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Challenges and trade-offs in the management of invasive alien trees

Brian W. van Wilgen · David M. Richardson

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Abstract Over 430 alien tree species worldwide are known to be invasive, and the list is growing as more tree species are moved around the world and become established in novel environments. Alien trees can simultaneously bring many benefits and cause substantial environmental harm, very often leading to conflicts over how they should be managed. The impacts grow over time as invasions spread, and societal perceptions of the value of alien trees also change as understanding grows and as values shift. This leads to a dynamic environment in which trade-offs are required to maximise benefits and minimise harm. The management of alien tree populations needs to be strategic and adaptive, combining all possible management interventions to promote the sustainable delivery of optimal outcomes. We use examples, mainly from South Africa (where issues relating to invasive alien trees introduced for forestry have received most attention), to argue for holistic and collaborative approaches to alien tree management. Such approaches need to include bold steps, such as phasing out unsustainable plantation forestry that is based on highly invasive species, and in which the costs are externalised. Furthermore, it would be advisable to impose much stricter controls on the introduction of alien trees to new environments, so that problems that would arise from subsequent invasions can be avoided.

Keywords Biological invasions · Conflicts of interest · Ecosystem services · Economic assessments · Tree invasions

B. W. van Wilgen (✉)
CSIR Natural Resources and the Environment,
P.O. Box 320, Stellenbosch 7599, South Africa
e-mail: brianvanwilgen@gmail.com

B. W. van Wilgen · D. M. Richardson
Centre for Invasion Biology, Department of Botany and Zoology, Stellenbosch University, Matieland 7602, South Africa

Introduction

Conflicts of interest bedevil and complicate conservation efforts on many fronts. Such conflicts include direct competition for land (human utilization vs. conservation) and a myriad of "biodiversity versus X" permutations. A substantial proportion of conservation budgets are spent on addressing such conflicts or seeking ways to avoid them. Conflicts centred on alien (introduced) species present a particularly vexing category of conservation problem. Many of the most damaging invasive species in all groups were initially intentionally moved to the areas where they now cause problems. In many cases, such invasive species are still viewed as beneficial in at least parts of areas where they are invasive, and by particular sectors of society. The dimensions of the conflicts that arise and the options that exist for resolving these conflicts are highly taxon- and region-specific. Here, we explore the situation for invasive trees.

Invasive alien species are an increasing threat to biodiversity and ecosystem functioning in many parts of the world. Species from all taxonomic groups have been moved around the world, intentionally or accidentally, due to human activities. Some species in all groups have become invasive, spreading from sites of introduction to invade ecosystems in new regions, where a proportion of the species have undesirable impacts. The drivers and human dimensions of biological invasions are changing very rapidly, and each major group of invasive species poses particular challenges to ecologists and ecosystem managers.

Until fairly recently, relatively few tree species featured prominently on lists of the most widespread and damaging invasive species, but the picture is changing rapidly (Richardson and Rejmánek 2011). Thousands of tree species have been moved to areas outside their natural ranges where they are used for many purposes. Some species were introduced to new areas centuries ago, but the numbers of species being moved and the extent of plantings (for a growing number of purposes) has increased rapidly in the past century. A recent global review listed 434 species of trees that are known to be invasive (i.e. spreading over substantial areas in regions well outside their native ranges) somewhere in the world (Rejmánek and Richardson 2013). Species introduced for horticulture dominate the list (218 species), followed by those used in forestry (90), for food production (61) and in agroforestry (31). Many known invasive tree species are not yet invasive in some areas, contributing to a substantial "invasion debt" (sensu Essl et al. 2011). Hundreds of other tree species are naturalized and many of these will be added to the list of invasive species soon.

Trees differ from other invasive alien plant species in that they are relatively slow-growing, long-lived and large. They can come to dominate native vegetation, bringing about large changes to structure and processes, and impacting negatively on biodiversity. Unlike almost all other groups of invasive species, the majority of invasive trees are considered useful in some contexts and by some sectors of society in regions where they are spreading. They have wide appeal, and evoke emotional responses where control efforts are initiated (van Wilgen 2012; Dickie et al. 2014). The control of invasive alien trees is in some respects made easier because they are large and highly visible, making detection relatively simple, but because of their large size, control costs rapidly become prohibitive as the extent and age of tree invasions increases (Marais et al. 2004).

Many parts of the world have national, regional or local programmes for dealing with invasive species. Such initiatives usually include measures that target widespread invasive species, "emerging" invaders (those that still occur at lower densities or over limited areas and where eradication may be an option), as well as strategies for preventing the introduction and dissemination of new alien species that have a high risk of becoming invasive. Implementing such programmes in cases where the targeted species are both desirable resources and problematic invaders is a major challenge, and there are few if any examples of coordinated, high-level control programs that explicitly seek to achieve the best outcomes through appropriate trade-offs. For example, in New Zealand (where invasive alien conifers are a recognised problem), a recent review (Froude 2011) commented that "there is currently no national framework across all agencies within which to undertake prioritisation consistently so as to deliver greatest return on collective investment". In other regions, invasive trees are not considered a problem, or are not given priority in conservation planning (Richardson et al. 2008).

This paper examines the imperative for the sustainable and effective management of invasive alien trees, the options available for such management, current approaches that are being applied, and emerging challenges facing managers seeking to maximise benefits and reduce harm. The paper draws mainly on examples from South Africa, where issues associated with alien trees introduced for forestry appear to have received the most attention. The South African situation is arguably unique in that it is a largely treeless environment with a long (>350 years) history of colonization (accompanied by the aggressive introduction of trees) that has led to extensive and well-established populations of invasive alien trees (van Wilgen and Richardson 2012). We stress the need for developing, considering and implementing objective and defendable trade-offs when setting management goals, and discuss some promising developments towards this goal.

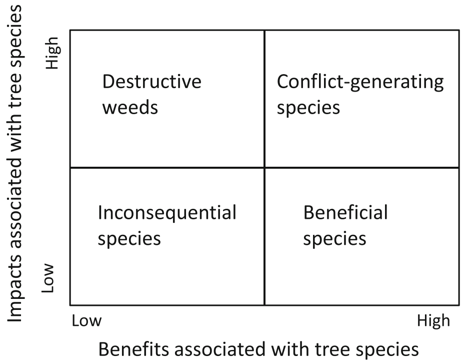

Fig. 1 Types of invasive alien trees based on their relative degree of impact on the environment and the benefits associated with their cultivation and utilization

Benefits and impacts of alien trees

Types of trees

The benefits and impacts of invasive alien trees vary in their type and magnitude, depending on the species, their invasive potential, the extent to which they have invaded, and the nature of the invaded environment. The magnitude of benefits and of impacts can be viewed as separate, independent continua, which allows for the classification of species into four broad types (Fig. 1). Many introduced tree species are not invasive, and are either inconsequential, as they have neither substantial impacts nor benefits, or beneficial in cases where they produce useful products, such as wood or fruit, or provide useful ecosystem services, such as sand stabilization or erosion control. Neither of these types is of relevance to this review, which focuses on invasive trees. It is important to note that the position of any species within this framework is dynamic. Crucial factors in this regard are the residence time and introduction effort (propagule pressure), but management interventions and changing socio-political conditions can also determine the position of species in this ordination space.

A few invasive alien tree species provide very little in the way of benefits. Such trees are easily classified as destructive weeds, and there is little disagreement with respect to any attempts to eradicate or contain such species. Because of the wide variety of uses of trees for humans, there are very few species that can be placed unequivocally in this category. Possible examples are *Acacia paradoxa* (Zenni et al. 2005) and *Solanum mauritianum*. The final type includes species that are both useful and invasive—it is these species that generate much of the controversy and conflict. Finding sustainable solutions to their management is a considerable and escalating problem. Prominent examples include species in the genera *Acacia*, *Casuarina*, *Pinus*, *Pseudotsuga*, *Populus*, *Prosopis* and *Salix* (Simberloff et al. 2010; van Wilgen et al. 2011; van Wilgen and Richardson 2012; Dodet and Collet 2012). The number of species falling into this category is increasing rapidly, since the initial benefits of many tree species become negated by the impacts when the species become invasive. With an increase in the area planted, the number of species planted and the time since introduction, the number of conflict situations is escalating.

Benefits

The benefits of alien trees that are both useful and invasive arise largely from two sources, timber production and aesthetic value and appeal. Between 2005 and 2010, planted forests, 25 % of which are introduced species, grew by 5 million ha to 264 million ha (7 % of the total global forest area). In addition, 100s of species of trees have also been moved to new continents and planted as ornamentals, sometimes in very large numbers. Other benefits include:

- *Food for humans* Most cultivated fruit trees are not invasive, but a few are, including *Ficus carica*, *Morus alba*, *Psidium guajava*, and *Eriobotrya japonica*;
- *Fodder for livestock* Many tree species, especially nitrogen-fixers, are widely promoted as sources of fodder for livestock around the world. Common examples include mesquite (*Prosopis* species), honey locust (*Gleditsia triachanthos*), white leadtree (*Leucaena leucocephala*), and carob (*Ceratonia siliqua*);
- *Carbon sequestration* Trees, especially forestry plantations, are often promoted as a means of carbon sequestration to offset greenhouse gas emissions (e.g. Wright et al. 2000);
- *Erosion control* Alien trees are used to ameliorate the effects of erosion, especially in degraded areas, in many parts of the world (e.g. Jensen Augustine et al. 2006; Phillips et al. 2013);
- *Agroforestry* The use of trees to promote rural development by providing a range of previously

unavailable options for food and fodder is widely promoted in developing areas (e.g. Leakey et al. 2005);

- *Energy* Alien trees can be a significant source of energy for household cooking and heating in rural areas, although data on these uses are scattered and incomplete (Wise et al. 2012); and
- *Conservation* The protection of threatened species by planting them outside of their native ranges. Many species of northern hemisphere coniferous trees have been established in plantations for ex situ conservation purposes (www.camcore.org; accessed 6 May 2011). The threatened New Zealand Christmas tree (*Metrosideros excelsa*) was also widely promoted for establishment in South African coastal areas (ironically as a non-invasive substitute for *Leptospermum laevigatum*) until it was found to be invasive (Richardson and Rejmánek 1999).

Impacts

Alien trees also have substantial impacts on the ecosystems that they invade (Richardson and Rejmánek 2011). They can radically change vegetation structure, converting grasslands and shrublands into woodlands or forests. These changes alter nutrient cycling, hydrology and fire regimes, and impact negatively on native biodiversity. In South Africa, the main concern relates to the impact that invasive trees have on water resources. Currently, invasive alien plants (mainly trees) are estimated to be reducing surface water runoff in South Africa by 7 % (Le Maitre et al. 2000; Görgens and van Wilgen 2004), but the potential reductions would be more than eight times greater if invasive alien plants were to occupy the full extent of their potential range (van Wilgen et al. 2008). Invasive alien trees also have severe negative effects of grazing resources, and thus livestock production, and on native biodiversity (van Wilgen et al. 2008). Because of their large size and high visibility, invasive trees can have substantial visual impacts which may affect tourism values in many parts of the world.

Changes over time

The net value of tree species that initially provide benefits, then later become invasive and spread, changes over time. Usually, introduction and widespread planting is followed by a period in which the net value is positive, arising from harvested products or other benefits associated with trees (Fig. 2). However, in cases where the species become invasive, benefits are eroded as the impacts of invasions grow, and net values become negative. The picture differs for different species, and even between species in the same genus (Fig. 2). For example, most Australian *Eucalyptus* species have not become aggressive invaders in South Africa, with the notable exception of *Eucalyptus camaldulensis* which aggressively invades riparian areas (Tererai et al. 2013). The situation also varies geographically, with *Pinus* species in South Africa being particularly problematic as invaders in Mediterranean-climate fynbos shrublands, but not yet as problematic in grassland areas. Attitudes also change over time as values and priorities change, and as unforeseen impacts begin to manifest themselves. For example, the initial reasons for introduction (to beautify, or to add new options for timber, fruit and fodder) are being replaced with national pride (Robin and Carruthers 2012), by drives to plant indigenous rather than alien species, and by the rise of a conservation ethic focussed on biodiversity conservation that followed the Earth Environmental Summit in Rio de Janeiro in 1992. Attitudes can become polarized, especially between those with vested interests in growing trees or trading in their products, and conservationists. Opinions are also influenced by messages that oversimplify a complex issue. On the one hand, there are widespread beliefs that all trees are desirable, because they are perceived to promote rainfall, stabilize catchments, sequester carbon, and provide shade and habitat for wildlife. On the other hand, alien invasive trees are depicted as undesirable because of their impacts on biodiversity and ecosystem services (van Wilgen 2012). The balance of opinion between those holding opposing views is also constantly changing, adding to the complexity of the issue.

Dealing with invasive trees

The control toolbox

Successfully and sustainably maximising benefits and minimizing the impacts of invasive alien trees

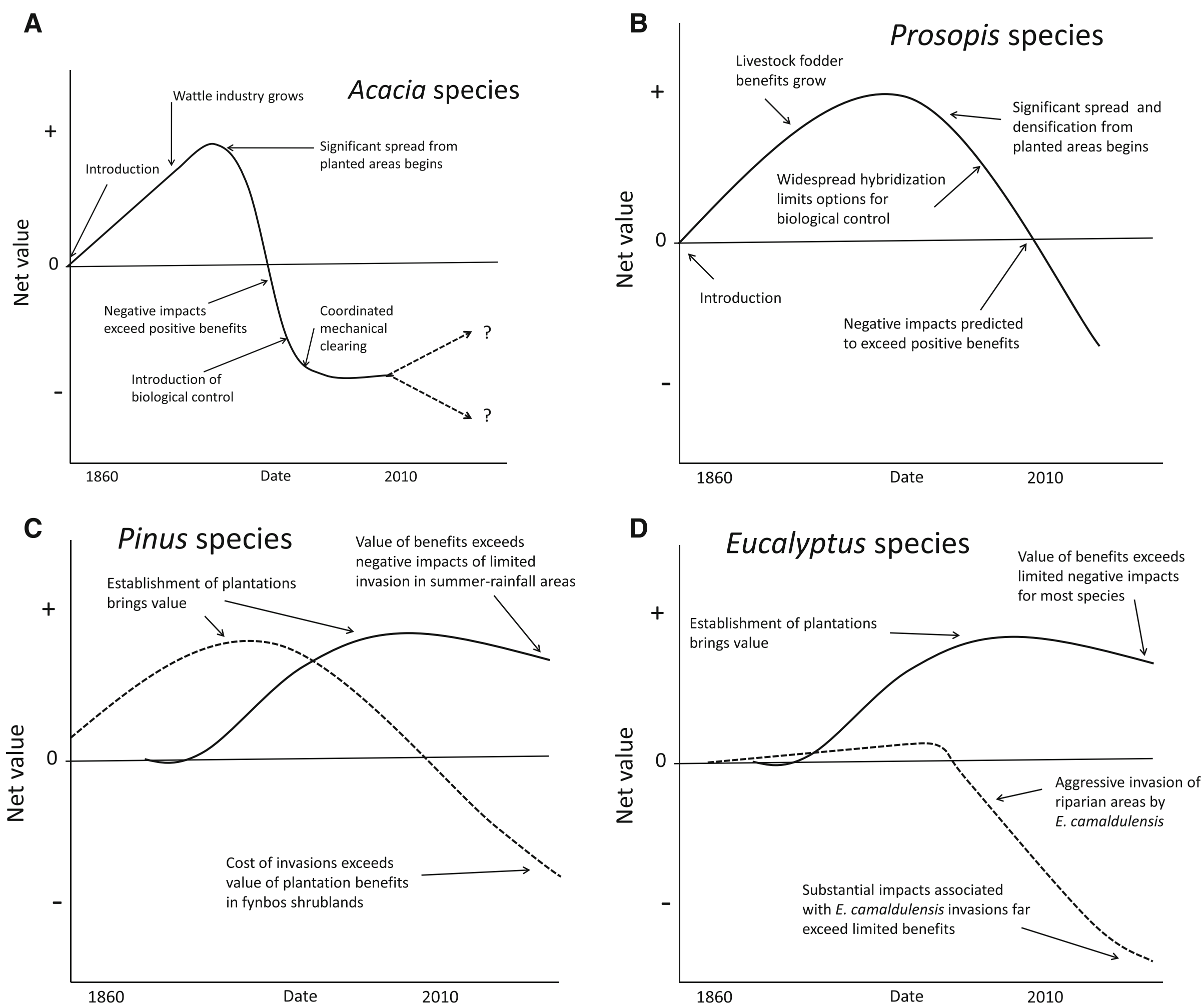

Fig. 2 Conceptual illustrations showing changing net values (sum of benefits minus sum of impacts) over time associated with alien tree species in South Africa. The illustrations show: **a** trajectories for *A. mearnsii* (possible future scenarios are indicated by *dashed lines*; after van Wilgen et al. 2011), **b** the trajectory for *Prosopis* species (derived from Wise et al. 2012), **c** the trajectory for *Pinus* species in summer-rainfall areas (*solid line*) and in winter-rainfall areas (*dashed line*) (derived from information in van Wilgen and Richardson 2012), and **d** the trajectory for *E. camaldulensis* (*dashed line*), and other *Eucalyptus* species (*solid line*) (Forsyth et al. 2004)

would require the development and implementation of integrated strategic approaches to management. Van Wilgen et al. (2011) proposed such an approach for the management of invasive alien *Acacia* species. The approach called for the grouping of invasive species into categories defined by their potential value (ability to generate benefits), and the degree to which they have become invasive. For each category, an appropriate mix of available management approaches (Table 1) should be employed to maximize their effect. When used in suitable combinations, the prospect of achieving optimization would be maximized. This generalised scheme could be adapted for all invasive tree species, where appropriate combinations of control options could be applied to different groups depending on their net value and the stage of invasion. As the outcomes of management cannot be accurately predicted, van Wilgen et al. (2011) suggested that management should be adaptive, with continuous monitoring and assessment, and realignment of goals if necessary. The most problematic cases would include those where the costs of control exceed the cost of impacts, and where the return on

Table 1 The toolbox of options for the management of invasive alien trees

Management option	Goal	Notes and key references
Risk assessment	Reducing the risk of introducing potentially invasive trees or assessing the risk of different management interventions at any stage of the introduction–naturalization–invasion continuum	Protocols for screening potential new introductions to determine the risk of them becoming invasive are now widely applied to alien trees in the literature and the formal application of these models is increasingly required as part of national legislation for the management of invasive species (Auld 2012)
Eradication	Complete elimination of species that have limited distribution ranges in the new environment	Eradication is possible in many cases, but we know of no clearly documented cases of the eradication of an alien tree. Several objective assessments of eradication feasibility have been published recently (Zenni et al. 2005; Moore et al. 2011; Kaplan et al. 2012, 2014)
Containment using mechanical and chemical control, and fire	Reducing invasions and their impacts	Can be effective at limited spatial scales, but unsustainable (except perhaps in selected priority areas) when populations reach advanced stages of invasion and occupy large areas, unless combined with effective forms of biological control (Moran and Hoffmann 2012; Fig. 4)
Biological control to reduce seed output	Reductions in rates of spread	Biological control to reduce seed output has been successful for Australian *Acacia* trees, but less so for *Prosopis* trees, in South Africa (Moran et al. 2005; Klein 2011). In one study (Le Maitre et al. 2008), it was estimated that biological control agents have reduced the seed loads on *Hakea* shrubs by more than 95 %. This reduced population growth rates, maximum seed dispersal distances and the formation of new invasion foci, which in turn would have increased the overall effectiveness of mechanical control (Fig. 4)
Biological control to damage or kill plants	Reductions in vigour, and population size	This has only ever been attempted on invasive alien trees that have no commercial or other perceived value, for example *Acacia saligna* in South Africa, where the introduction of a pathogenic fungus has resulted in extensive damage to the plant, and has brought about a substantial degree of control (Impson et al. 2011; Klein 2011)
Payment for ecosystem services	Sustained funding for ongoing mechanical and chemical control	Water utilities in South Africa are willing to pay for clearing of invasive trees in their catchment areas to protect water resources (Turpie et al. 2008)
Harvesting from invasive plant populations	Increased benefit from (and reductions of) invasive populations	Some proponents of the use of alien trees suggest that utilization of invasive populations can contain spread (Borokini and Babalola 2012), but this has not been demonstrated in practice. Although it seems logical to utilize the products of alien tree control programs, a problem is that such projects lead to the development of new markets and a dependency on the invasive species (Macdonald 2004)
Development of sterile trees	Elimination or at least marked reduction of invasive potential of commercially-farmed species	Several options exist for inducing sterility in commercially farmed trees (Strauss et al. 1995). This technology is extremely expensive and has yet to be shown to offer a clear solution to the problem of seed pollution Achieving total sterility of every single individual in large plantations is highly unlikely

Table 1 continued

Management option	Goal	Notes and key references
Prioritization of phases of management and/or areas	Maximising efficiency by focussing control effort on those parts of invasive populations where intervention is most cost-effective, or selecting areas with greatest impacts and/or where the chance of control success is greatest.	Many modelling studies have identified the most effective intervention strategies for invasive trees (Higgins et al. 2000; Krug et al. 2010; Roura-Pascual et al. 2010). Spatial prioritization could be effective at large spatial scales where multiple alien plant control projects are funded from a single source, and where funds could be allocated to priority projects (Roura-Pascual et al. 2009; Forsyth et al. 2012). Prioritization can also lead to conflict in cases where there is not agreement on the criteria used for prioritizations (van Wilgen et al. 2012a)
Education and awareness	Increasing broad support for control, and reducing the risk of unintentional actions that would promote spread	This could improve broad societal support for alien tree clearing projects, but is challenging given the range of perceptions about the (real or imagined) positive features of trees (van Wilgen 2012; Dickie et al. 2014)
Voluntary certification	Sustainable management of forest resources, including plantations of alien trees. Certification provides consumers of forest products with reassurance that these products come from sustainably-managed plantations	Prominent certification schemes discourage or disallow the use of trees that are invasive, but this clearly does not work as many plantations of demonstrably invasive trees species have been certified (Schepers 2010; World Rainforest Movement 2003). Criteria for certification need to be substantially revised to deal with the multi-facetted threats associated with invasiveness of forestry trees, giving due cognisance to the complexities of globalized forestry enterprises (Le Maitre et al. 2004)
Legislation	Defining responsibilities for control at a landscape scale, and placing additional responsibilities on growers who use invasive species	Legislation can be useful for persuading or requiring landowners to manage invasive alien trees, but it is largely ineffective because: there is often insufficient capacity to police implementation; invasive trees are difficult and often prohibitively expensive to control; and in some cases (e.g. South Africa) the state is the biggest offender
Management of invaded habitat as a "novel ecosystem"	Ensuring the continued and sustainable delivery of key functions and services, in some cases accepting that invasive species fulfil useful purposes, especially where conditions are modified to the extent that the return of native species is unrealistic	Where habitats have been substantially modified through multiple human factors, removing invasive alien trees and restoring native-dominated communities and ecosystem functions is sometimes either impossible or undesirable. For instance in riparian ecosystems in many parts of the world that are heavily invaded by alien trees, physical conditions have been modified to such an extent that native elements can no longer establish or survive, even when the invasive trees are removed. In such cases, manipulating of the density and abundance of key alien species to achieve desired ecosystem functions and services is an appropriate, pragmatic management goal (Richardson et al. 2007)

investment from control operations would be negative (Fig. 3). In such cases, a common response is to continue (often ineffective) control operations in order to be seen to be "doing something" in what has been termed a "strategy of hope" (van Wilgen et al. 2011). A more appropriate response may be to identify those areas where the return on investment from control would still be positive, and to restrict control operations to such high-priority areas. The other category of problem is that where high value is obtained from species that simultaneously cause high levels of impact. In such cases, entrenched interests make it extremely difficult to deal with the problems of invasion, even if the overall benefits would be positive. Possible responses could include phasing out productive cultivation in areas where the impacts are particularly high, finding ways of internalising the (currently externalised) negative costs, or switching to sterile cultivars or non-invasive species (van Wilgen and Richardson 2012).

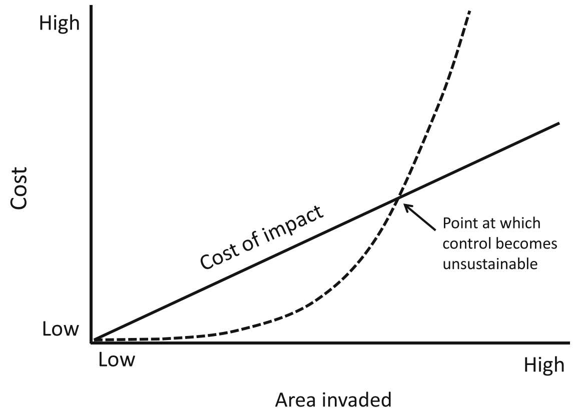

Fig. 3 Hypothetical representation of increases in the costs of impact, and the costs of control, associated with alien tree invasions. The cost of control increases exponentially as the invaded area and the density and size of trees increase. Control becomes economically unsustainable at the point at which the costs of control are exceeded by the costs suffered as a result of invasion

Effectiveness of control

Invasive alien tree control programs are in their infancy worldwide, with relatively few examples of outstanding successes. Australia has adopted a focus on the control of Weeds of National Significance (WONS), and of 32 WONS targeted to date, six are trees (*Parkinsonia aculeata*, *Jatropha gossypifolia*, *Mimosa pigra*, *Prosopis* species, *Salix* species, and *Vachellia nilotica*; http://www.environment.gov.au/biodiversity/invasive/weeds/weeds/lists/wons.html). Mechanical and chemical control programs against WONS trees have had limited success in Australia, while biological control has been implemented for three species, and is under consideration for two more. In South Africa, invasive alien trees in 17 genera (*Acacia*, *Casuarina*, *Eucalyptus*, *Jacaranda*, *Leptospermum*, *Melia*, *Metrosideros*, *Morus*, *Pinus*, *Pittosporum*, *Populus*, *Prosopis*, *Psidium*, *Robinia*, *Salix*, *Schinus*, and *Solanum*) were classified as either abundant or common by Nel et al. (2004). Of these, 16 species have been subjected to biological control, and in six cases (five Australian *Acacia* species and the closely-related *Paraserianthes lophantha*) the level of control achieved has been substantial (Klein 2011). However, mechanical and chemical control efforts against other species, although often quite large, have not been very effective (with localised exceptions), unless combined with effective biological control (van Wilgen et al. 2012b). For example, Moran and Hoffmann (2012) reported that combining mechanical and biological control resulted in a substantial decline in the abundance and/or aggressiveness of most of the targeted trees. Attempts to control species that have commercial value (such as most forestry trees) can be difficult to implement. For example, proposals to introduce seed-reducing biological control onto *Pinus* species in South Africa had to be abandoned when it was suggested that this could promote the spread of pitch canker (Lennox et al. 2009). In other parts of the world, invasive alien tree control programs are either non-existent, or are severely hampered by restrictions on permitted control methods (for example, in most European countries, the use of biological control and herbicide applications on trees is simply not permitted). While it is frequently suggested that the promotion of commercial utilization of invasive trees could help to gain control of invasions (Borokini and Babalola 2012), we are not aware of any convincing examples of where this has succeeded.

Managing conflict and making trade-offs

Alien trees as a source of conflict

Human influences on the Earth's ecosystems are growing exponentially, bringing increasing pressure on ecosystem goods and services, and adding to the urgency of finding ways to adequately conserve biodiversity. As competition for diminishing resources increases, conflicts arise over how ecosystems should be managed. Such conflicts need to be carefully managed if durable and positive outcomes are to be found (Redpath et al. 2012). Young et al. (2010) recognised six broad categories of conflict (conflicts over beliefs and values; conflicts of interest; conflicts over process; conflicts over information; structural conflicts; and inter-personal conflicts). Examples of most if not all of these categories can be found in the conflicts that characterise the management of alien trees. Many people value all trees, and believe they are good, while others recognise the impacts that invasive alien trees can bring about, and subscribe to value systems that would rather promote indigenous trees over alien trees, for reasons of compatibility with a conservation ethic, national pride, or a desire to avoid negative impacts. There are numerous conflicts of interest when it comes to the management of alien trees. These include, for example, the secular interests of timber growers, or nursery operators, as opposed to those of conservationists (van Wilgen and Richardson 2012); conflicts between those who wish to sequester carbon (which demands extensive tree-planting) as opposed to those who wish to reduce negative impacts on water resources and on biodiversity (Allen et al. 1997; Jackson et al. 2005; van Wilgen and Richardson 2012); and conflicts over whether or not it is appropriate to use trees to promote rural development (Akabwai 1992; Cohen 2005; Zeila et al. 2004), for example, the use of *Prosopis* trees in arid parts of Africa is particularly contentious (Maundu et al. 2009, Wise et al. 2012). Conflicts around information often arise because good data on distribution and impacts are lacking, and because predictions of future impacts are of necessity based on models that make assumptions, and can therefore be challenged.

There may, however, be other types of conflict that are specific to the invasive alien tree problem. Plantation forestry is promoted as a beneficial form of land use that produces valuable timber, creates employment, and contributes to the economy in regions where it is practiced. However, where the plantation species are invasive, these effects are generally not taken into account (externalised). Owners or managers of land adjacent to these plantations suffer the consequences of invasion, leading to conflicts over responsibilities for dealing with invasions. In the case of South Africa's fynbos biome for example, invasive pine trees are predicted to reduce water yields from invaded catchments substantially, thus impacting on the prospects for economic growth in this water-constrained region (van Wilgen and Richardson 2012). When considered at a spatial scale larger than the plantation itself, it is possible that the overall value added by plantations would be exceeded by the value of lost water. In such cases, phasing out plantation forestry (thereby substantially reducing propagule pressure) could deliver the best outcome in economic terms. There is of course disagreement over the estimates of value and impact, because data are lacking, misunderstood, or perceived and interpreted in different ways, and the levels of confidence in predictions of future impact can be contested. Suggestions that consideration be given to systematically phasing out plantation forestry in areas where the trees are highly invasive (van Wilgen and Richardson 2012) predictably sparked strong reactions from the forest industry (Wild 2012). There may also be conflict over who should be held responsible for invasions. For example in South Africa, forestry plantations were initially established by the government, but later taken over by the private sector, who point to the fact that invasions were in place before they assumed responsibility for the plantations (the situation is the same in New Zealand, where older plantations are referred to as "legacy plantings", N.J. Ledgard, pers. comm.). Whether or not plantings should be removed altogether to remove propagule pressure and increase the chances of gaining control of invasions is also contentious, as the effectiveness of the measure cannot be predicted with any level of confidence.

The use of biological control against invasive alien tree species is another potential source of conflict. The use of biological control against invasive Australian *Acacia* species with economic benefits has been restricted to insects that do not damage vegetative plant parts (Dennill and Donnelly 1991). It took many years of negotiation with the wattle industry before they accepted that these releases would not harm the industry. South Africa remains the only country that has introduced biological control against Australian *Acacia* species (Impson et al. 2011), even though they are problematic in many parts of the world (Richardson et al. 2011). Research into the use of seed-feeding insects against pines was abandoned because of concerns expressed by the forest industry, although this may be reconsidered in the light of evidence regarding the impacts of invasive pines (Hoffmann et al. 2011). Biological control of invasive *Prosopis* species in South Africa has been similarly restricted to seed-feeders in the light of the perceived value of the pods as fodder for livestock, but these have proved to be inadequate for effective control (Zachariades et al. 2011). Recent predictions that the economic value of *Prosopis* in South Africa will be exceeded by the negative impacts (Wise et al. 2012) have brought about a re-examination of the policy of restricting biological control to seed-feeders alone, but other African countries remain reluctant to consider these options (A. Witt, pers. comm.).

Formulating trade-offs

The goal of ecosystem management should be to maximise benefits and minimise harm. Initially, alien trees were introduced as a source of timber and other products in a landscape where trees were rare. They thus added benefits, but (as outlined above and in Fig. 2) benefits were eroded over time, values have changed, and opinions on the way forward are polarised. Clearly, if progress is to be made, people will need to make trade-offs in the interest of achieving the most beneficial outcome for the most people. In South Africa, some attempts have been made to quantify the costs and benefits of alien invasive trees, with a view to informing policy decisions on the matter. For example, De Wit et al. (2001) provided an analysis of costs and benefits associated with black wattle (*Acacia mearnsii*) in South Africa at a national level, and concluded that a scenario in which no attempts were made to control the spread of the species beyond the limits of plantations was not sustainable. They found further that the most attractive control option would be to combine physical clearing and plant-attacking biological control, while at the same time continuing with commercial growing activities. Wise et al. (2012) estimated that the net economic value of mesquite trees (*Prosopis* species) would soon become negative under prevailing scenarios of spread, and that more effective control methods, such as biological control, would be needed to prevent substantial economic losses. Similarly, van Wilgen and Richardson (2012) reviewed the history of conifer introductions to South Africa and the benefits and impacts with which they are associated. They suggested that different approaches should be considered, including the systematic phasing out of commercial forestry in zones where it delivers low returns, and the introduction of more effective, focussed and integrated, region-specific approaches to the management of invasive conifers. Implementing any of these recommendations, given their controversial nature, would have to be based on a high level of confidence that the outcomes would be more beneficial than harmful. That would in turn require broad societal agreement on the common goals of ecosystem management, a transparent assessment of all costs and benefits by recognised experts, a willingness to agree on acceptable trade-offs, and political courage to implement the bold steps that would be needed to achieve sustainable goals.

Future challenges

A number of steps have been taken to address alien tree invasions in South Africa and elsewhere (Table 1), including legislation to regulate the growing of invasive trees, government-funded, national-scale clearing programs (van Wilgen et al. 2011), systems for the payment for ecosystem services (Turpie et al. 2008), and certification aimed at promoting the sustainable management of alien tree crops (FSC 2000). It is becoming apparent, though, that these interventions are, by and large, not achieving the desired results. The legal requirements to control the spread of invasive tree species grown for profit are neither adhered to nor adequately enforced, because growers and government do not have the necessary resources to do so (van Wilgen and Richardson 2012). Government-funded clearing programs in South Africa have only been able to reach a small percentage of tree invasions despite significant spending (van Wilgen et al. 2012b; McConnachie et al. 2012), and as a result trees continue to spread, sometimes at rapid rates. Systems that utilize payment for ecosystem services to support clearing projects have not gained widespread use. Much has been written about the use of certification schemes (such as the Forestry Stewardship Council, FSC 2000) to encourage forestry companies to manage plantations on a sustainable basis (Auld et al. 2008; Marx and Cuypers 2010; Schepers 2010), but these typically do not address the issue of invasive trees, although several certification schemes explicitly require this.

In reality, it would be naive to expect landowners to abandon lucrative forestry plantations for the greater good. Similarly, in democracies at least, it is difficult for governments to justify policies to phase out plantation forestry when growth and employment are needed to maintain economic activity in the immediate short term, even if such policies would pay dividends at a later stage. However, unless the situation is addressed more effectively, the consequences in terms of escalating impacts will in many cases be serious for economic prospects, ecosystem services, and biodiversity protection. New demands, for example to use trees as a source of biofuels (Davis et al. 2010) or for carbon sequestration (Jackson et al. 2005), have added further complicating aspects to the debate about the environmental value of invasive alien trees. Strong vested interests and dependencies combine with the ongoing practices of externalising costs, and the emergence of new and pressing needs for timber products, to create an environment in which it will be very difficult to prevent or reduce the impacts of alien tree invasions. While invasion biology has made significant strides over the past few decades, it still lacks accepted laws and principles that could underpin accurate predictions of future invasions and impact (Richardson 2011). Invasion biologists have already sounded warnings in the peer-reviewed literature of the potential consequences of the rapid expansion of plantation forestry based on invasive alien trees (for example in South America, Richardson et al. 2008; Simberloff et al. 2010), but this is not enough to precipitate action. Invasion biologists should therefore strive to work with others to find and implement solutions.

Effectively dealing with alien tree invasions would require the adoption of a strategic and holistic approach that considers the use of all available interventions in an effective, integrated way (van Wilgen et al. 2011; Fig. 4). In addition, if win–win solutions (*vide* Redpath et al. 2012) are to be found, it will be imperative to involve all stakeholders in discussions about concerns and possible solutions. Such discussions should in turn be informed by in-depth assessments characterised by extensive, transparent review process by both experts and stakeholders. In such assessments, authors are encouraged to provide their own expert judgements when the data are sparse or equivocal (as long as these judgements are clearly identified as opinions), with checks and balances in place to ensure that all reasonable viewpoints are fairly reflected. Assessments also include explicit evaluation of the uncertainties on key issues, either quantitatively in terms of probability ranges or qualitatively. In the process, it will also be necessary for all parties to be willing to make trade-offs for the greater good.

Finally, experience suggests that there are no guarantees that invasions from new introductions can be effectively managed, or their impacts reasonably

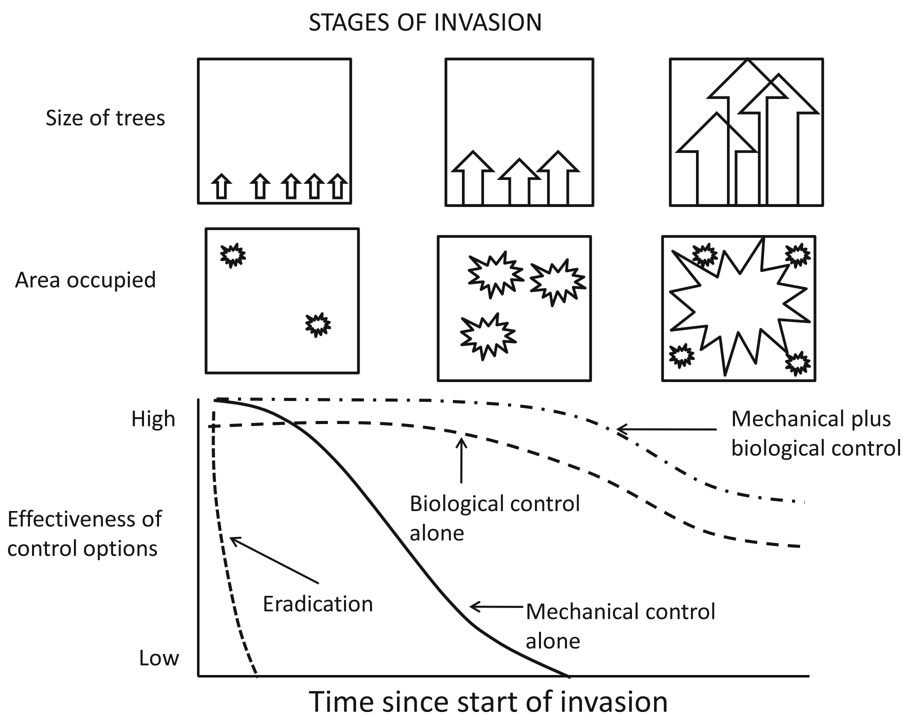

Fig. 4 The stages of invasion by trees, and the corresponding effectiveness of different types and combinations of control options. Eradication is only an option when tree populations are localised and the trees themselves are small. Mechanical control (in combination with appropriate forms of chemical control) can be effective in the early stages of invasion, but biological control offers the only effective and sustainable form of control in the long term. Biological control is seldom completely effective in the absence of other forms of control, and combinations of biological and mechanical control have provided the most effective control combination in some cases where it has been implemented on a large scale

mitigated, and it would be extremely prudent to take a conservative approach when considering any new introductions. Some key lessons have arisen from experience with commercial forestry and agroforestry (Richardson and Blanchard 2011), and these need to be built into approaches to deal with introductions of new trees. It is known that some species are inherently better invaders than others (particularly those that are prolific seed producers), suggesting that potential invaders can be identified and avoided.

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