dispersion), and the potential areas that invasive species would be likely to occupy if no action was taken to control them. It will also be necessary to develop a better understanding of the effectiveness of clearing operations. Finally, the role that biological control plays in changing the population dynamics of invasive alien plants, and contributing to the long-term maintenance of cleared areas, needs to be better understood.

The choice of appropriate courses of action regarding the clearing of invasive alien plant infestations can be assisted by the development of decision-support models based on the above understanding. For example, managers need to decide whether available labour and funds should be directed towards clearing light or dense infestations where these occur together, as these choices could have different outcomes because of the differences in costs and in the rate of spread of different species.[10] Such models have been developed[11,12] but have not yet been used in practice. The development of the project information system reported on here will provide an opportunity to develop these models further as well as to apply them for the first time in practice.

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Alien plant invasions in South Africa: driving forces and the human dimension

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Invasive alien plants pose a substantial threat to the rich biodiversity of South Africa, and to the sustained delivery of a wide range of ecosystem services. Biological invasions are driven by human activities and mediated by culturally shaped values and ethics. This paper explores the human dimensions of alien plant invasions in South Africa. We consider four primary forces, those which directly influence the likelihood and rate of invasion — arrival of propagules; changes in disturbance regimes; changes in the availability of limiting factors; and fragmentation of the landscape — and the roles of 22 secondary driving forces in shaping the outcomes of the four primary driving forces. Human societies and their dynamics and activities are an integral part of each of the secondary driving forces. A map of the interactions between and among the primary and secondary driving forces shows how they are interlinked and influence each other — either positively or negatively, or switching between the two. There are two key points for intervention: prevention of the introduction of propagules of potentially invasive species and developing collaborative initiatives with enterprises that rely largely on alien species (for example, horticulture, agriculture and forestry, including community forestry) to minimize the introduction and use of potentially invasive species. An example of the first type of intervention would be to implement more effective inspection systems at international border and customs posts. This type of intervention can only be effective if those who are directly affected — whether businessmen, tourists or migrants — understand the requirement for these measures, and collaborate. The need to build public awareness of the critical importance of the human dimension of invasions emerges as a key theme from this analysis and is the basis for better-informed decisions, more effective control programmes and a reduction of further invasions.

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Introduction

Invasive alien plants, hereafter called invaders, are widely considered as important a threat to biodiversity as direct human transformation of the natural environments and production of greenhouse gases.[1,2] Invaders also threaten ecosystem services, including water purification, soil generation, waste decomposition and nutrient cycling, which are critical to human survival. A recent overview for seven different countries estimates the global costs of control programmes plus the total costs of damage caused by invaders to be of the order of US$314 billion per year.[3] Invaders cost South Africans tens of billions of rand annually in lost agricultural productivity and resources spent on weed control.[4] An assessment of the economic impact of black wattle (*Acacia mearnsii*) gave a net present cost of $1.4 billion (R9.8 billion)[5]. The costs associated with invasion by black wattles are at least partly offset by the substantial social and economic

benefits derived from the wattle industry. Many other invading species do not have any commercial value or use to offset their costs to society and their impacts on the environment. South Africa is facing critical water shortages, both regionally and nationally,[6,7] and cannot afford the loss of 7% of its renewable surface water resources[8] to invading woody plants.

The most obvious and direct solution to a dilemma of this magnitude is to implement nationwide control operations, like the Working for Water programme, but these actions address only one aspect of this multi-faceted and complex problem. Other actions that are needed include: preventing invaders entering the country or escaping from cultivation, early detection before the invader becomes a major problem, flexible responses to events that trigger invasions, and rehabilitation of the cleared areas.[9] Before we can tackle any of these actions, we need to face up to the simple fact that human actions and activities play critical roles in facilitating invasions. We will not find effective solutions until we identify inappropriate actions and behaviours, and where and how to intervene to change them. This paper begins by reviewing invasion processes and describing the primary driving forces of invasion — those processes which have a direct influence on the rate and likelihood of invasion. Then we describe the secondary driving forces for invasion and how they influence the primary driving forces. We show that the primary driving forces are closely related to environmental conditions and perturbations, whereas the secondary driving forces are largely human-mediated vectors and pathways. We also show that the secondary forces can interact with the primary forces either to promote or to retard invasion. This gives us scope to identify and alter aspects of human behaviour and activities that facilitate alien plant invasions in South Africa.

Processes of invasions: understanding the driving forces

Understanding of the biology and ecology of invasive organisms has improved substantially in the half century since Charles Elton's[12] seminal synthesis launched the field of invasion ecology. The last two decades have been especially productive in this regard. Most studies have concentrated on understanding what attributes distinguish successful from unsuccessful invaders, what features predispose ecosystems to invasions, how these aspects are linked, and on deriving management strategies.[13–16] There have been important advances in the scientific understanding of the process of invasions, particularly for plants, and a reasonably robust set of generalizations has emerged.[17–20] In considering aspects of invasions, it is useful to conceptualize processes that limit or facilitate invasions as an invader negotiating a series of barriers.[17,21] Much work has been done since the 1980s to develop a better understanding of the determinants of these barriers and how invaders succeed in crossing three main categories of barriers: (a) geographic barriers, which propagules of a species (seeds, spores, cuttings or other parts able to develop into a new organism) must overcome to arrive in the new environment; (b) habitat barriers (general climatic and edaphic conditions and the prevailing disturbance regime); and (c) biotic barriers (resident biota that occupy space and compete for resources). Human activities influence the potency of these barriers in a number of key ways,[22] thus mediating what we have defined as the four primary driving forces for invasions, namely: arrival of new propagules, disturbance regimes, changes in limiting factors, and fragmentation of the landscape by human activities. Each of these is described below.

Primary driving forces

Arrival of new propagules

Humans have moved organisms around since prehistoric times by transporting crops and associated weeds from the Middle East across Europe and Asia, but relatively few species were involved.[23,24] Large-scale and long-distance movement of thousands of plant species began with the establishment of European colonies across the world and has continued ever since;[23,25–28] a process that has been called the 'MacDonaldization' of the world.[29] A key motivating factor has been the need to ensure reliable and sustainable supplies of food, fuel, forage and medicines, but many species have also been moved for reasons of fashion and novelty.[30,31]

Disturbance regimes

Very few environments are unaffected by disturbances such as fires, droughts or floods. Disturbances typically release resources and reduce the domination of the existing communities of plants. For example, fires and floods create areas of open soil for plants to colonize and change nutrient and water availability.[32] Plants in disturbance-prone environments are adapted to particular combinations of the frequency, seasonality and intensity of key disturbances.[33] Land transformation often leads, directly or indirectly, to changes in disturbance regimes. For example, it is more difficult for fires to spread through areas where the transformed patches are not fire-prone.

Human activities often change disturbance regimes to such an extent that they expose native species to novel conditions. Where such modified regimes are beyond the tolerance of some native species, such species decline or become extinct, and certain alien species can capitalize on the available resources. For example, fire suppression in grasslands can favour the incursion of woody species or herbs, while increased fire frequency and intensity can rapidly eliminate woody elements.[34]

Changes in limiting factors

Modern industrial and agricultural practices alter biogeochemical cycles by, for example, increasing atmospheric CO_2 and nutrient availability.[35] Most of South Africa's indigenous grasses have the C_4 photosynthetic pathways (one that is most efficient in areas with cool, temperate climates and high altitudes), whereas most of the introduced grasses have the C_4 type (more efficient in warm tropical climates).[80] Increases in atmospheric CO_2 (amongst other changes) enhance the growth of species with the C_3 photosynthetic pathway more than species with other photosynthetic pathways, particularly the C_4 grass species.[80] This may favour the invasion of predominantly C_4 grasslands by C_3 grasses and woody species.[36] Heavy use of fertilizers and atmospheric pollution leads to increased nutrient deposition in natural ecosystems.[35] Invaders often benefit more from the increased nutrient levels than native species, particularly in nutrient-poor environments.[1,37–40] Some invaders also alter natural ecosystem processes in ways that facilitate invasions by themselves and/or by other species. For example, the nitrogen-fixing shrub *Myrica faya* invades grasslands on Hawaii, which lack native nitrogen fixers.[41] Nitrogen enrichment following entry of this species facilitates massive invasion of nitrophilous grasses.[42]

Fragmentation of the landscape

Fragmentation arises when patches of land are transformed. Transformed areas are rarely contiguous, typically resulting in a multi-scale mosaic of patches of natural ecosystems with high

perimeter-to-area ratios set in a matrix of transformed land.[43] The perimeter of the patches forms a transition zone, or ecotone, between the matrix and the patch and is often highly vulnerable to invasions.[44–46] The disturbance regimes in the patches are typically different from those in the unfragmented ecosystem, increasing their vulnerability to invasion[32,47], as discussed earlier. As patches get smaller they become increasingly exposed to external influences. For example, small patches will receive a greater load of fertilizers from adjacent farmlands than larger patches and this can alter limiting factors (see above).

Interactions

The four driving forces are inextricably linked and can operate individually or together to facilitate or to hinder invasions. Land transformation can affect a number of the driving forces simultaneously or differently over time. For example, there may be a delay between the establishment of a plantation and invasion of adjacent natural ecosystems by invaders inadvertently introduced during establishment and management of the plantation. Or land transformation from a natural to an industrial area can result in increased atmospheric deposition of a range of pollutants on the adjacent natural areas, potentially altering the limiting factors in the natural ecosystems. Human activities indirectly affect all four primary driving forces and thus we call these activities secondary driving forces. The following section explores the secondary driving forces and how they interact with each other and with the primary driving forces.

Secondary driving forces

We have identified 22 'secondary driving forces', which are those factors that influence the primary driving forces. We have grouped them according to whether they operate predominantly at the international or at the national scale. This distinction is important because those operating at the national scale can be dealt with by national bodies, whereas those operating at the international scale require international alliances and partnerships, which are inherently more difficult to direct. The secondary driving forces are explained below.

International secondary driving forces

- Human population growth and migration

Population increases lead to greater demands for food and materials. These demands are met by increasing productivity through fertilization, adoption of new species, and by increasing the area under production.[1,35,37,48] Where demands cannot be met, people tend to migrate, taking propagules of their customary food and medicinal plant species with them[31,49] and inadvertently carrying invasive species.

- Expanding network of international trade and travel links

The extent of international links, and therefore the number of potential invasion pathways, increased dramatically during the last century. Many of the significant invasions that originated through trade have been of marine organisms which are transported in ship ballast water,[50] but seeds of many plant species can be moved, for example, in containers, transport vehicles, soil or contaminated seed lots.[26,27] The desire of tourists for souvenirs has also increased the movement of undesirable species, particularly during the second half of the 20th century.[27] Since 1994, South Africa's importance as a hub for international trade and commerce with the rest of Africa has increased considerably.[51] Growth in inter-African trade and the associated infrastructure is a key element of the New Partnership for Africa's Development (NEPAD) initiative of the African Union.[52] If these developments come about, they will increase the quantity and variety of goods being traded and thus the risk of propagule movement.

- Increasing magnitude of international trade

As the volume of trade grows, the number of alien plants or propagules arriving in a country increases[53]. The enhanced propagule pressure increases the probability of the successful establishment of an alien species in the country to which it has been introduced[47]. It also increases the likelihood of sampling a greater genetic diversity of the new species and thus the potential fitness of an alien for its new environment.

- Globalization of economies

International trade is expanding and linking economies across the world ever more directly, a process known as globalization. Historically, most international trade was in products or commodities, but the past few decades have seen significant growth in non-commodity items and services such as direct monetary exchanges. An example of this is the financial trading mechanisms proposed under the Kyoto Protocol. These allow CO_2-generating industries to offset or reduce the proposed carbon taxes by establishing carbon banking or storage industries in other countries.[54] This could encourage developing countries to establish plantations of fast-growing tree species,[55] many of which are highly invasive.[56,57]

- Global economic trends

Recent events have demonstrated the vulnerability of the South African economy to turmoil in international financial markets, especially those of other 'emerging economies'.[58] South Africa has also opened, to some extent, its markets to trade and monetary flows, which has resulted in major fluctuations in monetary exchange rates. For example, changes in the rand–dollar trading rates have greatly increased the amount of money that South Africa has to spend on repaying international debts and for its arms procurement programme, reducing expenditure on other items, including invasive plant control programmes. The volatile exchange rates are also having a significant influence on sectors such as mining, agriculture and forestry. Farmers are being forced to experiment with new crops or abandon formerly cultivated land.

- Globalization of the forestry/agro-forestry enterprise

Commercial plantation forestry is a significant source of alien invasion. First, the tree species themselves are often highly invasive.[57] Second, forestry operations have often facilitated invasions through poor weed control in the nurseries,[59] and by transporting invader seeds on forestry machinery. Third, the growing demand for forestry products is leading to an increase in the area under plantations[60] and, therefore, in propagule sources. Agricultural and forestry enterprises are finding and testing new plant species and varieties with commercial value or potential. The exchange and trade in plant materials often involves species known to be invasive elsewhere in the world but this is ignored because of the perceived benefits of the 'miracle' plants.[27,31,56] Two lists of species recommended by South Africa's national forestry authority for fuel wood and agroforestry include taxa known to spread naturally[61] or to be invasive.[62]

Forestry need not facilitate invasions only. Environmental certification has been implemented by many forestry companies and requires them to limit the distribution of invader propagules and support control programmes for invasive plants.[63] The timber trade in many developed countries, for example the

United States and countries of the European Union, will not import products lacking this certification. A certified product will specify how that item was grown, and whether or not the product is invasive, where it was produced and what control measures were adopted.[64]

- Improved communication methods (Internet, global databases)

Modern communication methods such as the Internet may speed the flow of information on the useful characteristics of a plant, prompting horticulturalists and other users to import these species without first considering their invasiveness. Many websites already contain information on plants with agricultural, horticultural and herbal value, some of which are run by commercial companies.[65] There are also several organizations which specialize in studying and researching the commercial potential of agricultural crops and tree species — such as the Central America and Mexico Coniferous Resources Cooperative (CAMCORE), a body to which some commercial forestry companies in South Africa belong[66] — or the Consultative Group on International Agricultural Research (CGIAR), which includes 16 research centres worldwide, many of which specialize in agroforestry systems.[67]

This trend may be countered, however, by the growing number of global databases on problem plants and their control.[68,69] These databases are also used by organizations responsible for quarantining and screening imports, for example in Australia and New Zealand.[56,70] Several countries maintain websites which list their major invaders with information on how to identify and control them.[69,71,72] International e-mail groups (such as the Aliens-L list server maintained by the Invasive Species Specialist Group of the IUCN in Switzerland) share information on invasive plants.

- Growth and maturation of invasion ecology into a robust, predictive science

Although the SCOPE programme on invasive species led to substantial and significant advances in invasion ecology at national and international levels[13], it is still a growing science. The recently launched Global Invasive Species Programme[73] was motivated by new information on the enormous economic costs of alien invasions and their increasing pervasiveness[27,74]. Increases in our understanding of the processes of invasions and their impacts should lead to improved polices and laws, strategies for control, and methods for screening plants for invasive potential.

- Global climate change

Global climate change is highly likely to lead to more frequent and intense extreme events, such as droughts and floods, which will create severe disturbances in the affected areas.[75] Climate change can, therefore, have a direct effect on disturbance regimes — one of the primary driving forces of invasions. For example, floods disturb river banks and re-route water courses, providing recruitment sites for colonizing plants with water-borne propagules such as black wattle (*Acacia mearnsii*) and other invaders.[76–78]

The climates of areas may also change in ways that favour invasions. For example, humid areas tend to be more susceptible to invasions than drier ones and the same is true of wetter habitats in dry regions.[78,79] An increase in long-term rainfall in a region therefore is likely to result in an increase in the level of invasion. Similarly, regional warming may also lead to conditions for invaders becoming more favourable at higher altitudes. This could be the case for woody invaders on the escarpment and in the headwater catchments of both sides of the Drakensberg.[80]

Increases in atmospheric CO_2 are likely to have major impacts on invasions via several mechanisms. Enhanced CO_2 will alter the competitive balance between plants with the C_3 and C_4 photosynthetic pathways. The changed dynamics could favour invasions by C_3 grasses of our natural grasslands, which have so far proved to be remarkably resistant to such invasions.[80] Elevated CO_2 levels could also favour tree invasions in grasslands;[81] there is evidence that this is already happening with *Prosopis* in North America.[82] This could lead to bush encroachment by indigenous species and promote invasions by alien species; both outcomes will reduce the productivity of natural pastures, alter the water balance by increasing evapotranspiration, and change fire regimes.

- International treaties

Some international treaties and conventions, such as the Convention on Biological Diversity, which South Africa has ratified, address aspects of the problems caused by invasive alien species.[83] Most governments that have ratified these conventions lack the political will and resources to implement them effectively. South Africa is also a signatory to the World Trade Organization trade protocols and other trade agreements which encourage the free movement of goods, including invasive and potentially invasive organisms.[84,85] In some cases these trade agreements even prevent countries from controlling trade using the precautionary principle on issues such as the prevention of alien invasions.

National secondary driving forces

- Human population dynamics

Urbanization in South Africa increased rapidly after 1986, when laws controlling the movement of black people were abolished.[86] This is reducing the population in rural areas, particularly the economically active segment, leaving the children and elderly behind. The depopulation of these rural areas is decreasing the local demand for wood resources. HIV/AIDS infection rates, which are reaching 20–30% in some communities, are further reducing population growth rates.[6,86–88] People aged between 20 and 40 will be worst affected, leading to marked changes in livelihood strategies.[89] Rural depopulation, diversion of resources to caring for the sick and the loss of adult labour could all lead to abandonment of land and lower rates of wood-cutting, facilitating invasions.

- Economic trends

South Africa's economic performance is controlled primarily by the performance of the global economy (see *Global economic trends* above) and by the national economy's efficiency and stability and the level of good governance in the country.[90] A collapse in the gold price, for example, may lead to large-scale unemployment and therefore to increased disturbance and fragmentation of the land as people return to the rural areas to subsist.

A country with a strong economy has the resources to invest in infrastructure (see *Expanding infrastructure* below) and orderly and effective land reform (see *Post-apartheid transformation* below). It also can invest in research on methods of managing invasive species, for example through biological control. A weak economy restricts options and the ability to implement policies or enforce regulations. This driving force can, therefore, have either a positive or negative effect on invasions.

• Expanding infrastructure

The development of new infrastructure such as road and rail networks provides a vector for the transport of propagules along new routes.[12,91,92] Seeds carried by earth-moving and construction equipment, and in construction materials, also are a significant source of invasions. In addition, road and rail networks promote the movement of propagules in vehicles operating along these routes. Inter-basin transfers of water are a mechanism for the transport of invasive aquatic organisms.[83,93]

• Post-apartheid transformation

One of the stated aims of the post-1994 government is to conduct land reforms, in which there is a substantial movement of dispossessed people back onto the land and an increase in the number of individual black farmers.[94–96] This process could range from orderly to chaotic, depending on the manner in which the government conducts its operations and the resources available[97] (see *Economic trends* above). If the process is orderly, then there is a stronger likelihood of controlling invaders than if the process is chaotic.

• Changes in laws, policies and regulations

The government has recently promulgated new regulations for controlling invading plants[98] and there are initiatives to ensure that the relevant provisions of the Convention on Biological Diversity (see *International treaties* above) are realized.[99] A project to develop a National Biodiversity Strategy was launched during 2003. This initiative will address invasive species and feed into the planning for the National Weeds Strategy. Experience in Australia[100] shows that such strategies could lead to more coherence through integrated and effective policies, laws and regulations for all aspects of alien invaders.

• Changing agricultural practices

Increasing fragmentation of the landscape is likely as state land is made available to small farmers[96] and existing farms are subdivided to accommodate more people. This will change the regional mosaic, as there are shifts between subsistence and commercial agriculture. Subdivision is much more likely where the land is relatively fertile and there are good water resources. This will enable those settled on the land to make a living by farming cash crops without requiring large amounts of capital investment. Intensive use of the land in this way is likely to lead to a reduction in aliens.

The development of woodlots will encourage invasions. Where fertilizer use increases, higher nutrient loads will encourage invasion. While more people may be settled on the land, some traditional practises may not change — the storage of wealth in livestock may continue, but within a smaller area — leading to increased soil disturbance and hence scope for invasion.[101] Livestock exchange will continue to be a vector of seed movement. Land care policies and programmes are being developed and encouraged by the national and provincial departments of agriculture.[94,101] This will have a direct effect on the status of invasions as people realize the negative consequences of aliens and control them.

There is now a strong emphasis by biotechnology companies on the development of genetically modified organisms. One of the key concerns is the insertion into crops of genes for the production of insect and pest toxins and herbicide resistance.[102] There are conflicting claims about the biosafety of these organisms, and there are many concerns which have not yet been resolved.

• Options available for alien invader control

Alien plants can be controlled by mechanical clearing, use of herbicides and through biological control, or combinations of these. Biological control is one of the most cost-effective means of restricting invasive alien plants over 5–10 or more years.[103,104] Once the necessary agent has been released onto its target plants, little further investment is required. However, thorough research needs to be carried out before the agents can be released, delaying their deployment for several years.

Screening and quarantine protocols are an effective method for preventing invasive organisms from arriving in the country.[70] Phytosanitary controls are already in place in South Africa,[83] but local customs authorities lack the resources to search cargo containers, vessels, vehicles or personal baggage systematically. Screening is limited to commercial imports. There are signs indicating forbidden goods at customs entry points but there is little attempt to enforce such warnings. Compared with the comprehensive, strictly enforced and well-publicized systems adopted by Australia and New Zealand, the measures in South Africa are lax and ineffective. These systems require considerable investment and it is not clear what the South African government's intentions are in this regard.

An obvious way of controlling alien invaders is for landowners to control invaders on their own land. Innovative approaches are needed to help landowners realize that the expenditure is in their own best interest.

• Fire

Changes in land ownership patterns and use (for instance, tourism or recreation) could lead to an increased frequency and altered seasonal patterns of fire. However, the projected greater fragmentation is likely to prevent individual fires from burning over large areas. Changing climates could also alter fire regimes by raising temperatures or reducing rainfall, or both, thus extending the duration and risk of fires as well as their intensity.[105] Invasive trees and shrubs increase fuel loads and fire intensities and frequencies.[106,107]

• Afforestation (commercial forestry, agroforestry, social forestry)

The pattern of ownership of plantation forestry is changing. New plantations are owned and managed by small growers (family operations), unlike the extensive plantations owned and managed by multinational corporations.[108,109] One of the driving forces behind these changes is the requirement for more social investment by the big forestry companies, as well as the way in which afforestation permits are granted. The result of this may be less effective management of alien invaders because small owners may lack the resources to address invaders in a systematic manner unless they work together, which requires significant organizational effort.

The increase in the number of woodlots will result in more sources for the spread of propagules, and a bigger perimeter to area ratio (contact zone) with the natural vegetation. These characteristics favour the spread of invaders.[110] New regions are being exposed to invasions as the area of new land under plantations increases. Thus plantations are now expanding into the montane grassland areas of the Eastern Cape province, and may extend into the Wild Coast area of the Eastern Cape and KwaZulu-Natal.

More than a century of plantation forestry in South Africa has resulted in a long residence time for some major forestry species, allowing for acclimatization and some hybridization.[83] This, in conjunction with large planted areas, increases the potential of

an invader to capitalize on rare events that facilitate spread. Plantation forestry (and agriculture) involves the frequent movement of heavy machinery. This differs from road and dam construction, which typically is a once-off event. Seeds of problem invaders picked up with plantation soil are often transported over large distances. Riparian zones also become conduits for rapid dispersal of seeds out of forestry zones. On the other hand, the development of an informal economic sector based on alien plant species utilization may limit invasions. The use of Australian wattles (*Acacia cyclops* and *A. mearnsii*) for firewood[111,112] is an example of this.

• Changing perspectives and paradigms in nature conservation

The approach to wildlife conservation in South Africa has changed substantially over the past few decades. Conservation areas are no longer seen as inviolate sanctuaries which must be sustained in isolation from the surrounding areas and their human communities.[113,114] The new approach includes limited access to reserves for harvesting and use of materials like thatching grass, increasing the probability of moving propagules into conserved areas. Similarly, trans-frontier parks may promote cross-border movements of propagules, although the benefits from more coordinated cross-border control programmes may cancel detrimental effects.[115]

• Horticulture

Changing fashions continue to drive a demand for new species of flowers, trees, bushes and shrubs. The horticultural trade generally promotes alien species at the expense of indigenous ones.[116,83] Many plant nurseries are still selling species which have been declared weeds for several years.[117] A high proportion of the total number of invaders are ornamentals, barrier plants and groundcovers.[118] Smuggling seeds through phytosanitary controls increases the risk of introducing invasive species.

• Changing perspectives regarding alien plants

The attitude of the general public towards alien plants is changing as the impacts become more evident and information is more widely publicized. Cultures of 'non-tolerance', 'indigenous is better' and more precautionary approaches to introductions and cultivation practices are developing. Small, but vocal, groups of opponents of invasive-plant management programmes need to be engaged with a view to resolving conflicts of interest.

Interactions between forces

All the driving forces interact directly and indirectly with both the primary and the secondary driving forces and within and across the national and international contexts where they operate (Fig. 1). All the international secondary driving forces act indirectly via one or more of the national secondary driving forces to influence the primary driving forces for invasions. Only two of these international forces, human population growth and movements and global climate change, are likely also to have a direct effect on the primary driving forces of propagule arrival and changes in limiting factors, respectively. The influence of international human population dynamics and human activities as secondary driving forces in the international context is shown by the number of links which connect these secondary driving forces to each other and to driving forces in the national context.

In the national context, the key role of the driving force of national economic trends is emphasized by the network of connections linking it directly and indirectly to many other driving forces, particularly the agricultural, horticultural and forestry enterprises. There are also important and direct linkages with the expansion of infrastructure, human population growth and post-apartheid transformation. Economic growth, or the lack of it, will play a key role in determining the strength of these secondary forces as well as their direction.

Human population growth at the national scale is also impor-

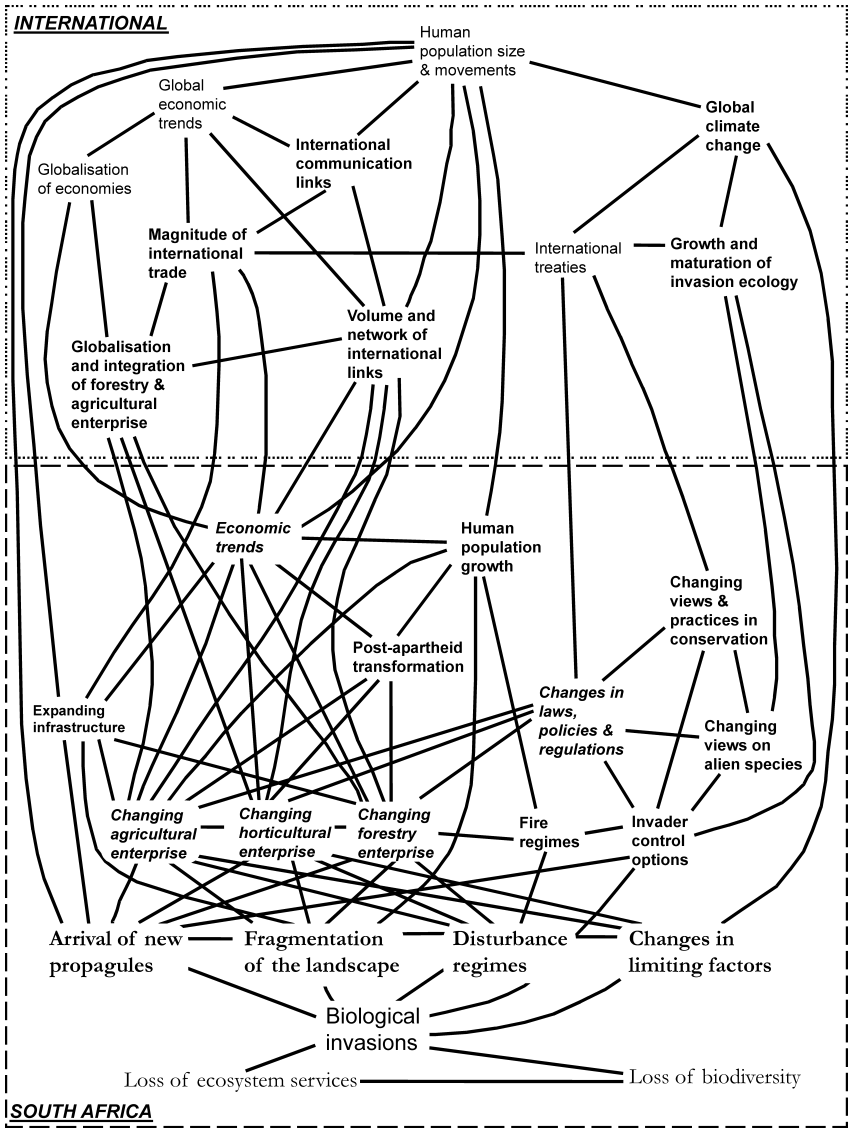

Fig. 1. A summary of the primary and secondary driving forces for biological invasions, illustrating their multi-dimensional nature and the main linkages which characterize their complex interactions.[119] The primary driving forces for invasion are shown in bold near the bottom of the diagram. The secondary driving forces, which operate internationally, are grouped in the upper half; those operating in the national context are grouped in the lower half. The more important and better-connected driving forces are shown in italics.

tant and has a significant effect on economic success. Rapid population growth diverts resources into the provision of infrastructure, facilities and services as well as increasing the need to provide more jobs. HIV/AIDS probably will reduce population growth rates and lessen the pressure but, at the same time, it will limit the most productive age group in the population and increase the demand for health and other social support services. It is difficult to determine the net influence of these complex and multi-directional linkages on invasions but they are likely to reduce the availability of resources to combat alien plant invaders.

Changes in national laws and regulations can play a critical role in determining the impact of agricultural, forestry and horticultural enterprises on invasions. Regulation to control the import, planting and management of known and potential invader species could minimize the adverse consequences of these industries. Poor economic growth could lead to policies which promote the use of any and all species in search of short-term benefits and result in significant environmental degradation and costs to the economy. However, policies, laws and regulations relating to invading plants will remain ineffective if the broad public does not understand why they are important and put pressure on their political, corporate and civil leadership to ensure that sufficient resources are allocated to implementing and maintaining them.

Although global climate is not directly linked to local fire regimes, it can have a significant impact by affecting plant growth, and thus fuel accumulation, and by changing the driving factors such as rainfall and dry periods.[41,120] This interaction would alter disturbance regimes, perhaps favouring invaders, as well as exacerbating the influences of changes in limiting factors.

Insights into invasion ecology have been used to develop screening systems[54,121] and new understanding is being gained from ongoing research.[20] But screening systems still have a high risk of identifying both false negatives (species that will be approved but can become invaders) and false positives (species that are rejected with a potential loss of economic benefits).[122] This makes these systems difficult to defend against powerful commercial interests or other national imperatives. Precautionary approaches are often unacceptable to politicians and commercial interests, especially in a country like South Africa, which urgently needs its economy to grow.

Uncertainty

This review has exposed some uncertainties which could play a decisive role in determining the future of invasions in South Africa. The root of these uncertainties lies in both the complex and diverse roles of humans as drivers of invasions and in uncertainties about the ecology of biological invasions. The key sources of ecological uncertainty include:

- Our poor understanding of the invasive ability and the adaptability of many invaders, and the importance of idiosyncratic factors — which weaken our ability to make reliable predictions and develop effective screening systems[16].
- The significant role that accidental introductions have played in the introduction of the most important invaders[1,27,35,123] means that there will always be unpredictable and unwelcome surprises. South African examples are the triffid weed (*Chromolaena odorata*) and Argentine ant (*Linepithema humile*) which apparently were introduced to South Africa accidentally in provisions during the Second World War and the Anglo-Boer War, respectively.[124,125]
- The significant role of time lags between introduction and noticeable invasions for several invaders implies that many species already introduced and in use may yet emerge as major invaders, perhaps triggered by unusual events.[126,127] A local example is red sesbania (*Sesbania punicea*) which was first noted as a rapidly spreading invader only 50–60 years after it was introduced.[126] The emergence of mesquite (*Prosopis* species) as a major invader appears to have been due to some very wet years and large floods in the Karoo during the 1970s and 1980s.[128] Hybridization between *Prosopis* species may also have played a role as the most aggressive invader is a hybrid form.[129]

Scenario planning offers a means for exploring the impacts of uncertainties and identifying key interventions that can help to shape the future of nations, organizations and people.[130] This makes the approach ideally suited to dealing with complex problems involving uncertainties about both ecological and socio-economic dimensions.[119]

The human dimension

Most research on biological invasions has focused on the biophysical aspects but there is growing realization that issues relating to invasive organisms cannot be dealt with solely by concentrating on these aspects.[15,123,131] Humans are both the cause of invasions and, potentially, the solution to the problem.[132] Choices about whether or not to control invaders are determined largely by culturally-shaped values and ethics.[131–133] The issues extend to, and almost always conflict with, national and international trade policies and practices.[15,85] The human dimension adds a new layer of complexity and uncertainty to an already multifaceted and rapidly escalating problem.

The complexities that can arise due to the way humans behave both individually and collectively have been touched on above. Even a cursory examination would highlight the importance of, for example, acclimatization societies and their desire to introduce species to make human colonists more at home in the new regions.[134] Many of the species introduced in this way were highly unlikely to succeed unaided in the new environment but became major invaders with human assistance. Examples include poplars, pines and eucalypts. Another example is the fashion-driven introductions of species for horticulture such as several of the less significant but still important Australian *Acacia* species, or the jacaranda and syringa, when South Africa already has a wealth of attractive ornamental tree species which are suited to the same environments. A more important problem is the introduction, promotion and poorly controlled dissemination and planting of 'miracle' species for use in land rehabilitation, community forestry and agroforestry.[85] Most of these species are highly aggressive and successful invaders, often with cultivars, races or genotypes specifically selected for traits favouring invasions such as abundant seed production, rapid growth (even in degraded environments) and vigorous coppicing.[135] There is a need for species suitable for growing under very adverse conditions, and also for multiple uses, but often the alien is favoured over the local for no apparent reason. In addition, little care is taken to ensure that there is any form of monitoring to detect and deal with unwanted invasions as early as possible. These examples highlight only some of the more direct roles; there are many other more indirect ways in which humans can facilitate or limit invasions.

Conclusions

Human value systems, and the acts and behaviour these give rise to, clearly have a significant influence on invasions.[31,49] The effects are expressed in many different ways, ranging from the

direct and deliberate introduction and cultivation of invasive species to the indirect effects of global climate change. Many of these acts began in prehistoric times, for example, the spreading of newly domesticated crops from the Middle East, but their scope and consequences altered dramatically during the colonial periods and have continued unabated despite the increasingly evident adverse effects on the ecosystem services that sustain our socio-economic systems[3].

The outcomes of the four primary driving forces — arrival of new propagules, changes in disturbance regimes, changes in the availability of limiting factors and fragmentation of the landscape — are influenced by human actions through a network of 22 secondary driving forces. The analysis of the network of links between these 22 forces, 10 acting primarily internationally and 12 primarily nationally, shows that some are more influential than others. The most powerful secondary forces are the movements of people and goods both nationally and across the globe, and human policies and legal systems which influence these movements.

Agriculture, forestry and horticulture are the most important activities driving the deliberate introduction of plant species and promoting their cultivation. This makes these businesses a key target for initiatives that seek to reduce the risk of invasions by preventing the introduction of invasive species or ensuring that these enterprises accept responsibility for managing the unwanted consequences of their propagation. Effective control and management of invasions cannot be divorced from the human dimension of invasions. Human value systems and ethics can both promote and control invasions. The outcome depends on how we, individually and collectively, respond to the challenges that invading plants pose to our well-being. The Working for Water programme has shown that the choice need not be whether to control invaders or create jobs and improve human well-being; both can be achieved simultaneously.

The most effective intervention prevents propagules arriving by establishing screening and early-warning systems. These only will work if people accept the need for the constraints they will place on the movements of themselves and their goods, and the associated costs. Australia and New Zealand have shown that a properly informed public will accept these constraints and costs. The challenge for South Africans lies in motivating the adoption of similar practices in a much more diverse society, and in a developing country which is not an island and, thus, is more easily invaded by species from adjacent countries.

This paper has shown that the human dimension is complex but tractable, and that a greater understanding of it is critical if we are to succeed in gaining the upper hand over the invasive species which threaten the well-being and livelihoods of all South Africans.

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