *level* and *patterns of invasion* across regions (see Catford et al. 2009; Enders et al. 2020). The hypotheses form the theoretical–conceptual understanding of biological invasions by highlighting the relative importance of certain factors that influence propagule pressure, invasiveness, and/or community invasibility (Catford et al. 2009). As many hypotheses share some similarities, some of them have been more relevant than others (Enders et al. 2020). In Box 19.2, we present a set of these hypotheses, linking some of them to the key factors of invasion developed below.

19.2 Distribution of Invasive Alien Plants and Animals in the *Campos Sulinos*

19.2.1 Data Collection

We used the National Invasive Alien Species Database (bd.institutohorus.org.br) to show general patterns about IAS in the *Campos Sulinos* region. The database includes species that are present in Brazil, with at least one occurrence record, and species that are currently naturalized in Brazil but invasive elsewhere. For this study, we only considered plants and animals with occurrence records within the limits of the *Campos Sulinos* region, and deliberately excluded marine organisms. For each species, we collected data about: (i) inclusion in the IAS official list of the states, (ii) origin (Africa, Asia, Australasia, Central America, Europe, North America, South America, or unknown); and (iii) the main reported human uses (plants: agriculture, forestry, forage, horticulture, none, others; animals: apiculture, aquaculture, hunting, food, pet, none, others).

The occurrence records for each IAS were obtained from two major databases: the national database of the Horus Institute for Environmental Conservation and Development, and the international platform of the Global Biodiversity Information Facility – GBIF (https://doi.org/10.15468/dd.9xa2x7). Additional occurrence records were requested for two environmental agencies: the State Secretariat for the Environment of Rio Grande do Sul (SEMA-RS) and the Biodiversity Authorization and Information System (SISBio/ICMBio; Supp. Table S19.1). We only considered occurrence records with geographic coordinates or municipalities inside the *Campos Sulinos*. The records for each IAS were rasterized into cells of 5 arc minutes resolution (ca. 8.3 × 8.3 km), resulting in 3175 total cells for the whole region. We obtained the total IAS occurrence records and the percentage of invaded cells for the region (number of cells that present at least one IAS/total number of grid cells). For each IAS, we calculated the percentage of records the species represented (number of records of the IAS/total number of records) and the percentage of cells the species was registered (number of cells the IAS occurred/total number of cells in the *Campos Sulinos*). We also obtained the total number of IAS per grid cell (i.e., IAS richness) to develop maps of IAS richness for evaluating invasion distribution patterns. Data processing and maps were performed in R environment (R Core Team, 2020) using the packages "rgbif" (Chamberlain et al. 2021) for acquisition of GBIF occurrences, "rgdal" (Bivand et al. 2021), "rgeos" (Bivand and Rundel 2020) and "raster" (Hijmans 2021) for geospatial analysis and "maps" (Becker and Wilks 2018) for mapping.

19.2.2 Results and Interpretation

We found that 70% of the grid cells inside the *Campos Sulinos* were invaded by at least one IAS, representing 9465 records across the region. A total of 184 IAS were registered (Suppl. Table S19.2), of which 46 were animals (41% of the records) and 138 were plants (59% of the records). Some of these IAS are shown in Fig. 19.2. Rio Grande do Sul was the state with the largest number of IAS (175 species, 72 of them exclusive), followed by Paraná with 95 species, and Santa Catarina with 70 species (Fig. 19.3). In general, most species had low occurrences (<1% of records), and only a few of them had higher values (Suppl. Table S19.2).

The highest occurrence records for plants were for *Eriobotrya japonica, Tradescantia fluminensis, Cirsium vulgare, Syngonium podophyllum, Christella dentata, Tradescantia zebrina, Impatiens walleriana, Eragrostis plana, Melinis repens*, and *Lonicera japonica* (Fig. 19.4a; Suppl. Table S19.2). The records of these plants were mainly from Rio Grande do Sul (>70% of the cells; Suppl. Table S19.2). The most represented families of plants were Poaceae (27 species) and Fabaceae (22 species). Regarding animals, those with the highest number of records were *Passer domesticus, Bubulcus ibis, Canis lupus, Sus scrofa, Lepus europaeus, Columba livia, Felis catus, Apis mellifera, Aedes albopictus*, and *Axis axis* (Fig. 19.4b; Suppl. Table S19.2). The records of these species were also concentrated in Rio Grande do Sul (>70% of the cells were in this state). Terrestrial vertebrates represented the higher proportion of invasive alien animals (44%), followed by invertebrates (30%) and aquatic vertebrates (26%). The most represented families of animals were Cyprinidae and Muridae, both with three species each.

We note that some species with high number of occurrences are not included in the official lists of the IAS of the *Campos Sulinos* region. For example, the plants *Cenchrus echinatus, Cyperus rotundus, Syngonium podophyllum*, and *Tradescantia fluminensis*, which had records in Rio Grande do Sul, Santa Catarina and Paraná (Suppl. Table S19.2), are not mentioned in any of the official lists. Although this divergence can be explained by the frequency the information is updated, since the

Fig. 19.2 Some invasive alien plants and animals with occurrences in the *Campos Sulinos* region (see also Suppl. Table S19.2)

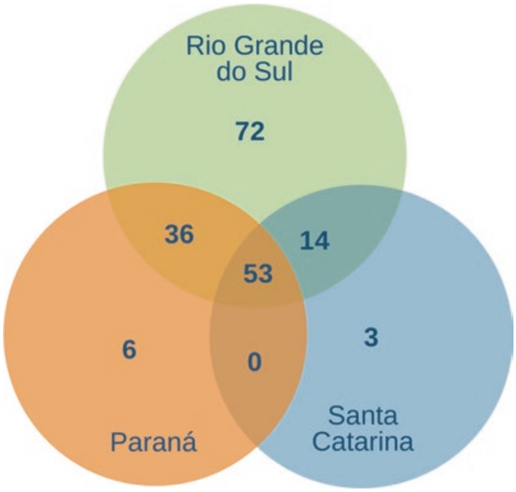

Fig. 19.3 Venn diagram with the number of invasive alien species (animals and plants) exclusive and shared in each state of the *Campos Sulinos* region (Rio Grande do Sul, Santa Catarina and Paraná). For the species list, see Suppl. Table S19.2

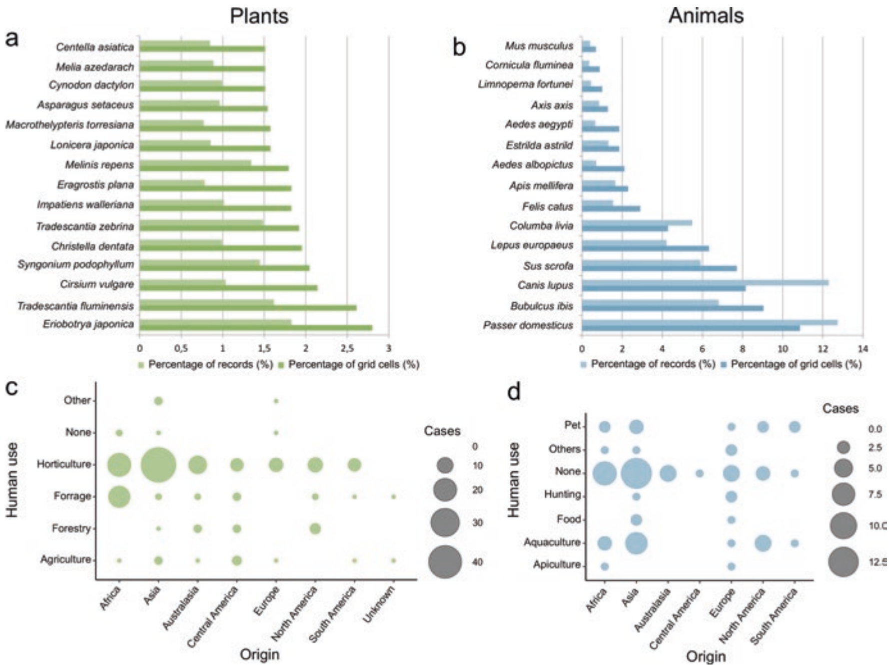

Fig. 19.4 Invasive alien species with the highest values of records (i.e., percentage of records) and occupied area (i.e., percentage of grid cells), separated for plants (**a**) and animals (**b**) in the *Campos Sulinos*. The species with the highest values are shown. Plants (**c**) and animals (**d**) were classified according to their human use and origin (number of cases). Note that one species can have more than one origin and/or use

national database is more constantly revised than the official lists, these species should be monitored to evaluate their further inclusion. The species *Aedes albopictus, Acacia podalyriifolia, Rattus norvegicus, Canis lupus*, and *Felis catus* are already included in the official list of Santa Catarina and Paraná states, but are not considered invasive in Rio Grande do Sul, despite occurrences in this state. We recommend evaluating the inclusion of the bird *Sturnus vulgaris* in the Rio Grande do Sul official list, as it is considered invasive in border countries (Uruguay and Argentina). We call attention to the records of *Bubalus bubalis, Apis mellifera*, *Eragrostis plana*, and *Senecio madagascariensis* in Santa Catarina, as these species are already invasive in Rio Grande do Sul and Paraná, but are not included in the Santa Catarina official list.

Most of the IAS with records in *Campos Sulinos* are from Asia and Africa, and there is an association between this origin and the type of human use. Many of the invasive alien plants are used for horticulture, introduced in Brazil for human consumption and/or ornamental purposes for gardening (Fig. 19.4c). Some examples are *Rubus* spp., *Lonicera japonica, Hovenia dulcis*, and *Ligustrum lucidum* (Suppl. Table S19.2). These results are in line with other studies which have also shown similar patterns and awareness about alien flora in Brazil (Zenni 2014), and in particular in the *Campos Sulinos* region (Fonseca et al. 2013; Rolim et al. 2014). The ornamental horticultural trade has been recognized as the main pathway for plant invasions worldwide since many species can escape from cultivation and have the potential to release in nature (Dehnen-Schmutz et al. 2007). The demand for ornamental plants is driven by consumers in search for attributes (e.g., fast growth) which are often related to invasiveness (van Kleunen et al. 2018). The horticultural industry generally ignores native flora and seeks to meet the demand by importing or breeding alien plants. This highlights the importance of valuing the beauty of native flora and encouraging its use (Rolim et al. 2021), preventing introductions that are not essential for human well-being. Moreover, an important group of invasive alien plants were introduced from Africa to forage production for cattle, such as *Melinis repens* and *Urochloa decumbens* (Fig. 19.4c; Suppl Table S19.2), although many native species are known for their high forage value (Nabinger and Dall'Agnol 2020).

Most animal introductions were probably unintentional transports, since a large number of species were not identified with any human use (Fig. 19.4d). However, by separating into terrestrial vertebrates, aquatic vertebrates, and invertebrates, we found some introduction patterns. Terrestrial vertebrates, such as *Amazona aestiva, Callithrix penicillata, Canis lupus,* and *Felis catus,* were mostly intentionally introduced as pets. Regarding invertebrates, only *Apis mellifera* was identified with human use (apiculture), whereas all the other species were classified as none use, suggesting unintentional introduction pathways. Aquatic vertebrates were mostly associated with aquaculture trade for human consumption, such *Cyprinus carpio, Oreochromis niloticus*, and *Micropterus salmoides* (Suppl. Table S19.2). Thus, in summary, most of the terrestrial and aquatic vertebrates were deliberately transported for different human uses, whereas invertebrates were mainly unintentionally introduced.

Regarding the spatial distribution, although for many cells there were no records (923 cells; gray area of the maps), a high number of IAS can be observed across some regions (Fig. 19.5). Most of the cells had few IAS (1–3 species), but areas closer to major cities, such as Rio Grande, Pelotas, Porto Alegre, and Curitiba, were

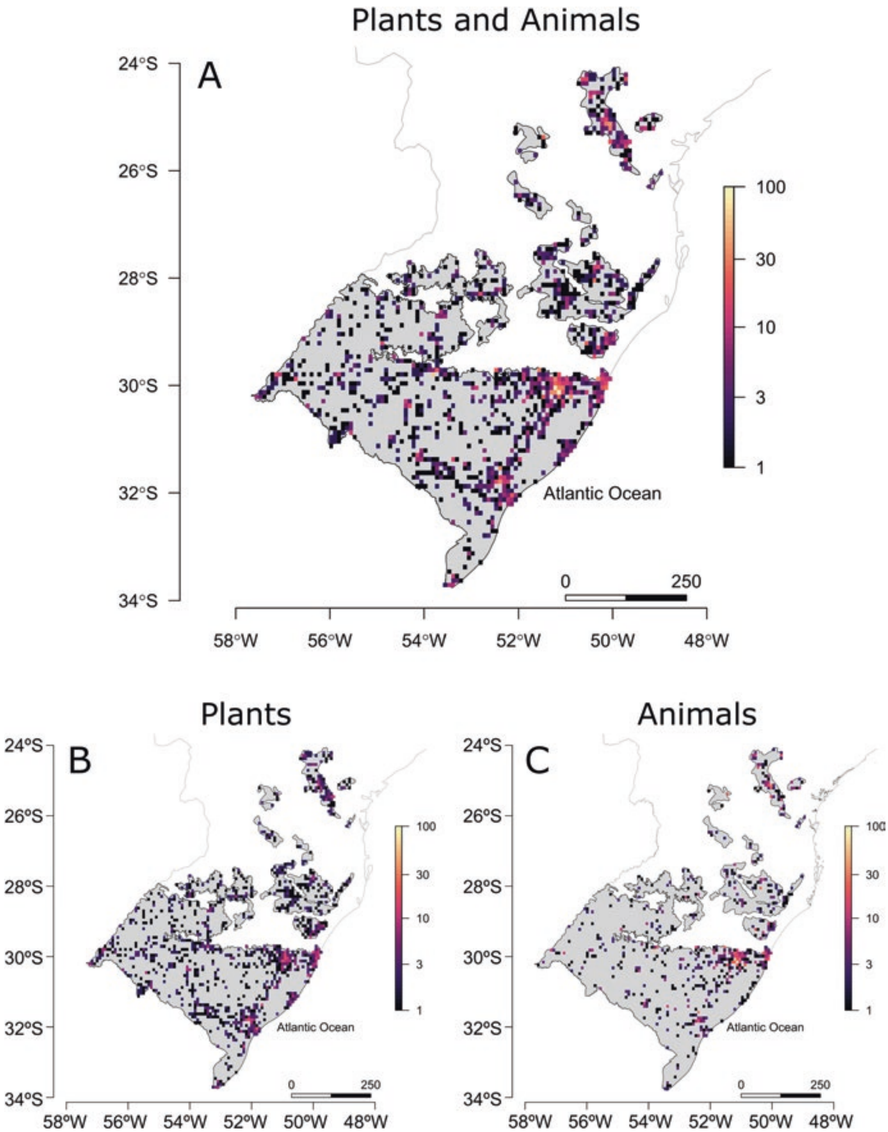

Fig. 19.5 Number of invasive alien plants and animals (**a**), only plants (**b**), and only animals (**c**) per grid cell (1–100 species per cell of 8.3 × 8.3 km) in *Campos Sulinos*. Gray area indicates that there is no occurrence record

richer (>10 species; Fig. 19.5). This highlights the human influence on the invasion process, not only by transporting organisms to the places where we live, but also by promoting suitable conditions for invasion to be successful (see key factors of invasion below). The case of animals reveals how important actions are for preventing non-desirable introductions, and for adequately evaluating the cost–benefit outcomes of intentional transports. Moreover, the importance of residence time in biological invasions has been shown in several other cases (Pyšek and Jarosik 2005), as the longer a species has been present, the more likely it is to establish. However, for most of the IAS in the *Campos Sulinos*, there is no information about the introduction date, thus we cannot disentangle all the causes of the observed pattern.

Understanding the geographical distribution of IAS is important to know which are the most frequent species and where are the most invaded areas. This knowledge can help to identify source regions, as well as vectors and routes that may help to guide management plans. Furthermore, it could be useful to prioritize resource allocation for selective prevention, early detection, and rapid response strategies. Nevertheless, the results presented here should be taken with caution, since the data may include biases as species record effort is not equal across the region (e.g., Hughes et al. 2021). For instance, the invasion level of some areas may be underestimated, since the absence of IAS could either mean lack of information (e.g., inaccessible grid cells where there is no data of the level of invasion) or a non-invaded cell (where the level of invasion is zero). At the same time, for more accessible areas (closer to cities and roads), there may be more occurrence records which can result in an overestimation. Furthermore, it is possible that part of the occurrence records does not indicate a biological invasion, as the GBIF database does not make such a distinction. For example, many alien plants that are cultivated in urban areas, such as gardens and street margins, and registered in the database have the potential to invade natural systems in the near future. We encourage researchers, stakeholders and managers to include IAS records on databases to continue approaching the reality of this problem.

19.3 Key Factors and Impacts of Invasions

19.3.1 Factors of Invasion

For understanding the distribution patterns of invasions, much research has focused on identifying the major factors that enhance the probability of alien species to be transported, introduced, established, and spread. Besides propagule pressure, the abiotic (e.g., environmental conditions and resource availability) and biotic factors (e.g., species interactions) control different barriers (survival, reproduction, and dispersal) that affect the progression of the invasion stages (Fig. 19.1; Theoharides and

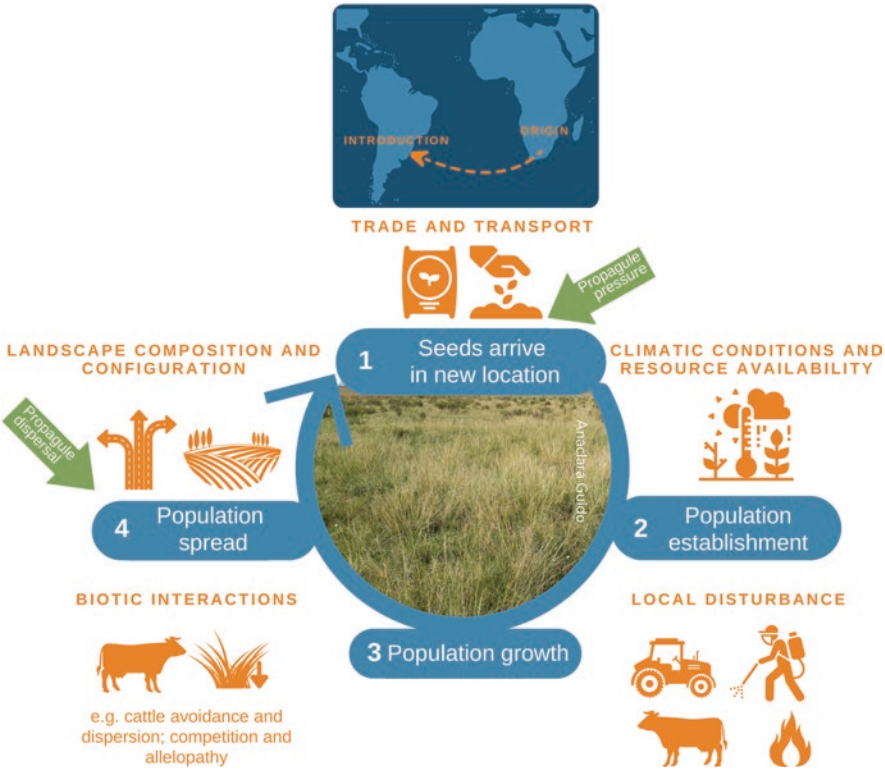

Fig. 19.6 Key factors that promote the invasion of *Eragrostis plana* in *Campos Sulinos* grasslands

Dukes 2007; Catford et al. 2009). The species *Eragrostis plana* is used here as an example to present some factors that promote its invasion in *Campos Sulinos* grasslands (Fig. 19.6).

19.3.1.1 Propagule Pressure

Human activity, such as agriculture, horticulture, and other trades, can shape the early stage of invasion by determining the number of species and/or individuals introduced, as well as and the number of introduction attempts (Lockwood et al. 2005). For instance, the transport of a species into a new region is influenced by socioeconomic and cultural processes that define the manner by which a species is carried (i.e., *transport vector*) and the route between the source and release locations (Lockwood et al. 2007). This pathway could be intentional or unintentional as a result of commodity, vector movements or through natural dispersal (Hulme et al. 2008), which would determine the abundance and rate at which species are introduced to new localities (Lockwood et al. 2005, 2009; see the *Propagule pressure hypothesis* in Box 19.2). For the *Campos Sulinos*, many intentional transports of alien species were shown (Fig. 19.4), but some have unknown causes of introductions, which hinders identifying source regions and vectors. Unintentional introductions can occur in ships' cargo, in seed stocks, or with livestock and travelers from other regions (Mack and Lonsdale 2001). For example, the invasion of the bivalve *Limnoperna fortunei* in South America started with the transport of ballast water from ships trading with Southeast Asia in the Río de la Plata estuary (Darrigan and Pastorino 1995). Therefore, the transit of human-mediated vectors (land, sea, or aerial) has been considered a proxy of propagule pressure and dispersal, as the more abundant and often a vector is transported into an area, the more likely an organism will be carried.

Moreover, human activity at the landscape scale has been considered a proxy of propagule arrival, as it could be the cause of species dispersal by overcoming natural barriers across and/or within regions (With 2002; Theoharides and Dukes 2007). For example, human-built corridors, such as roads, can enhance the propagule pressure in some localities and disperse IAS across regions (Vilà and Ibáñez 2011). In *Campos Sulinos* grasslands, the level of the invasion by *Eragrostis plana*, *Cynodon dactylon*, *Senecio madagascariensis*, and *Ulex europaeus* (see Fig. 19.1) was positively related to the density of roads and urban areas, which probably promote their dispersal across Rio Grande do Sul (Cordero et al. 2016; Guido et al. 2016).

19.3.1.2 Environmental Conditions and Resource Availability

Invasive alien species' survival, growth, and reproduction depend on suitable environmental conditions (e.g., precipitation and temperature ranges) and resource availability (e.g., nutrient level). At a regional scale, climate sets the broad limits of species distribution, and if environmental conditions are not suitable, the invasion fails immediately during the introduction stage (Fig. 19.1). Ecological niche models using bioclimatic variables are often used to predict the potential distribution of IAS worldwide (e.g., Guisan et al. 2014; Liu et al. 2020). For instance, climate matching, combined with intentional captivity or cultivation of alien species, greatly increases the likelihood to escape and establish in the wild. This was the case of *Lithobates catesbeianus* (bullfrog), which was intentionally introduced in southern Brazil in 1935 for aquaculture (Both et al. 2011). Nowadays, its populations are widely spread across Brazil, as individuals escaped captivity and were released by farmers due to the low economic gains, finding suitable climate conditions for survival and reproduction (Nori et al. 2011). However, similar climate conditions could result in different levels of invasion due to other interacting abiotic factors that operate at finer scales (González-Moreno et al. 2014). For example, resource availability (e.g., water, light, and nutrients) is a key factor for species establishment, and thus can impose a constraint barrier for survival. According to the *Fluctuating resource hypothesis* (see Box 19.2), temporal heterogeneity in resource availability opens a window of opportunity for species invasion (Davis et al. 2000). Thus, human activities that cause resource enrichment or release increase community invasibility. For instance, nutrient addition (e.g., nitrogen and phosphorus fertilization) and changes in disturbance regime, such as grazing, fire, and mechanical soil disturbance (e.g., plowing), are important factors that enhance invasion success of plants in the *Campos Sulinos* by modifying the availability of limiting resources (see, e.g., in Fig. 19.6). A long-term experiment in Uruguay showed that adding alien legumes and phosphorus to natural grasslands, a common practice to enhance forage for cattle in the region, increased dominance of the invasive grass *Cynodon dactylon* in an irreversible way (Pañella et al. 2022). Moreover, disturbances that operate at different spatial scales, from landscape context (e.g., habitat fragmentation) to local regimes (e.g., forage management), are key factors shaping the level of invasion across ecosystems (see *Disturbance Hypothesis* in Box 19.2). For example, the abundance of *Eragrostis plana* was positively related with the loss of grassland cover in the landscape (Guido et al. 2016) and overgrazing regime at the local paddock (Baggio et al. 2018; Fig. 19.6).

19.3.1.3 Biotic Interactions

During the stages of the invasion process, alien species are also influenced by biotic interactions among the species from the recipient community, which can facilitate or impede their success (Elton 1958; Mitchell et al. 2006; Traveset and Richardson 2020). Negative interactions in the native range, such as predation and competition, can be less intense in the alien range (see *Enemy release hypothesis* in Box 19.2), and in exchange, IAS encounter new organisms they did not have previous interactions with. Resident species can limit the invasion by affecting their survival, growth, and reproduction, which constitute the main mechanisms of biotic resistance to invasion (Elton 1958; Levine et al. 2004). The classical biotic resistance hypothesis states a negative relationship between the diversity of the recipient community and invasibility, suggesting that more diverse communities are less susceptible to invasion, mainly due to the efficiency in the use of limiting resources (see *Biotic resistance hypothesis* in Box 19.2; Elton 1958). Moreover, functional species composition is also important, as resident species that share similar traits with the invader are likely to compete strongly by niche overlap assumptions (see *Limiting similarity hypothesis* in Box 19.2; MacArthur and Levins 1967).

On the one hand, positive interactions with native species can make the recipient community more susceptible to invasion (Traveset and Richardson 2014, 2020; Aslan et al. 2015). For instance, the establishment of plants can be facilitated through mutualistic interactions with belowground microorganisms which may enhance IAS survival and persistence (Nuñez and Dickie 2014; Menzel et al. 2017). Moreover, pollination and seed dispersal between IAS and resident species is essential for plants overcoming barriers to successfully invade. The reproduction barrier can be overcome by enhancing diaspores production, and dispersion can be succeeded by assisting propagules to colonize distant areas (Traveset and Richardson 2011, 2014; Aslan et al. 2015). The consideration of biotic interactions in invasion biology has facilitated a better understanding of the mechanisms that allow (or not) IAS to integrate recipient communities. For example, across the *Campos Sulinos* region, birds and cattle have been associated with *Ligustrum lucidum* and *Eragrostis plana* dispersal, respectively, through the consumption of their reproductive structures (Marciniak 2015; Minervini and Overbeck 2021).

As biological invasions are context-dependent in space and time, and alien species might only become invasive when certain propagule pressure, biotic, and abiotic factors are met, it is important to consider these driven factors as interactive, and not dissociated, conditions (Heger and Trepl 2003). For example, climatic events (e.g., droughts) and human-mediated disturbance (e.g., overgrazing) can cause fluctuations in resource availability through abiotic (e.g., space and light availability) and biotic process (e.g., changes in community composition and diversity), altering different constraints that may (or may not) lead to a successful invasion.

19.3.2 Major Impacts of Invasion

Invasive alien species are among the five most significant global drivers of biodiversity loss (IPBES 2019), affecting the conservation of natural resources and human well-being (Blackburn et al. 2014). The *Campos Sulinos* region is not an exception. Invasion impact can be evaluated by adopting three dimensions: range, abundance, and the per-capita or per-biomass effect of the invader (Parker et al. 1999). However, the impact can vary in relation to the attributes of recipient ecosystems and the invading species, and the outcomes are highly dependent on human level perception, thus objective assessments have been challenging. An attempt to assess the impact through standardized approaches, the Environmental Impact Classification for Alien Taxa (EICAT; Blackburn et al. 2014; Kumschick et al. 2020) and the Socio-Economic Impact Classification for Alien Taxa (SEICAT; Bacher et al. 2018), has emerged by separating the environmental and socioeconomic impacts. These protocols are receiving international support and have been recently used by the IUCN Red List of Threatened Species (IUCN 2020a, b). In this section, we focus on describing negative impacts of invasion, dividing them into two major groups, (i) environmental impacts, which consist of a significant change in an ecological pattern or process (ii), and socio-economic impacts, which are directly affecting human well-being. The invasive alien species *Eragrostis plana* is used as an example to explain the different impacts in the *Campos Sulinos* (Fig. 19.7).

19.3.2.1 Environmental Impacts of Invasion

Environmental impacts could be assessed at different levels of biological organization (i.e., individual, population, community, and ecosystem) which involves many processes behind. At an individual level, IAS can alter the growth of resident

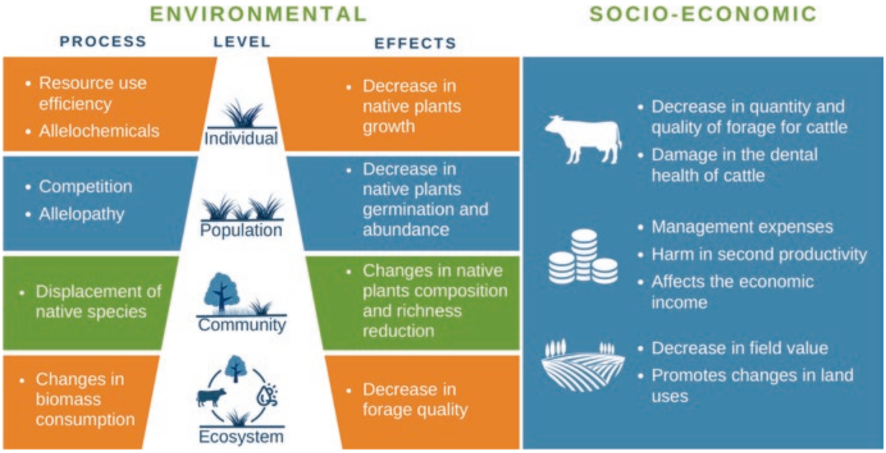

Fig. 19.7 Environmental and socio-economic impacts of *Eragrostis plana* invasion. Environmental impacts are distributed according to ecological levels. (Source: synthesis of results from Guido and Pillar (2017), Guido et al. (2017, 2019, 2021) and Dresseno et al. (2018))

organisms, which are frequently easy to measure and to extrapolate to higher level impacts. For instance, a pair-wise experiment in the *Campos Sulinos* showed that *Eragrostis plana* has negative effects on the growth of neighboring native plants by reducing their height, and the production of tillers, leaves, and biomass (Guido et al. 2019; Fig. 19.7). These impacts can often be translated into declines in rates of reproduction and survival, which affect population dynamics. For example, a decrease in native plant abundances with increasing cover of *Eragrostis plana* has been shown (Guido and Pillar 2017; Dresseno et al. 2018; Fig. 19.7). There are many ecological mechanisms by which the invader impacts populations, such as competition for resources (Crawley 1990), predation (Medina et al. 2014), chemical or physical inhibition of growth (Grove et al. 2012), or disruptions of mutualistic networks (Traveset and Richardson 2011, 2014). For instance, some invasive alien plants have the potential to release phytotoxins that inhibit the germination and/or growth of native species (Callaway and Ridenour 2004; see *Novel weapons hypothesis* in Box 19.2). This mechanism has been studied for *Eragrostis plana* and *Cynodon dactylon* in the *Campos Sulinos*, as these species showed allelopathic potential that could lead to suppression of neighboring native plants (Favaretto et al. 2015; Guido et al. 2020). However, this isolated process might not be enough for explaining their high invasiveness (Guido et al. 2020), and competition ability is probably the most important mechanism beyond their invasion success (see *Evolution of increased competitive ability hypothesis* in Box 19.2; Guido et al. 2019). Another example is the invasive alien frog *Lithobates catesbeianus*. Its calls impact native amphibians by changing their acoustic signals, decreasing the probability of mate selection and thus reproductive success (Medeiros et al. 2017). This species also impacts native amphibians through predation and disease transmission by the spread of the fungal *Batrachochytrium* spp. (Oda et al. 2019; Ruggeri et al. 2019).

Invasion alters the structure of recipient communities, as they often promote changes in species composition, richness, diversity and/or dominance of resident species (Crystal-Ornelas and Lockwood 2020). For example, the invasive alien fishes *Oncorhynchus mykiss* and *Micropterus salmoides* impact native ichthyofauna by reducing the richness, abundance, and/or biomass in rivers of Rio Grande do Sul state (Sosinski 2004). In southern Brazilian grasslands, the invasion of *Eragrostis plana* reduces the number of species in plant communities, as it has been observed that 30% of *E. plana* cover displaces in average 10 native plants (Guido and Pillar 2017). As a consequence, much of these changes have been associated with biotic homogenization of recipient communities (taxonomic, functional, and/or phylogenetic), as the expansion of alien species can replace native biota, diminishing floral, and faunal distinctions among regions (Olden 2006).

Recipient community changes generally have consequences on the cycles of matter and on the energy flow of systems, and thus biological invasion has major impacts on ecosystems functioning (Simberloff 2011; Vilà and Hulme 2017). Invasion can alter trophic networks, ecosystem productivity, nutrient cycling, hydrology, habitat structure, and various components of disturbance regimes (e.g., Ehrenfeld 2010; Damasceno et al. 2018; Damasceno and Fidelis 2023). For example, *Eragrostis plana* invasion alters biomass consumption by livestock on grasslands due to its high values of leaf toughness (Guido et al. 2021; Fig. 19.7). Grazers avoid its consumption by overgrazing native species, which, in turn causes a positive feedback of invasion (Bremm et al. 2016; Guido et al. 2021). Thus, invasion can also alter local disturbance regimes (Mack and D'Antonio 1998), affecting resident species regeneration and enhancing invasibility, which might cause positive feedback of the invasion process (Damasceno and Fidelis 2020; Guido et al. 2021). For example, some invasive alien plants are more flammable than natives, and thus can enhance flame height and temperature, mostly due to changes in fuel properties (e.g., more percentage of dead biomass and lower fuel moisture), leading to more severe fires (Gorgone-Barbosa et al. 2015). As a consequence, native vegetation may be negatively affected, and invasion probability increases. Some IAS in the *Campos Sulinos*, such as *Ulex europaeus, Melinis minutiflora, Pinus* spp., and *Urochloa decumbens* are usually pyrophytic and highly flammable (Gorgone-Barbosa et al. 2015; Pausas et al. 2012; Cornwell et al. 2015), changing local fire behavior.

19.3.2.2 Socio-Economic Impacts of Invasion

Invasive alien species can impact many ecosystem services and thus affect the activities related to human well-being, such as (i) agriculture, horticulture, livestock, and forestry production; (ii) health; (iii) tourism and leisure; (iv) and infrastructure and buildings (Nentwig et al. 2016; Vilà et al. 2019). Adelino et al. (2021) recently estimated the economic costs of biological invasions and showed that *Aedes* spp., *Limnoperna fortunei* and *Eragrostis plana* were the costliest IAS in Brazil by affecting different market sectors. For example, agriculture was the most impacted activity with an economic cost estimated at USD 39.61 billion, followed by health with USD 665.85 million, which are both attributed to invasion damage and also management strategies cost (Adelino et al. 2021).

Particularly in the *Campos Sulinos*, the effects of IAS on agriculture and livestock production are remarkable. The invasion of *Eragrostis plana* impacts extensive cattle production, one of the main economic activities in Pampa biome, by reducing forage palatability, damaging cattle dental health, and thus affecting secondary production and economic incomes (Medeiros and Focht 2007; Guido et al. 2021; Fig. 19.7). In addition, the value of invaded grasslands can considerably diminish, and might also promote changes in the use of the land by transforming natural grasslands into agricultural or forestry uses (Ferreira and Filippi 2010; Fig. 19.7). Another example is the invasion of the wild boar *Sus scrofa,* which has caused economic and social conflicts mainly due to damage to the agricultural sector. In southern Brazil, wild boars could damage 5–30 ha/year of corn crops (Salvador 2012), and the impact caused is worst for small farmers (<50 ha), who may lose the entire planting for a year (Batista 2015). Moreover, there is the risk of disease outbreaks, as wild boar could be reservoirs of diseases that impact commercial pig farming (Salvador and Fernandez 2017).

Moreover, the invasion by *Limnoperna fortunei* (Fig. 19.2) is an example of notable impacts on infrastructure and buildings, as its settlement affects water processing plants, power plants (nuclear, hydroelectric, thermal), refineries, steel mills, fish culture facilities, water transfer canals and aqueducts, and watercraft (Boltovskoy and Correa 2015). Furthermore, many IAS are vectors of human diseases and thus pose a serious threat to public health. This is the case of *Aedes* spp., which in Brazil is responsible for the spread of at least three different arboviruses (i.e., Dengue, Zika, and Chikungunya) that threaten human health (Marcondes and Ximenes 2015), costing millions of reais (BRL) with insecticides, larvicides, and medical care (Teich et al. 2017).

19.4 Prevention and Control: Options and Challenges for Management

Brazil recognizes that biological invasion is a problem that needs to be addressed with required management actions (Zenni et al. 2016). Some initiatives have been implemented to try to decrease the impacts, to prevent new introductions and to eradicate and control already established IAS populations. Prevention, early detection, and rapid response to IAS in Brazil are foreseen in the National Strategy for Invasive Alien Species (Resolução CONABIO n° 7 – 2018). Several national action plans have been implemented by the *Instituto Chico Mendes de Conservação da Biodiversidade* since 2012, covering different groups of species and ecosystems (ICMBio 2019). Complementarily, there has been an effort of other organizations, such as Horus Institute for Environmental Conservation and Development, The

Nature Conservancy (TNC), Inter-American Biodiversity Information Network (IABIN), as well as from the Global Invasive Species Program (GISP), to provide information about IAS in Brazil (Zenni et al. 2016).

At the state level, Rio Grande do Sul, Santa Catarina, and Paraná have programs where strategies for IAS management have been proposed. Besides the publication of the official species lists, there are complementary regulations to establish limits of use of IAS. For that, each listed species is categorized into two alternative categories: (I) banned species, or (II) permitted species with regulations for their uses. The first category included species that are prohibited from being transported, raised, released, or translocated, cultivated, propagated by any means of reproduction, trade, donation, or intentional acquisition in any way. An example of this category in the *Campos Sulinos* is *Limnoperna fortunei*, banned across the three states, and for which exists a Federal management program. The second category refers to species that are mostly associated with production systems, and thus can be used under controlled conditions, with restrictions that are subject to specific regulations from each state. An example within this category is *Apis mellifera*, an IAS whose use is restricted for honey production.

Although efforts have been increasing during the last decade, most of the management plans of protected areas in Brazil do not foresee actions concerning IAS with detailed goals, interventions, monitoring plans, budgets, and timelines, indicating the lack of knowledge and training of local managers (Dechoum et al. 2018). Moreover, much of the work has been done independently by several groups, without a complementary action and coordinated agenda within and across the three states, thus the achievement of positive results regarding IAS management has been challenging.

19.4.1 Management Strategies

The management of IAS involves several actions that need to be well defined and prioritized for effective and successful goals (McGeoch et al. 2016; Stone and Andreu 2017). One of the first steps is to assess the stage of the invasion process of the target species (Fig. 19.1), because the more recent the invasion process, the higher the probability to achieve successful results (Ziller et al. 2020). In parallel with the stages and barriers of the invasion, three successive actions form the recommended practices to manage IAS: (1) prevention, (2) eradication and (3) control (Hulme 2006; Blackburn et al. 2011; Fig. 19.1). Which species to manage and where to focus the management effort are the most challenging questions, and thus protocols to guide these decisions must exist (Ziller et al. 2020).

If the target alien species was not introduced yet, but the risk of invasion is identified, management should focus on the *prevention* of introduction in more vulnerable sites (McGeoch et al. 2016; Fig. 19.1). Prevention actions aim to impede the arrival of propagules to a certain location, constituting the most cost-effective intervention. It can be reached by (i) interception of the material; (ii) treating the material that is suspected to be contaminated (e.g., quarantine), and (iii) prohibition of commercialization (Wittenberg and Cock 2001). To be successful, it is crucial to identify the likely vectors and routes involved to establish regulations that limit its introduction. This has been included in the Aichi Biodiversity Target 9 of the Convention on Biological Diversity (CBD), in which the participant countries, including Brazil, must identify and prioritize their pathways of introduction to prevent IAS. In Brazil, the introduction of alien species without official authorization is considered an environmental crime (Federal Law 9.605/1998).

In the *Campos Sulinos*, many invasive alien vertebrates were deliberately introduced and escaped or released into nature (Fig. 19.4). For example, we show that some species were commercialized as pets (e.g., *Canis lupus, Felis catus*, *Estrilda astrid*, and *Trachemys scripta*) and for aquaculture trade (e.g., *Ictalurus punctatus* and *Oreochromis niloticus*). To prevent these cases, risk analysis, considering the risk of establishment, spread, and impact on nature, should be urgently carried out. Only after balancing the risks and the potential advantages, a final decision about proceeding with the importation should be reached (Wittenberg and Cock 2001). Complementarily, the selected species to be imported should have a preventive plan to avoid their release or escape into the wild. In addition, public education is crucial to minimize pet releases by informing the owner of the species characteristics and needs, and also the risk the organism represents to native species.

Moreover, many unintentional introductions in the *Campos Sulinos* concern invertebrates, and thus much effort should be focused on their invasion vectors, which are often associated with international trade and tourism routes. Prevention actions often include a treatment for the suspected introduction vectors (e.g., quarantine, cleaning, thermal shock, and fumigation), based on regulations and laws. For example, to prevent new introductions of aquatic invertebrates (e.g., *Limnoperna fortunei* and *Corbicula fluminea*) by the traffic of ships, the ballast water must be exchanged offshore before arriving at the harbor (IBAMA 2020). In the case of plants, species used for horticulture in the *Campos Sulinos*, and particularly from Africa and Asia, should be more carefully analyzed before introduction, since many of these cases resulted in a biological invasion (e.g., *Tradescantia fluminensis, Lonicera japonica, Melia azedarach*, and *Ulex europaeus*; Fig. 19.4). Besides the importance in carrying out a risk analysis, prevention actions should also focus on sensitizing the population about the value of native vegetation and its potential use. For example, there are many native plants in the *Campos Sulinos* with high potential for forage or ornamental value that are neglected (Rolim et al. 2021) and whose use can prevent further and unnecessary introductions.

Prevention of invasion is not always feasible, since the species is often already introduced, or even established, in the system and *eradication* and *control* actions need to be implemented to limit its spread (Fig. 19.1). Eradication consists in the extirpation of an entire population within a specific area (Pyšek and Richardson 2010; Hulme 2006). However, eradication is not always possible since the connectivity of IAS populations can rapidly increase, hindering early detection and rapid response, and thus successful examples have been challenging worldwide. *Control* aims to reduce the abundance and density of established and/or widespread IAS populations and contain them in an acceptable threshold that minimizes their impact (Wittenberg and Cock 2001; Fig. 19.1). Eradication and control programs have been based on different methods of IAS removal, such as mechanical (e.g., handpicking, pulling, or cutting for plants), chemical (e.g., use of biocides), habitat management (e.g., grazing, mowing, or burning the area), and hunting (Wittenberg and Cock 2001). The selection of one technique, or a combination of them, would depend on the target IAS, the type of system, and the level and time since invasion.

To locally control invasive alien grasses in grasslands, mechanical removal is often used. It can be conducted by manual removal by hand, cutting, or even hoeing of isolated individuals and/or populations. To avoid reestablishment, monitoring and repeated long-term actions are important since species can resprout or germinate from the seed bank (ICMBio 2019). For example, in South Brazil grasslands invaded by *Eragrostis plana*, 4 years of annual removals by different methods (clipping, herbicide, and hand-pulling) were not enough to locally extinguish the species (Guido & Pillar 2017; Guido et al. 2021). Another control strategy is to promote abiotic conditions through management decisions that limit the invasion by affecting the survival, reproduction, or dispersal. For example, when alien C_4 grasses invade areas close to forests under regeneration, shading can control their spread, as many of them are shade-intolerant species (e.g., *Eragrostis plana* and *Cynodon dactylon;* ICMBio 2019). Moreover, management practices like fire can be useful to control species densities, such as of *Melinis minutiflora* and *Ulex europaeus*; although it is not suitable for all invasion foci and could also have non-targets effects (e.g., native species regeneration and reinvasion from the seed bank; Madrigal et al. 2012; Damasceno and Fidelis 2020; Assis et al. 2021). The use of herbicides (e.g., glyphosate) is also a common technique to control invasive alien grasses in the *Campos Sulinos*, such as *Urochloa decumbens* (e.g., Thomas et al. 2018), *Eragrostis plana* (Guido and Pillar 2017), and *Cynodon dactylon*. However, the application of herbicides needs to be carefully evaluated, as its use in protected areas in Brazil is under restriction (ICMBio 2019), and non-target species could be also impacted (Guido and Pillar 2017).

For most species, there is often no single method of control, and the use of combined control techniques may help to reach better results. For example, *Pinus* spp., escaped from cultivation, is one of the most invasive trees in the *Campos Sulinos*. Depending on tree age and time since the invasion, different techniques can be used to manage them. If trees have <4 cm of diameter, fire will exterminate young individuals, which can also be hand-pulled. Adult individuals can be cut at the base of their trunk (e.g., Dechoum et al. 2019), have their bark ringed (at least a ring of 40 cm), or be killed by the combination of the technique of bark ringing and the application of herbicide. When invasion is massive and older in grasslands, a combination of different techniques should be applied, such as cutting of trees and removal of the timber, followed by prescribed fires after 6 months (enough time to dry out all residuals; Durigan et al. 2020). In the case of animals with different development phases, there may be different control methods throughout its life cycle. For example, for *Limnoperna fortunei*, biocides can be used to control larvae, while mechanical methods, such as surface scraping, are applied to adult individuals (IBAMA 2020).

Local management of an IAS should also be complemented by broader actions to contain the spread within and across countries or regions. For that, the identification of the main vectors associated with propagule dispersal is crucial for coordinating actions in neighboring municipalities, states, and countries to integrate and optimize the efforts. Otherwise, a species that is being controlled in one state might reinvade from the border of a neighboring state through water, land, or air traffic. This would require an effective biosecurity approach that builds on knowledge of potential invaders, susceptible systems, and main pathways of spread. Moreover, strategies that promote the conservation of the *Campos Sulinos* at landscape level may reduce the risks of invasions across the region by constraining propagule dispersal of already established IAS (Guido et al. 2016).

Nevertheless, isolated, and short-term practices are often ineffective tools to manage invasions. Long-term planned actions which account for the mitigation of ecological and socioeconomic impacts should be also considered (García-Díaz et al. 2021). For instance, adaptive management can be defined as "learning by doing", involving practices that can be changed according to the results from the management actions (Walters and Holling 1990; Williams and Brown 2016), and not from only one event (Leffler and Sheley 2012). Therefore, monitoring is crucial and should be addressed to (re)evaluate the progress of management planning (Williams and Brown 2016), and thus helping to select the best techniques to be used in each situation (Zalba and Ziller 2007). García-Díaz et al. (2021) suggested six guidelines to help decision makers to plan a long-term management of IAS: (1) map the presence and distribution; (2) investigate the time of residence; (3) evaluate the impacts; (4) identify feasible interventions from an ecological and socioeconomic point of view; (5) detect negative impacts of the interventions; and (6) provide a balance of costs and benefits of interventions and the negative impacts.

19.4.2 Restoration of Invaded Grasslands

Invaded areas have been the focus of ecological restoration programs by assisting the recovery of certain properties that were degraded by invasion (Gaertner et al. 2012). This process involves implementing actions that will set an ecosystem on a trajectory towards a non-invaded reference situation. Most restoration efforts are focused on a succession-based approach for vegetation, where the reestablishment of disturbance and/or physical conditions would be enough for ecosystem recovery (Suding et al. 2004). The recovery of the vegetation structure may cause suitable environmental conditions for the colonization by animals, reestablishing trophic interactions in the ecosystem and thus their main functions (Ruiz-Jaen and Mitchell Aide 2005). However, highly invaded systems often have shifted to a new alternative state by breaching biotic or abiotic thresholds to achieve spontaneous recovery

(Suding and Hobbs 2009; Pañella et al. 2022). Thus, restoring invaded areas has the double challenge of controlling the IAS, which is part of the causes of ecosystem degradation, and also promoting the conditions that make community recovery possible (see Thomas et al. 2023, Chap. 20, this volume).

The isolated control of IAS can be insufficient for achieving long-term restoration goals, since reinvasion (or new invasions) are likely to happen, and invasion may have imposed constraints to achieve native community recovery (D'Antonio and Meyerson 2002). For example, the seedbank of invaded areas can have a high dominance of IAS, and disturbance resulting from control methods can have a positive effect on its germination (Gorgone-Barbosa et al. 2016; Dairel and Fidelis 2020). If there are no active restoration actions after the control of *Melinis minutiflora* in open ecosystems, the area is suitable for *Urochloa* spp. invasion (Damasceno and Fidelis 2020) since this species dominates the seedbank (Dairel and Fidelis 2020). In *Campos Sulinos*, 4 years of continuous removals of *Eragrostis plana* were not enough for degraded grasslands to resemble non-invaded reference grasslands (Guido and Pillar 2017; Guido et al. 2021). In addition, after 50 years of the presence of *Pinus* spp., native species may not be able to regenerate by resprouting from belowground bud banks since these organs suffer a drastic decrease in density (Ferraro et al. 2021). Also, the thick layer of needles does not allow species to reestablish, and even after the removal of the needle layer (by manual removal or fire), bud bank of grasses and forbs may not be enough to guarantee vegetation regeneration (Zanzarini et al. 2019). These results have challenged traditional restoration efforts owing to many different constraints, promoting the search for active strategies for the reassembly of native communities.

Active restoration strategies for revegetation mainly involve native plant reintroduction by sowing, topsoil transfer, seedling transplant, and hay transfer (Vieira and Overbeck 2015). This reintroduction may cover the bare soil and increase biodiversity, which could in turn enhance the biotic resistance to reinvasion (Elton 1958; Schuster et al. 2018). However, studies about active restoration in invaded areas in the *Campos Sulinos* are still scarce (see Thomas et al. 2023, Chap. 20, this volume). One example of positive results is the case of a Brazilian Army reserve in the Pampa region (Rosário do Sul, RS), where a recovery process of the bird community was observed during the initial recovery of a grassland on a site with a history of agriculture (soybean) and further degraded by invasion by *Eragrostis plana* (da Silva and Fontana 2020). However, Thomas et al. (2018) suggest that hay transfer and sowing native grasses had unsatisfactory results to reintroduce species in invaded areas by *Urochloa decumbens*. These examples illustrate that even within the same region, different approaches may be required, depending on the ecosystem affected, the target IAS to manage and the type of degradation that has occurred. Thus, more information is needed to better guide IAS management and active restoration strategies, and particularly in the *Campos Sulinos* region where there are still major gaps of knowledge (Guerra et al. 2020). For instance, it would be helpful to identify which groups of species constrain selected invaders and also promote community reassembly process (Bakker and Wilson 2004; Funk et al. 2008). In addition, since fire and grazing are important factors in the *Campos Sulinos* (Baggio et al. 2021;

Fidelis et al. 2021; Paruelo et al. 2021), restoration plans should also incorporate these natural disturbances as part of the recovery process (Buisson et al. 2019, 2021, 2022; Silveira et al. 2020).

19.5 Invasions under Global Change Scenarios: The Way Forward

The ongoing global scenario, which includes climate and land use changes, is expected to influence biological invasions by affecting propagule pressure, environmental conditions, and biotic interactions. Effects of global change likely will include (1) modification of environmental background conditions, promoting shifts in species distributions, and thus resembling communities; (2) increased probability of extreme climatic events, resulting in greater disturbance and pulses in resource availability; and (3) triggering of human responses to these changes (Bellard et al. 2013; Catford and Jones 2019; Turbelin and Catford 2021). Although there is considerable uncertainty, it is predicted that invasions will increase with rises in temperature and increases in extreme climatic events. IAS are able to shift their niches faster than natives (Wiens et al. 2019), showing a great capacity to adapt to climatic conditions. Moreover, biological invasions are not only a consequence of the ongoing global change but are also one of its interacting main drivers (Sala et al. 2000). Exploring the multifactor effects of global change may improve the predictions and bring more efficient tools to diminish the threats reported to *Campos Sulinos* biodiversity.

In the *Campos Sulinos*, given climate change projections (Marengo et al. 2009), the ongoing land use conversion of natural grasslands (Baeza and Paruelo 2020; Baeza et al. 2022), and the lack of conservation and management efforts (Overbeck et al. 2007), biological invasions would be continuing to increase at alarming rates. For instance, it is one of the South American regions that would increase the number of invasive alien grasses under climate projections (Barbosa 2016). Most of the invasive alien grasses in this region are from tropical areas in Africa, and thus the increment in the minimum temperature may increase the ability of these species to expand their alien ranges.

However, we must understand how complex the process of invasion is and the main mechanisms behind it to manage and predict future invasions. It is important to invest in scientific and technical knowledge to better address the scarcely documented impacts and to project future scenarios. Skills for early detection of invasion processes and rapid response for successful management need to be developed, just as public awareness needs to be improved. The documentation of general patterns of invasion, as provided in this chapter, helps to guide management strategies. For example, as shown in Fig. 19.5, the most invaded areas across the region are associated with higher direct human impact. We call attention to the many areas that have no data, which could be the result of false negatives of invasions, and thus encourage the inclusion of records of IAS in accessible databases. It is important to centralize the information about how, why, where, and by which IAS the *Campos Sulinos* are currently and potentially invaded. Public databases, such as the one used in this chapter, play an important role to collect, centralize, analyze, and update data to move forward.

Finally, studies on biological invasions have been increasing in the last decades in the *Campos Sulinos*. For instance, the region has the advantage of having official lists of IAS for the three states, complemented by some laws and regulations. However, many of the actions have been done independently and in parallel by each state and for several different groups, including scientists, managers, society, and politics (Zenni et al. 2016; Dechoum et al. 2018). A more coordinated and articulated agenda among academia, stakeholders, and people involved across states is needed to integrate, guide, and optimize the efforts and resources for increasing positive results in this challenging scenario. For this, actions should cover the region as a whole to share management responsibilities for the prevention of new introductions, and to eradicate and control the established populations. Biological invasion is caused by human actions; thus we need to raise public awareness, together with government agencies, academia and not-for-profit organizations about the importance of human dimension in the invasion process for better-informed decisions and more effective management and restoration programs. For instance, it would be important to build a unique protocol for the entire *Campos Sulinos* region including (i) the assessment of the current and potential IAS, (ii) priority-setting plan of which species to manage and where, (iii) identification of main pathways of introduction and dispersal, (iv) unify monitoring protocols, (v) investment in scientific and technical knowledge to generate information and develop appropriate skills, (vi) education and people awareness, and (vii) public information systems. With this information, it is possible to enhance the chances of producing large-scale positive results at the lowest cost possible for the whole region.

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