Chapter 29
Biological Invasions as a Component of South Africa's Global Change Research Effort

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Abstract In this chapter, we assess how much research in South Africa has been directed towards biological invasions relative to other elements of global change. Using Web of Science, we systematically reviewed literature relevant to South African ecosystems published between 2000 and 2018 and relating to biological invasions, climate change, overharvesting, habitat change, pollution, and/or atmospheric CO_2. We identified 1149 relevant papers that were scored in terms of their coverage of drivers and driver interactions that affect biodiversity or ecosystem services. A strong spatio-temporal effect was observed on research effort. Firstly, effort differed between realms, with habitat change, pollution and overharvesting receiving the largest research focus within terrestrial, freshwater and marine/estuarine realms respectively. Secondly, certain globally well-studied phenomena were not documented in local literature (e.g. there were fewer than five papers on ocean acidification). We identified 21 different interactions between drivers, with the interactions between invasive species and habitat change (for example altered fire regimes in invaded landscapes) being the most prominent. However, fewer than 4% of papers addressed interactions between three or more drivers. This suggests that while the importance of understanding driver interactions is recognised, there has been little in the way of researching the compound effects of driver interactions in South African ecosystems. The long-cited statement that invasive species pose the -second-largest threat to biodiversity conservation, behind habitat change, matches the relative research output for this driver in South Africa. Developing a comprehensive

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quantitative picture of the relative importance of global change drivers will nonetheless be challenging, not only in the unambiguous delineation of drivers, but also due to the unequal availability of research results at comparable spatial and temporal scales. The relative maturity of work on invasive species could provide a basis for exploring such complex interactions and thus contribute to overcoming such barriers.

29.1   Introduction

Given the many global threats to biodiversity and ecosystem services, just how important are biological invasions? Obtaining even an approximate answer to this question would be valuable for invasion biologists, because of the apparently increasing intensity of threats such as anthropogenic climate change, and increasing public awareness of and policy focus on such threats that influence research investment. It is a challenging question to answer, because most of these threats (which can be viewed as "drivers") interact with one another over a range of spatial and temporal scales, and because they operate through varying mechanisms. Possibly because of this, South Africa lacks a clear prioritisation of such drivers in its environmental research policy frameworks (van Wilgen 2009). In this chapter we make an initial attempt to explore the available literature, to quantify the research effort on biological invasions relative to other elements of global change in South Africa, to identify major research gaps, and to highlight the challenges inherent in obtaining a quantitative answer regarding the relative importance of biological invasions as a global change driver in the country.

At the global level, Sala et al. (2000) made one of the first attempts to project what the implications of five major drivers of change (land use, climate, N deposition, biotic exchange and atmospheric CO_2) might be by 2100, their relative importance, and their interactions in different ecosystems. In the Sala et al. (2000) analysis, land use change was projected to have the largest influence terrestrially, with biological invasions ("biotic exchange") ranked below climate change and nitrogen deposition in importance. Only in freshwater lakes and Mediterranean ecosystems did Sala et al. (2000) rank biological invasions as the most important of the global change drivers into the future. Furthermore, as a result of negative synergistic driver interactions, Mediterranean-type ecosystems were predicted to experience the most adverse consequences of global change of all ecosystems over the current century. Some support for this projection in South Africa comes from an analysis of the impact of alien plants in national parks, where the highest number of transformer plants, with the greatest cumulative impact were found in parks in the Mediterranean-climate Fynbos Biome (Foxcroft et al. 2019). Sala et al. (2000) projected that future effects of land use would dwarf that of most other change drivers across most biomes. Eighteen years later, experts still agree on the pervasive adverse impacts of land and sea use (Knapp et al. 2017), although IUCN data suggest that over-exploitation (hunting, fishing and gathering of plant material) has the greatest species-level

impact (Maxwell et al. 2016). In terms of international prioritisation, climate change receives by far the most research focus (Mazor et al. 2018), while despite their significance as direct threats at a species level (Maxwell et al. 2016), pollution and overexploitation of resources have received far less research attention (Mazor et al. 2018).

Terrestrial South Africa occupies only 0.8% of the world's land area, but it is one of the most biologically diverse countries globally (Mittermeier et al. 2004; van Wilgen et al. 2020, Sect. 1.1.1). This means that the country has a disproportionate responsibility to conserve its ecological resources while simultaneously meeting the needs of its people. Indeed, the biggest current threat to terrestrial biodiversity in terms of land area in South Africa is land use, due to ecosystem transformation for agriculture and human settlement. Around 80% of the land surface area in South Africa is recognised as agricultural land (Department of Agriculture 2007). While this figure includes all rural land not declared as protected areas, and only a proportion of this land is actually cultivated, many of the management practices employed on this land are not biodiversity-friendly (e.g. predator persecution, overgrazing, lack of alien clearing and management). The combination of high endemic biodiversity and significant land use pressures in many South African ecosystems may create a complex mix of vulnerability to global change drivers, particularly biological invasions. While theory predicts that the invasibility of high diversity systems should be low, empirical observation finds positive relationships between native and invasive species richness (Levine and D'Antonio 1999). Anthropogenic disturbance acts to increase invasibility through a variety of mechanisms, and this has led to multiple opportunities to accelerate the rate of invasion in species-rich South African ecosystems (see also Wilson et al. 2020a, Chap. 14).

The direct effects of climate change on South African ecosystems have been difficult to discern, with evidence available for relatively few species and processes (Skowno et al. 2019). This is especially due to inherent variability in climate, most notably of rainfall, that complicate the detection and attribution of observed trends to recent climate change. Nonetheless, important effects of rising atmospheric CO_2 may already be clearly discernible in grasslands and savannas, not only in southern Africa but globally as well (Stevens et al. 2017). This is due to well-established beneficial effects of increasing carbon uptake for the resilience of woody plants in disturbance-prone environments (Bond and Midgley 2012; Kgope et al. 2010; Midgley and Bond 2015). Other examples of likely attributable impacts of climate change include shifts in migratory behaviour of African swallows (Altwegg et al. 2012), and increased frequency of large fires (Southey 2009).

Biological invasions will play out amongst, and interact with, all the other change drivers for example post-fire regeneration failure linked to intensifying drought conditions (Slingsby et al. 2017). While biological invasions on their own can impact negatively on biodiversity and the delivery of ecosystem services, it may be their interaction with multiple global change drivers that further raises their relevance for research effort within a global change framework. The various interacting elements of global change need to be managed collectively, or at least need to be explicitly considered when formulating management interventions if two

of the major goals of ecosystem management, to conserve biodiversity, and to ensure the sustainable delivery of ecosystem services, are to be achieved (Brook et al. 2008; Niinemets et al. 2017; Pacifici et al. 2015). Typically, this is not done, as the complexity and cost of such research may constitute a barrier to addressing these interactions. Consequences for management and policy responses are that invasive alien control programs focus on invasive species with little consideration of interacting drivers, climate change is addressed through proposing adaptation and mitigation measures, and pollution is controlled through national regulations that may not be context-specific. Given the complexities of each known environmental change driver, their different definitions in different contexts (Millennium Ecosystem Assessment 2005; Lavorel et al. 1998; Mather et al. 1998; Salafsky et al. 2008) and a limited mechanistic understanding of how these drivers interact (Leuzinger et al. 2011; O'Connor et al. 2015), it would be important to understand the knowledge base underpinning each and to determine which interactions are well documented in the literature. In this chapter, we report on a quantitative literature review for South Africa to assess (1) how much research has been directed towards biological invasions relative to research on other elements of global change; (2) which interactions between these elements have been investigated; and (3) how this research effort differs between terrestrial, freshwater and marine ecosystems.

29.2   Methods

In this study, we considered the change drivers recognised in the Millennium Ecosystem Assessment and Global Assessment on Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) on biodiversity and ecosystem services, and on one another, i.e. invasive species, climate change, over-harvesting, habitat change and pollution. We also added CO_2 to the list of change drivers (as per Sala et al. 2000), and considered emerging infectious diseases as a part of invasive species (see Ogden et al. 2019). We considered only direct effects, so for example the effect of climate warming on fire and subsequent effects on biological invasions would be considered separately as (1) the effect of climate change on natural disturbance regimes (included under habitat change) and then (2) the effect of habitat change on alien species. While we acknowledge that social and political changes will have significant impacts on all the drivers considered, we consider only the environmental components of global change in this chapter.

   To assess the research effort that has gone into each driver on biodiversity and ecosystem services, or the interaction between each pair of drivers in the South African context, we reviewed papers on the Web of Science. The details of the search terms used are provided in the Supporting Information, but the basic pattern was to identify the particular driver using as exhaustive a list of synonyms as possible (e.g. for alien species we used *alien* OR *invasiv* OR *exotic* OR *non-indigenous OR non-native* including alternate hyphenation) along with

"South Africa∗" AND (ecosystem∗ OR biodiversity) AND (impact∗ OR effect∗ OR trend∗). Only papers relevant to South Africa were considered, and we included only the Science Citation Index Expanded and Book Citation Index—Science for articles published between 2000 and 2018, i.e. millennial research published following the first analysis undertaken by Sala et al. in 2000. The search produced 3218 research articles, 2107 of which were unique. For each paper, we read the title and abstract and removed any studies that took place outside of South Africa (we also excluded those studies conducted in neighbouring countries such as Namibia, Swaziland and Lesotho) as well as those deemed to be beyond the study scope. The latter category included experimental studies with no clear link to a future time period (e.g. impacts of very high carbon dioxide concentrations), studies that valued ecosystem services as well as those that described restoration efforts, purely ecological studies with no direct consideration of change drivers, studies that detailed management options for biodiversity and ecosystem services (including studies on biological control of invasive species) and descriptions of new alien species or their establishment. The final dataset that was scored consisted of 1149 papers.

For each paper, we read the title and abstract and recorded (binary 0 or 1) as many direct driver effects on biodiversity and ecosystem services (out of the possible 6) or interactions of drivers. For example, a paper that demonstrated the impacts of drought on pollutant concentrations, with subsequent eutrophication and algal blooms would be counted as a direct effect of pollution on biodiversity and ecosystem services as well as an interaction of "Climate on pollution" and "Pollution on habitat" (Dabrowski et al. 2014). We also recorded the realm (terrestrial, freshwater or marine and estuarine) in which the study took place.

The number of papers assigned to each interaction was used to construct a schematic of driver interactions as covered by the literature across all papers (Fig. 29.1) and within each realm. While meta-analysis to assess the relative strength of each driver was beyond the scope of this review, the number of papers was assumed to be a proxy for research effort. In addition, for each direct effect and interaction identified, we read through the papers (abstracts and where applicable the full text) to identify the key topics, scope and trends discussed to distil the core nature, whether positive or negative, and direction of each of the interactions and direct effects on biodiversity in South Africa.

29.3   Results and Discussion

29.3.1   Broad Global Change Research Patterns in South Africa

While habitat change received the most research attention across realms, several other drivers have also received attention, in particular for their role in mediating the functioning of ecosystem services and maintenance of biodiversity in more natural
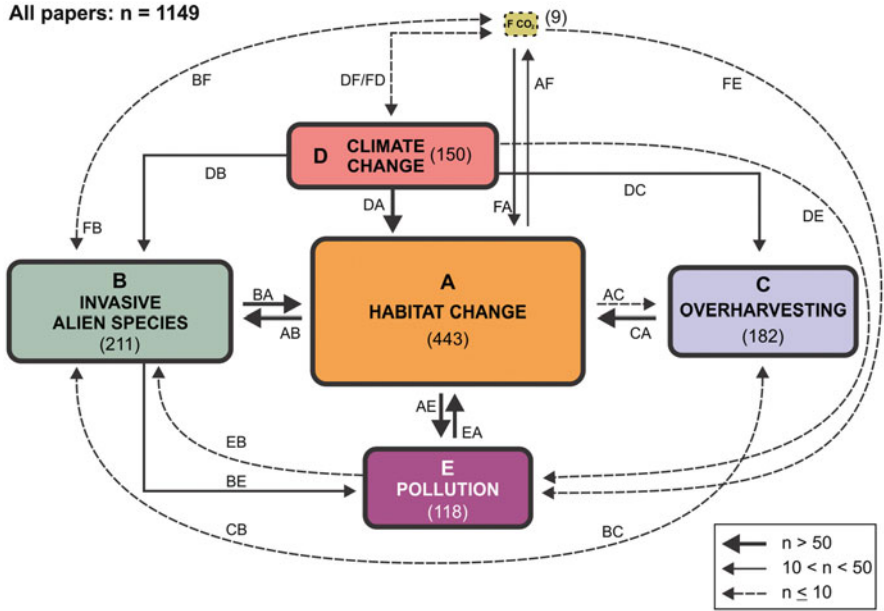
Fig. 29.1 Interactions between six major drivers of environmental change in South Africa as based on scientific papers published between 2000 and 2018 across all environmental realms (terrestrial, freshwater, and marine and estuarine, $n = 1149$ papers). The size of each box (A–F) represents the number of papers detailing a direct effect of that driver on biodiversity and ecosystem services (number of papers in brackets). Interactions are shown as arrows, labelled according to the driver letters (e.g. the effect of overharvesting on habitat change is CA, and the effect of habitat change on overharvesting is AC). These designations are used when interactions are discussed in the text. Thick solid arrows/lines represent direct effects or interactions documented by more than 50 papers, thin solid arrows/lines are effects/interactions documented in 11–49 papers, while dotted arrows/lines are effects or interactions represented in 10 or less papers

areas. Several key factors emerged from our assessment. Firstly, it is clear that some drivers of ecosystem change in South Africa have received more research attention than others (Fig. 29.1), and it is apparent that this focus has differed between major realms, with habitat change, pollution, and overharvesting dominating in terrestrial, freshwater, and marine and estuarine ecosystems, respectively (Fig. 29.2). Secondly, several interactions that are well known globally have either not been written about in the South African context or were not picked up by our search terms. In most cases, the latter explanation seems unlikely. For example, some of these omissions, such as the direct link between atmospheric CO_2 emissions from vegetation and climate change, are not particularly relevant at sub-regional scale, while others were surprising. For example, there were fewer than five papers on the direct effect of atmospheric CO_2 on oceans (acidification). Finally, we recognise that we have assessed only a particular temporal component of the South African literature, because we excluded carried out before 2000. Nonetheless, given that global change research was in its infancy in the twentieth century, we believe that our sample
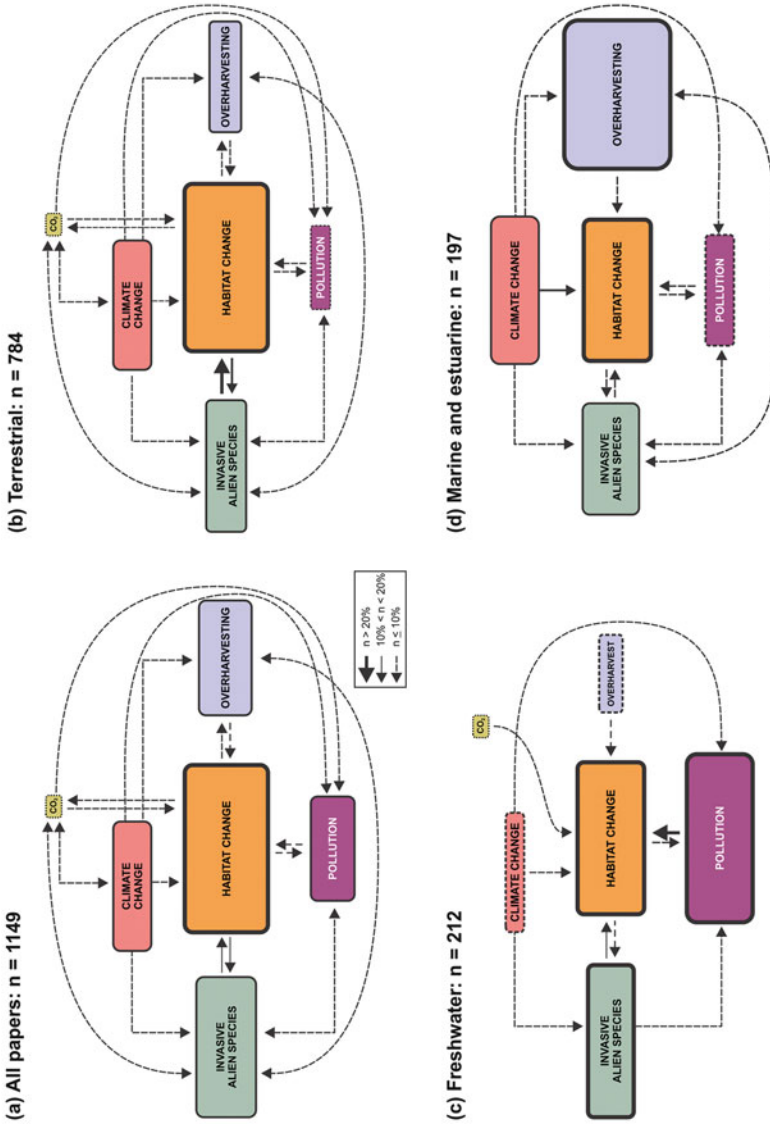
Fig. 29.2 Interactions between six major drivers of environmental change in South Africa as based on scientific papers published between 2000 and 2018 across all environments (**a**) and in (**b**) terrestrial, (**c**) freshwater and (**d**) marine and estuarine environments. The size of each box represents the relative number of papers detailing a direct effect of a driver on biodiversity and ecosystem services compared to other drivers, while the thickness of the box border relates to the absolute number of papers: Thick solid arrows/lines represent direct effects or interactions documented by more than 20% of papers, thin solid arrows are effects/interactions documented in 10–20% of papers, while dotted arrows are feasible interactions represented in 10% or less of papers (see Key)

provides a fair reflection of the direction taken by global change researchers in the twenty-first century.

It is well known that environmental change drivers act in concert and often interact to have profound impacts beyond simple additive effects (Brook et al. 2008; Franklin et al. 2016; Scherber 2015; also see Box 29.1). However, controlling for all drivers in experimental design and modelling is challenging, so this is not always done satisfactorily (O'Connor et al. 2015), and where acceptable control is achieved, studies may be focussed on individual species (Niinemets et al. 2017). We identified 21 interaction types from the South African literature across realms and in terrestrial ecosystems, compared to 13 interaction types in marine and estuarine environments and only 11 interaction types in freshwater systems (Fig. 29.2, each identified by a directional arrow). The only interaction types documented in more than 20% of papers within a particular realm were the interactions between alien species and habitat change in terrestrial environments and between pollution and habitat change in freshwater environments (Fig. 29.2). Furthermore, we found that 65% of papers dealt with only one direct driver and that half of the papers scored documented only direct driver effects and no interactions. Less than 1% of papers documented more than three of the identified interaction types, and 96% of papers documented only two interactions or less. This suggests that while many interactions are recognised, there are barriers in the way of researching the compound effects of driver interactions and thus in understanding their combined effects in South African ecosystems. Interactions between all drivers and habitat change were best researched (528 or 46% of papers, documenting nine interaction types), both in terms of altering natural disturbance regimes and the quality and structure of habitats. Habitat change and alien species were documented to have the highest number of interactions with other drivers (five receiving arrows and four driving arrows each), while the number of papers documenting interactions with alien species was second highest (276 or 24% of papers).

Box 29.1 Case Studies of Interactions Between Global Change Drivers in South Africa

Several case studies from South Africa demonstrate the complex and often unexpected interactions between change drivers. These examples highlight both the need to consider drivers and their interactions collectively in determining the implications of change for the protection of biodiversity and ecosystem services and the role of alien species management in these outcomes.

1. A recent assessment of global change in South African National Parks considered the effects of six change drivers in each park (van Wilgen and Herbst 2017). The most pervasive threats within national parks (i.e. present in the most parks with high or moderate impacts) were change in freshwater systems and climate change. Invasive species were predicted to have high

Box 29.1 (continued)

impacts with high confidence in more parks than any other driver. This suggests that while invasive species may not be the most pressing driver of global change, they are the easiest to detect and arguably the easiest to manage. By reducing the threat of invasions through direct control of problem plants and animals, biodiversity would be given a better chance to overcome the negative effects of other stressors being faced in the twenty-first century.

2. A combination of a prolonged drought, a >20% increase in extent of invasive *Pinus* species (Pine trees) in river catchment areas between 2000 and 2015 (Henderson and Wilson 2017), and a 600% increase in human population since 1950, with associated increase in demand for water, resulted in a large-scale water crisis in Cape Town, that almost saw the taps run dry in 2018 (Le Maitre et al. 2016; Otto et al. 2018). While the climate and population pressures are unlikely to abate, clearing of invasive trees in catchments, as well as reductions in the rates of water use have been highlighted as two key adaptation options.

3. Invasion of the natural vegetation by alien trees from forestry plantations is taking place at increasing rates in the Eden District Municipality in the Fynbos Biome. In response to a series of natural disasters (flash floods, destructive wildfires, persistent droughts, and storm surges along the coast) in the district, Nel et al. (2014) examined the feasibility of offsetting the damage under different climate change scenarios. The study suggested that appropriate land use management, including clearing invasive trees, could reduce the impacts of natural hazards, and offset the effects of climate change, to a large degree.

4. Overfishing of predatory fish has led to a growth in populations of *Jasus lalandii* (West Coast Rock Lobster). This, in combination with environmental changes, has allowed *J. lalandii* to expand its distribution eastward. This dispersal has resulted in complete regime shifts, with loss of herbivorous species, such as urchins on which the lobsters feed, and associated loss of commercially important *Haliotis midae* (Abalone) that rely on urchins for cover as juveniles. At the same time kelp (*Ecklonia maxima*) has quadrupled in abundance and filter feeders increased by as much as 2600% (Blamey and Branch 2012; Blamey et al. 2010). Such regime shifts have significant implications for fisheries management and the people dependent on fisheries (Cury and Shannon 2004).

5. Mangroves represent an ecosystem type that appears to be particularly susceptible to multiple change drivers, and suffer the impacts of both local drivers (e.g. direct harvesting and pollution), as well as more remote drivers such as pollution and erosion in upper catchments (Hoppe-Speer et al. 2015). While mangrove conservation can have significant biodiversity and carbon sequestration benefits, source to sea conservation initiatives that

Box 29.1 (continued)

include alien clearing and rehabilitation are vitally important to protect them.

6. Interaction between a number of change drivers (pollution, invasion and habitat change) has been implicated in a 2008 pansteatitis outbreak in *Crocodylus niloticus* (Nile Crocodiles) within the Kruger National Park. Potential causative factors include interactions between river impoundment and pollution, both upstream and downstream from the park, potential switches in diet related to invasion by alien fish, river eutrophication and algal blooms, along with drought, and high temperatures (Dabrowski et al. 2013; Woodborne et al. 2012).

While research effort does not constitute a measure of the relative importance of drivers or their interactions, it is interesting to note that patterns of driver importance have recently been more directly assessed elsewhere. In an authoritative global assessment, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) found habitat change to be the largest driver of change in both terrestrial and freshwater systems globally, and overharvesting to be the dominant driver of change in marine systems (IPBES 2019). While pollution was not the largest outright driver of change in freshwater systems, it was found to have its largest relative impact in this realm (IPBES 2019). It was noted further that invasive species had similar proportional impacts across realms, and that these impacts were currently less than those of other drivers, though estimated to be accelerating. The assessed relative importance of drivers of change across the globe is remarkably similar to the proportional research effort that we found for South Africa, suggesting that proportional research effort has been informed by global trends in environmental threats, and may even be interpreted as a proxy measure for the relative importance of drivers (Fig. 29.2). The considerable relative research effort towards biological invasions in South Africa (Fig. 29.1) in comparison to their relative estimated global impact (Fig. 29.3) is however the largest discrepancy. This may be because research on biological invasions has received a disproportionate share of funding through the creation of a centre of excellence dedicated to the topic (Richardson et al. 2020, Chap. 30), and through funding by government through the Working for Water programme (Abrahams et al. 2019).

29.3.2 How Do Biological Invasions Interact with Other Drivers of Global Change?

Biological invasions are obviously a direct driver of changes to biodiversity and ecosystem services, in South Africa and elsewhere. In a South African context, these
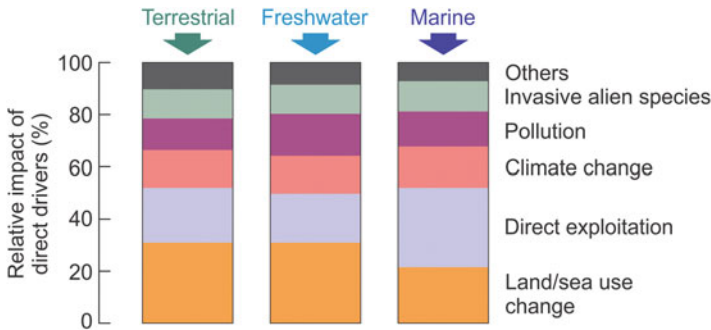
Fig. 29.3 The relative global impact of direct drivers on terrestrial, freshwater and marine ecosystems as estimated from a global systematic review of studies published since 2005, and conducted as part of the IPBES global assessment report (colours adapted to those used in Figs. 29.1 and 29.2). Together habitat change and overharvesting (direct exploitation) are responsible for >50% of all impacts on biodiversity, although proportions differ between realms [Adapted and reproduced with permission from IPBES (2019)]

direct impacts are best understood in terms of water resources, rangeland productivity, and biodiversity and are covered elsewhere in this book (Le Maitre et al. 2020, Chap. 15; O'Connor and van Wilgen 2020, Chap. 16; Zengeya et al. 2020, Chap. 17). In this section, we consider what research has been carried out in South Africa that could help us to understand how other drivers of global change can influence biological invasions (Table 29.1). In addition, we summarise South African research that has examined how biological invasions exacerbate or ameliorate other drivers of global change and attempt to estimate how important these interactions might be in the future. These issues are understandably complex, and each driver could potentially interact with each other driver (see examples in Box 29.1). Examples that have received particular research attention in the South African context include the influence of climate change on habitat change (arrow DA, Fig. 29.1), which has received the highest relative attention in marine systems (Fig. 29.2); the influence of pollution on habitat change (arrow EA in Fig. 29.1), in particular for freshwater systems; the influence of habitat change on pollution (arrow AE in Fig. 29.1), largely as a result of particular land uses, that have knock-on effects in freshwater systems; and (to a lesser extent) the influence of climate change on grazing and overgrazing, which is considered a form of overharvesting (arrow DC in Fig. 29.1). A full exploration of all of these interactions is, however, beyond the scope of this chapter.

The effect of habitat change on biological invasions was addressed in 116 publications identified in our review (Table 29.1). There may be some conflation between the land use component of habitat change and invasive species, because certain land uses (e.g. forestry) rely on alien species and as such are a direct introduction pathway for alien species, but it is clear that habitat change can promote invasion. For example, many alien species establish more readily in degraded habitats or in response to fire (arrow AB in Fig. 29.1, e.g. Kalwij et al. 2008). At a micro-scale,

Table 29.1 Interactions between biological invasions and other drivers of global change that have been studied and reported on in South Africa

Direction of influence	Driver	Arrow*	Number of papers	Notes
Drivers of global change that influence biological invasions	Habitat change	AB	116	There are some attribution issues when it comes to 'habitat change' in that several land uses act as direct pathways for the introduction and spread of alien species. Once present in a landscape however, habitat disturbance can make ecosystems more susceptible to invasions. Fire can alter habitats and facilitate invasions.
	Climate change	DB	38	Climate change can create conditions that are either more, or less, suitable for particular invasive species. Climate change will also influence fire, which in turn influences invasions through habitat change. Climate change may negatively affect native species, thereby reducing competition or predation/herbivory for alien species.
	Pollution	EB	10	Eutrophication of water bodies facilitates invasion by alien plants. Addition of nutrients to soils facilitates invasion or alters competitive advantage for alien versus native species.
	Overharvesting	CB	5	Overgrazing (a form of overharvesting) can promote invasions in rangelands. In marine systems in particular, overfishing alters predation and competition and can promote invasion by native as well as alien species.
	CO_2	FB	4	Some alien species have started to be used in place of native species in traditional medicines which could lead to further spread of these species. Increased CO_2 could promote invasion by alien trees as well as alter tree/grass/fire dynamics.
Influence of biological invasions on driver of change	Habitat change	BA	207	Invasion changes the composition, structure and functioning of ecosystems in many ways. Alien increase evapotranspiration and reduce surface and ground water resources; replacement of palatable plants with unpalatable plants can reduce the productivity of rangelands; invasions by alien plants can change the fuel characteristics of native vegetation, making fires more intense. Invasion of treeless landscapes by alien trees can provide nesting sites for native raptors and other birds, expanding their ranges.

	Arrow		
Climate change	Not shown	None	The presence of alien species is not thought to influence rainfall and temperature at landscape level and has not been reported in South Africa.
Pollution	BE	28	Extensive use of pesticides or herbicides in control operations can have non-target effects. Alien plants may produce allelopathic chemicals, or enrich nutrient-poor ecosystems through nitrogen fixation.
Overharvesting	BC	10	Invasion by native species as a result of multiple drivers has been shown to exacerbate the decline of overfished species (see Box 29.1). Use of alien species for example as biofuels could reduce harvest pressure on natural mineral resources. Use of aliens for other purposes such as medicines, food or timber have also been proposed, but there are many complexities to the costs and benefits associated with these suggestions (see text).
CO_2	BF	8	Both woody encroachment by native species and invasion by alien trees can increase biomass and thus sequester CO_2. However, the costs and benefits of this are complicated and water loss is a key consideration. Above and below ground sequestration rates also differ. Carbon stored above ground can easily be lost through fire.

*The Arrow column refers to interactions as depicted in Fig. 29.1

land-use practices influence the content and size of soil organic matter and subsequently the composition of native and alien earthworm communities (Haynes et al. 2003). Interactions between land use/habitat change, climate change and invasions are of particular concern going forward. For example, millions of hectares of land currently suitable for crop farming (particularly maize) may become unsuitable, while other areas may increase in suitability (Bradley et al. 2012). This provides both risks and opportunities for conservation. Opportunities exist for restoration where land is abandoned. However, the presence of invasive species and altered ecological conditions will complicate rehabilitation (Gaertner et al. 2011; Meek et al. 2013), as will additional climate factors like wind erosion and drought (Botha et al. 2008). In addition, restoration costs required as a result of unsustainable farming practices are often prohibitively high (Herling et al. 2009). Change in land use practice such as the widespread adoption of genetically modified crops to increase agricultural production in South Africa (Wynberg 2002) also comes with unquantified potential impacts for invasion and disease emergence.

The effects of climate change on biological invasions has been addressed in 38 published papers. Climate change can impact on biological invasions by making conditions for invasive species either more or less suitable than before (arrow DB in Fig. 29.1). While some invasive species will undoubtedly be maladapted to the changing climate (Irlich et al. 2014), climate-induced pressures on native species may further enhance the competitive advantage of invasives, particularly for those species with high phenotypic plasticity (Chown et al. 2007). Distribution changes in invasives as a result of climate change have been modelled in South Africa for several species or species groups (e.g. Parker-Allie et al. 2009), including disease species (Berman 2011; Osorio et al. 2017). Several of these studies have postulated that climate change will exacerbate the threat levels to native species already threatened by invasives, when the two drivers act in concert. In addition, climatic conditions favouring wildfire (e.g. Southey 2009) will intensify the positive interactions between invasive species and fire intensity. Other interactions have been less well studied, with fewer than 10 papers on the effects of pollution, overharvesting and changes in CO_2 on biological invasions (see Table 29.1 for a few examples). Atmospheric CO_2 increase has been shown to accelerate carbon uptake and growth in many terrestrial plant species, particularly woody (Ainsworth and Long 2005) and young individuals of fast-growing species with low resource limitation (Ali et al. 2013). Despite this, there has been almost no work to quantify the effect of this driver on the success of invasive plants. Given that CO_2 has increased by almost 40% since invasive species were introduced into South Africa (Keenan et al. 2016) it is conceivable that this driver may already be adding significantly to their invasive potential. The implication is that current levels of control effort would be further outpaced through faster establishment, greater growth rates, resistance to biological control agents, earlier reproduction and even greater seed set. Nitrogen-fixing invasive woody species in the Greater Cape Floristic Region would be particular beneficiaries through their potential to allocate greater amounts of carbon to their symbiotic bacteria.

The question can also be asked as to whether biological invasions influence other drivers of global change, and if so, how? Again, the interaction with habitat change has been the most studied, with 207 papers identified in our analysis (Table 29.1). Invasion changes the composition, structure and functioning of ecosystems (arrow BA in Fig. 29.1, e.g. see Chamier et al. 2012) at a micro (e.g. soil processes) and macro level (e.g. through changes in disturbance regimes, te Beest et al. 2012) by adding species with different characteristics to the native species that they replace. In cases where the alien species become dominant, these changes can do more than just exclude native biodiversity through competition. Increases in evapotranspiration change the hydrological characteristics of ecosystems, leading to decreases in surface and ground water resources (Le Maitre et al. 2020, Chap. 15). Trees in the genera *Prosopis* and *Acacia* displace palatable grasses, and along with invasive cacti, physically restrict the access to pastures by livestock (O'Connor and van Wilgen 2020, Chap. 16). Invasion of natural ecosystems by alien plants can also change the structure and biomass of vegetation, adding fuel and supporting fires of higher intensity. Increased fire intensity can in turn increase the damage done by fires, as well as the difficulty of controlling fires, as has been demonstrated in a few South African studies (Kraaij et al. 2018; van Wilgen and Scott 2001).

Not all habitat changes are perceived as negative though. Some of the impacts of invasive species can be seen as positive, even if the overall net impact is negative. For example, Cooper et al. (2017) noted that the invasion of treeless landscapes by alien trees can provide nesting sites for native raptors and other birds, expanding their ranges; and Coleman and Hockey (2008) found that the invasion of bare rocky seashores by alien mussels has boosted populations of African Black Oystercatchers, *Haematopus moquini*). These types of effects can complicate management, and lead to conflict. Examples include alien trees used in commercial forestry (van Wilgen and Richardson 2014) and trout species introduced for recreational angling (Woodford et al. 2016). In many of these cases, the net outcome is negative (i.e. the sum total of negative impacts outweighs the benefits), indicating that invasions by the species concerned are undesirable (De Wit et al. 2001; Wise et al. 2012).

The influence of biological invasions on pollution was identified in at least 10 papers. In ecosystems characterised by nutrient-poor soils, invasion by nitrogen-fixing alien plants can raise nutrient levels, with negative consequences for ecosystem restoration (Nsikani et al. 2017). Of concern into the future is the use of herbicides or pesticides for the control of invasive species as well as diseases, such as malaria. These chemicals can precipitate impacts beyond the target organisms (arrow BE in Fig. 29.1), including people (Bornman and Bouwman 2012), particularly when they are not applied correctly (Adams et al. 2016; Dube et al. 2009). The magnitude of this problem cannot be accurately quantified in South Africa, both due to limited studies and also widespread use of herbicides and pesticides in agriculture. While a handful of studies on the herbicides used to control invasions exist (<10 in our sample), there are almost no records of the extent of herbicide use within major government programs.

The effects of biological invasion on other drivers of global change may well be trivial, as there are no clear mechanisms by which this could happen. For example, we found no studies of the influence of biological invasions on climate change in South Africa. Invasive species could theoretically be used as biofuels and as such reduce harvest of natural mineral resources, but as with use of alien species for agricultural or related purposes (discussed above), there are many potential costs including trade-offs with use of the same land for biodiversity conservation (Blanchard et al. 2015). There were only a handful of studies on the use of alien species to sequester carbon, but these were largely inconclusive and highly context-specific. While the planting of trees in parking lots appears to hold some carbon benefit (O'Donoghue and Shackleton 2013), in general costs associated with water use (Chisholm 2010), the slow speed of carbon sequestration in South African systems like savannas (Coetsee et al. 2013) and the loss of carbon when aliens burn, suggest that any benefit would be trivial.

29.4   Differences Between Realms

The impacts of each driver, and of their interactions, were different in different realms (marine, freshwater, and terrestrial). There were some obvious differences in research effort between terrestrial, freshwater and marine/estuarine realms. While our research terms may not have reflected the full breadth of global change research available equally well across realms, we are confident in the identified patterns of research effort. Biological invasions were best researched in terrestrial environments, with almost double the number of papers discussing terrestrial biodiversity impacts (147) compared to aquatic impacts (79). However, a greater portion of freshwater research (23%) considered invasive species as a change driver, in comparison to terrestrial systems (18% of papers). Given that 'habitat change' research encompasses a diverse array of fields (e.g. the National Biodiversity Assessment recognises Agriculture and Aquaculture, Energy production and mining, Human intrusions and disturbance, Natural system modification, Residential and commercial development, and Transportation and service corridors separately), and direct conversion of habitat will have a greater impact than modification, it is not surprising that habitat change received the most terrestrial research attention (43% of terrestrial papers). Further to this, terrestrial habitats are easier to study than their aquatic counterparts, which often require sophisticated equipment or highly skilled technicians (e.g. divers). In addition, South Africa has very good abiotic data from the terrestrial environment (e.g. climatic variables), which has not historically been the case in aquatic environments.

Freshwater systems have borne the brunt of terrestrial land-use change, which may have resulted in somewhat of an attribution issue. That is, pollution was more likely to be scored as a direct driver in freshwater habitats as opposed to scoring the associated land uses (habitat change) causing the pollution, which take place beyond the freshwater environment itself (Dabrowski et al. 2014). Despite the dominance of

pollution as a global change research theme in freshwater environments (76 papers or 36% of freshwater ecosystem-related papers), impoundments and flow modification remain a critical determinant of freshwater ecosystem structure and function (66 papers recorded direct effects of habitat modification in freshwater environments) (Bredenhand and Samways 2009). Water extraction itself significantly alters freshwater system function and has lasting effects on surface and groundwater (Knuppe 2011).

The dominance of overharvesting research in marine environments is logical, given the need to provide accurate information on fish stocks to support the billion Rand (ZAR) industry and the many local livelihoods dependent on it (Hutchings et al. 2009). Interestingly, a much larger proportion of marine research was dedicated to climate change impacts (19.3% of marine/estuarine papers) compared to terrestrial (12.7%) or freshwater (5.7%) research on the topic. This was largely as a result of impact assessments of storm surges and extreme events on estuaries.

29.5 The Future of Global Change and Global Change Research

While it is not possible from this assessment to determine the accuracy of the long-cited statement that invasive species appear to be the second largest threat to biodiversity, this driver has received the second highest research focus in South Africa (Fig. 29.1). South Africa's National Biodiversity Assessment (Skowno et al. 2019) (which provided an independent semi-quantitative assessment of global change risks to a range of species from all realms) found that biological invasions ranked in the top two threats for the terrestrial, sub-Antarctic and inland aquatic realms. Invasions posed a far lower threat to marine, estuarine and coastal systems. For a set of 658 aquatic species assessed, invasive species emerged as the most significant threat to amphibian, aquatic plant and freshwater fish species in the IUCN threatened categories. Invasive species were noted as a significant risk to estuarine species and systems. However, such assessments suffer from a shifting baseline problem, because they are skewed towards current threats and processes. The major historical impact (since European colonisation), across environments, has been an erosion of native biodiversity with an accelerating reduction in natural habitat (including fragmentation) since the mechanisation of agriculture and comparable advances in fisheries. These more recent trends are associated with rapid increases in pollution (energy and agriculture-related) and proliferation in the number and range of invasive species. We therefore have a landscape that has been fragmented, depleted of native species (especially mammals) and subjected to the disruptive effects of pollution, and altered disturbance regimes. It is onto this fragmented landscape that the impacts of climate change will now be superimposed (Fig. 29.4). The dominance of particular drivers into the future is therefore uncertain, particularly in the face of changing ocean circulation, rainfall patterns, rising

temperatures and associated changes in the way people will use land and biodiversity (Fig. 29.4). The arrival in South Africa of new invaders, such as *Euwallacea fornicatus* (the Polyphagous Shot-Hole Borer) (Paap et al. 2018; Potgieter et al. 2020; Box 11.3), which has the potential to decimate trees in urban, natural and agricultural habitats, are warnings that we should prepare for the unexpected.

Our assessment of research effort to date raises some concerns, in that it appears that the research approach to date has been piecemeal. While significant effort has been made to research the various aspects of global change, very little of this has considered the implications of multiple drivers acting in concert, and almost no research has been dedicated to holistic, mechanistic understanding of the impacts of the full suite of global change drivers acting simultaneously (<1% of papers dealt with 4 or more interaction types). Although there is a strong argument for better coordination and the development of a national framework of testable hypotheses, attempts to understand the collective impacts of so many processes are fraught with difficulties. It is easy to become overwhelmed by both the magnitude of the problem and the sheer number of interacting factors and drivers. One of the key problems is that for most of the change drivers, there is a lag effect in their impacts (e.g. invasive species in the process of establishment, build-up of pollutants, a warming trajectory that will proceed regardless of current interventions, drug resistant bacteria, loss of genetic diversity and adaptive potential in wild and agricultural species). So where to from here?

The relative focus of South Africa's global change research effort largely matches assessments of the relative importance of these drivers carried out elsewhere, suggesting that our research focus does consider those aspects that are important. While the strong research focus on terrestrial invasions in South Africa appears at
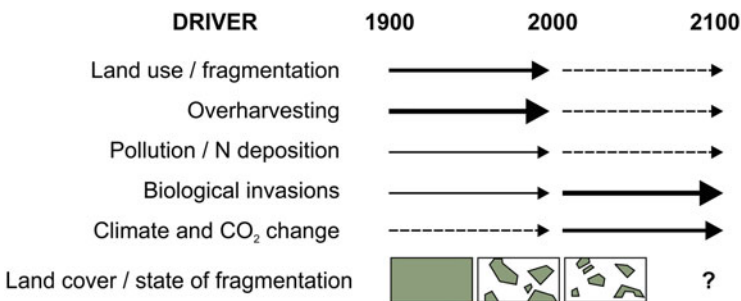

Fig. 29.4 Historical and potential future changes to the relative importance of different drivers of global change in South Africa. Historically, land use and overharvesting have been major drivers of biodiversity loss and ecosystem fragmentation, with pollution and biological invasions becoming more prominent with agricultural intensification and increasing globalisation of trade and travel. Impacts of climate change are only beginning to emerge, but are expected to be significant in coming decades, with strong interactions with invasive species and emerging diseases. How land use, resource use and pollution proceed will largely depend on national and international governance and innovation, and are difficult to predict. The ecological state of South Africa and indeed the globe by the end of the twenty-first century will depend very much on the actions taken in the coming decades (see also Wilson et al. 2020b)

odds with the finding of their lower relative importance as a global change driver, this emphasis is supported by the level of threat identified from invasions in the National Biodiversity Assessment. Indeed, the research effort towards invasions in different realms appears to match the relative threat posed by invasions (Skowno et al. 2019), with the least studies and the least impact to date recorded in marine environments. This may however be a result of limited sampling for marine inva- sives (Picker and Griffiths 2017; Robinson et al. 2020, Chap. 9) which may increase as pathways such as ballast water receive increasing attention.

Biological invasions obviously interact with other drivers of global change, but research rarely considers the combined impacts of interactive drivers, not even in terrestrial environments where more research has taken place. Developing a com- prehensive quantitative picture of the relative importance of global change drivers will be challenging, not only in the unambiguous delineation of drivers, but also due to the unequal availability of research results at comparable spatial and temporal scales. The relative maturity of work on invasive species could provide a basis for exploring such complex interactions and thus contribute to overcoming such bar- riers. Several assessments (e.g. IPBES 2019; Sala et al. 2000) point towards inva- sions becoming more important into the future. If future research on biological invasions is going to consider other drivers, then it should focus on those that appear to be important—climate change across all realms, habitat change in terrestrial ecosystems, pollution in freshwater ecosystems, and overharvesting in marine ecosystems.

Electronic Supplementary Material

The data-set "South African global environmental change literature 2000–2018" compiled as part of this project will become available on zenodo.org: https://doi.org/ 10.5281/zenodo.3265810

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