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Managing wilding pines in the Cape Floristic Region, South Africa: Progress and prospects

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ABSTRACT

The occurrence and continuing spread of wilding pines (genus *Pinus*) in the Cape Floristic Region (CFR), South Africa, impacts negatively on water resources, threatens the region's rich biodiversity, and increases the damage caused by uncontrolled wildfires. The invasive potential and threat of wilding pines has been regularly reported since the 1940s, leading to the development and implementation of various control strategies. The last substantial review of pine invasions and their management in the CFR (in 2012) recommended several actions, including securing more sustainable funding and adopting alternative control methods. We review the last 12 years of wilding pine research and management in the CFR, and provide updates on spread and impact, government funding, payments for ecosystems services initiatives, and contributions of the South African Forest industry. We note an increase in private funding, specifically to address invasion in priority catchment areas in the Greater Cape Town region, as well as a recent decline in government funding. Steps have also been taken to revive research aimed at biological control of pines originating from the Iberian Peninsula. The forest industry has deployed species with lower fecundity in some parts of the CFR and has also started experimenting with hybrids that could potentially be less invasive. New methods for applying herbicides may prove to be more efficient than currently used methods. We discuss five opportunities for addressing current shortcomings in the management of wilding pines, namely broadening sources of funding to increase sustainability, effectively integrating all available management techniques, accommodating the need for commercial forestry, focussing scarce funds on priority areas, and raising awareness. We stress that failure to contain rampant invasions by wilding pines will have far-reaching consequences for conservation in the CFR.

1. Introduction

The genus *Pinus* (Pinaceae) comprises approximately 111 species subdivided into the fire-adapted, hard diploxylon sub-genus *Pinus* and the soft haploxylon sub-genus *Strobus* (Gernandt et al., 2005). In South Africa, more than 80 *Pinus* spp. have been introduced since the 1600s

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and 57 are considered invasive or potentially invasive (van Wilgen and Richardson, 2012). Current regulations under South Africa's National Environmental Management: Biodiversity Act (Act 10 of 2004) (NEM: BA) list eight *Pinus* species as invasive. Despite attempted management spanning decades, wilding pines continue to spread in South Africa, particularly in the Cape Floristic Region (CFR) (van Wilgen et al., 2020).

The CFR covers about 90 000 km^2 from Nieuwoudtville southwards to Cape Town and then eastwards to Makhanda. Dominant vegetation types include fynbos and renosterveld shrublands, Afrotemperate forests, and short shrublands in the arid karoo (Rebelo et al., 2006). Fynbos is the dominant vegetation type in the CFR but covers only 6% of South Africa. The CFR accounts for over a third of South Africa's floral diversity (9383 plant species), with 68.3% of the species being endemic (Manning and Goldblatt, 2012). One of the main threats to fynbos is invasion by alien trees and shrubs, including *Pinus* species (Richardson et al., 2020). Fynbos requires regular fires for its persistence (van Wilgen et al. 2010), but fires also trigger the release and spread of wind-dispersed winged seeds from serotinous cones on pine trees, resulting in the spread of *Pinus* species (hereafter wilding pines). Over several decades, wilding pines have transformed large parts of the CFR into woodlands or forests dominated by *Pinus* species (Richardson and Higgins, 1998; van Wilgen et al., 2016).

Due to the recognised impacts of pines, the government has initiated control efforts since the 1970s. Control was initiated in the CFR by the then Department of Forestry (van Wilgen and Richardson, 2012), and this was continued in 1995 by the government's Working for Water (WfW) programme (van Wilgen et al., 2016). Large tracts of the CFR have been subjected to control, with WfW spending approximately ZAR 463 million on the repeated clearing of 11,579 ha (van Wilgen et al., 2020). In addition, the Agricultural Research Council's Plant Protection Research Institute explored the potential for biological control as a management option for *Pinus* species (Moran et al., 2000). To avoid conflicts with the forest industry, the programme only considered seed-feeding biological control agents on two Mediterranean pines (*P. halepensis* Mill. and *P. pinaster* Aiton) that were not important for timber production (Moran et al., 2000). In 2009, concerns about the possible spread of Pine Pitch Canker (*Fusarium circinatum* Nirenberg & O'Donnell) led to the programme being abandoned (Lennox et al., 2009). In a few localised areas successful clearing has occurred using mechanical methods (e.g. Fill et al. 2018), and McConnachie et al. (2015) estimated that the cover of invasive trees could have been almost 50% higher in the Hawequas area if the interventions of the WfW programme had not taken place. However, when assessed at the scale of the CFR, pine invasions have continued to grow.

The management of wilding pines is challenging because of their ongoing spread into rugged and inaccessible terrain from unregulated plantations, driven by repeated wildfires, and hampered by a lack of biological control and a shortage of funding. A review of the history of introduction, benefits, and impacts of pines over the past three centuries in South Africa (van Wilgen and Richardson, 2012) proposed three potential approaches to managing pines in South Africa: (1) phasing out certain pine plantations in the CFR, and more effectively managing others: (2) continuing pine plantation forestry in the grassland regions of the country, and only re-planting proven non-invasive pine hybrids or species; and (3) phasing out invasive pine species in areas where they currently serve ornamental, amenity, and recreational needs, and replacing them with non-invasive trees. In this paper, we review recent research and management developments relevant to the control of wilding pines in the CFR since 2012, examine trends in outcomes, and examine opportunities for increasing the effectiveness of management.

2. The distribution of wilding pines in the Cape Floristic Region

The distribution of most *Pinus* species in the CFR is well documented (Poynton, 1977; Richardson et al., 1994a; Henderson, 2001). However, recent localised and spatially explicit distribution information is generally lacking. In 1996, Le Maitre et al. (2000) estimated the cover of *Pinus* species to be 550 and 89 km^2 in the Western and Eastern Cape provinces respectively. Their survey was based on a mix of heterogeneous data sources, including expert opinion. Cover was estimated in "condensed ha" using the formula C = d/100 x A, where C is the area in condensed ha, d is the % cover, and A is the area in ha within which the cover was assessed (for example, 100 ha that has a 25% cover of wilding pines would be recorded as 25 condensed ha). In 2006, the Department of Environmental Affairs commissioned a study to assess the distribution of selected alien plant taxa across South Africa. The methods used in this study are described by Kotzé et al. (2020a, 2020b). All *Pinus* species were treated as a single taxon, and only invasive trees in natural vegetation were enumerated (i.e. plantations were not included). The survey was finalised in 2008 and a second survey was completed in 2023. The estimated cover of *Pinus* species in the CFR was 430 km^2 in 2008, increasing by 33% to 573 km^2 in 2023 (J.D.F. Kotzé, unpublished data).

Additional information is available from the South African Plant Invaders Atlas (SAPIA), which was established to collate data on the distribution of invasive alien plants (IAPs) growing outside of cultivation in southern Africa (Henderson, 1999). SAPIA has some limitations as the records have been collected opportunistically and are restricted to roadsides (Henderson and Wilson, 2017). Moreover, no new records have been added since 2018. Henderson and Wilson (2017) reported the number of quarter degree grid cells (QDGCs) occupied by invasive alien plant species in 2010 and 2016. During this period, the number of QDGCs occupied by *Pinus pinaster* and *P. radiata* increased from 85 to 108, and 70 to 95 QDGCs respectively (these two species are essentially confined to the CFR). Their recorded distribution therefore increased by 27 and 35% respectively, due both to additional records and ongoing spread. In a recent assessment Rebelo and Coertze (2024) used Sentinel-2 satellite imagery at 10 m resolution and a Random Forest machine learning classifier to estimate the cover of wilding pines within the CFR to be approximately 907 km^2. Indications are therefore that pine invasions have continued to grow despite mechanical control efforts.

The SAPIA data can be supplemented with records from iNaturalist (www.inaturalist.org), which has been increasingly used to monitor IAP distribution. As of 14 December 2023 there were 2034 verifiable research-grade records on iNaturalist of wilding pines outside plantations in the CFR (Fig. 1). Combined records from SAPIA and iNaturalist show an increase in the number of pine records in the CFR since 2007, due both to additional records and ongoing spread (Fig. 2a). The dominant invasive pine species from both SAPIA and iNaturalist databases are *P. pinaster* followed by *P. radiata* (Fig. 2b). In addition, the CFR contains most wilding pine records from South Africa (Fig. 2b).

3. The benefits of pines in the Cape Floristic Region

Pines were primarily introduced to South Africa for commercial timber production, and plantations of pine trees currently cover over 547,729 ha in South Africa (Dovey et al., 2021), of which 11% of are in the CFR (State of Forests Report, 2018). Plantation forestry contributes 1.2 % to the National Gross Domestic Product (DFFE, 2020), and forest products contribute at least 4.5% to total manufacturing in South Africa, making forestry one of the top five sectors within manufacturing (Forestry Sector Master Plan, 2020). Forestry, logging and related services employs 40 482 people in South Africa (3691 in the Western Cape, Stats SA 2020). Most forest operations are in rural environments, providing indirect benefits to an estimated 648,000 people (State of Forests Report, 2018). De Beer (2012) found that the plantations in the CFR contribute to the livelihoods of several needy communities through provision of direct and indirect employment along the timber value chain. The study, however, also showed

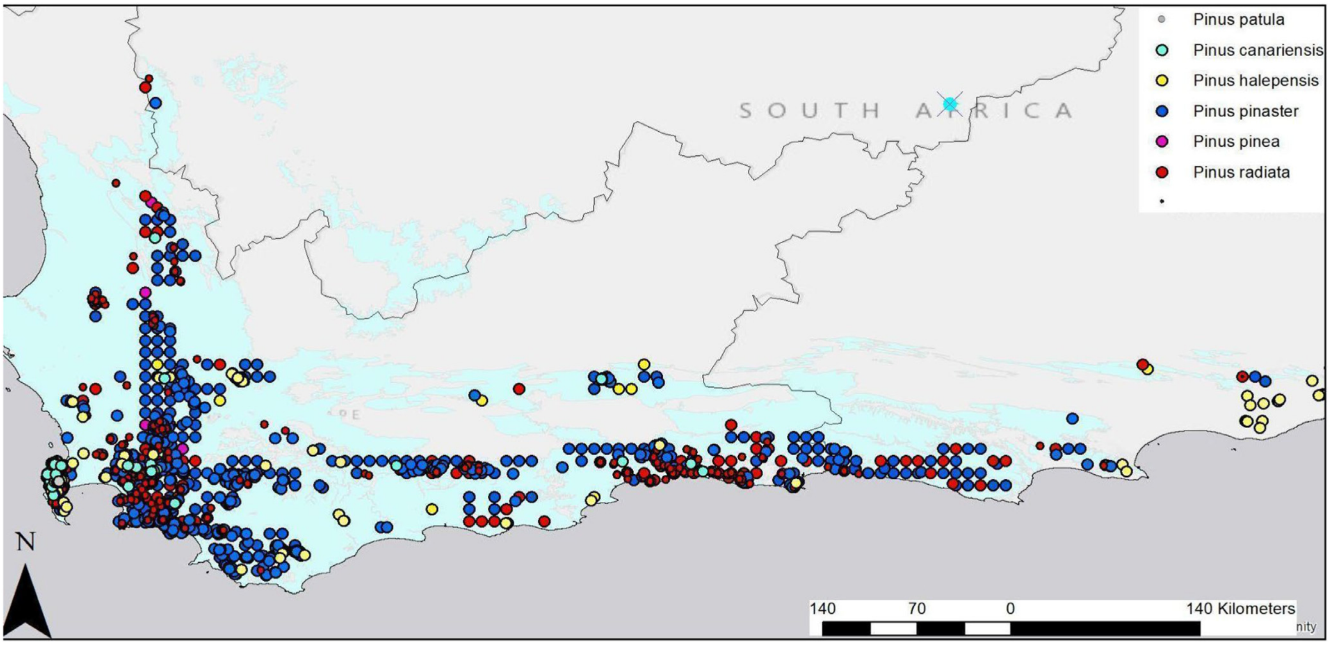

Fig. 1. Distribution of wilding *Pinus* species in South Africa. Data sourced from the South African Plant Invaders Atlas (2023) and iNaturalist (2023).

unequal spread of the benefits with some areas receiving negligible benefits from forestry despite being adjacent to forestry areas (De Beer et al., 2014).

As a commercial land use system, pine plantation forestry can be regarded as having a lower environmental impact than other forms of intensive agriculture. Managed plantations use limited herbicides and pesticides compared to other commercial crops. They have a low requirement for chemical fertilizers, and regular management practices offer good protection against soil erosion (du Toit et al., 2014). Approximately 30% of plantation estate land is under natural

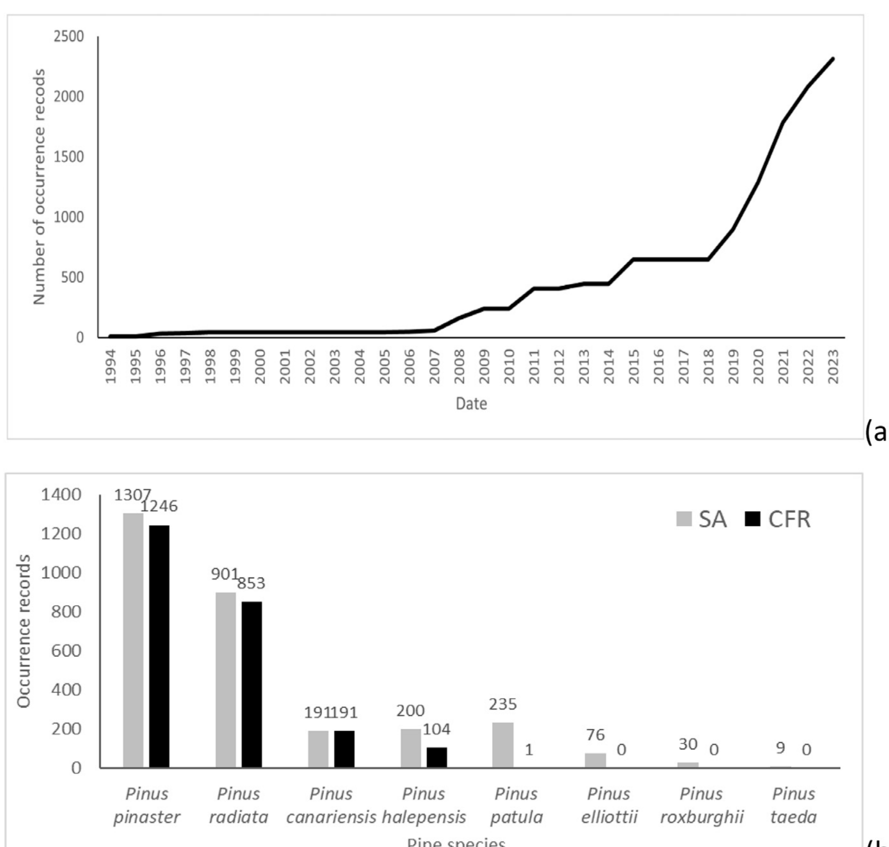

Fig. 2. (a) The increase in the combined number of records of wilding *Pinus* species in South Africa from the South African Plant Invaders Atlas (SAPIA) and iNaturalist, (b) Total number of occurrence records for each pine species in South Africa (SA) and the Cape Floristic Region (CFR) recorded by both SAPIA and iNaturalist.

Table 1
List of champion trees of South Africa; individual trees and groups of trees declared as protected under Section 12 of the National Forests Act of 1998 by the Department of Forestry, Fisheries and the Environment 2019 (Department of Agriculture, Forestry & Fisheries, 2018).

	Tree Species	Description	Height (m)	Stem dimeter at breast height (m)	Location
1	*Pinus taeda* (loblolly pine) The Buffelsnek Pine	Tallest pine tree measured in South Africa	60.1	1.20	Buffelsnek State Forest, Knysna, Western Cape
2	*Pinus pseudostrobus* (false Weymouth pine) The Three Matrons	The largest pine trees in Limpopo Province, planted in 1914	49.2	1.56	Woodbush State Forest, Magoebaskloof, Limpopo
3	*Pinus radiata* (Monterey pine) The Eastern Cape Pine	Tallest pine tree in the Eastern Cape, planted in the late 1880s	51.0	1.50	Isidenge State Forest, near Stutterheim, Eastern Cape
4	*Pinus halepensis* (Aleppo pine) Arderne Aleppo Pine	Landmark tree planted by tree pioneers Ralph and Henry Arderne	32.9	1.74	Arderne Garden, Claremont, Cape Town, Western Cape

vegetation, and these create ecological networks that contribute towards biodiversity conservation at the landscape level (Samways et al., 2010), even though biodiversity is decreased under the planted trees.

Pine plantations and agroforestry systems can contribute to carbon sequestration through tree growth (i.e. storage in the living biomass) and long-term storage in harvested wood products, with potential benefits for mitigating the drivers of climate change (Dovey et al., 2021; Sheppard et al., 2020; Flynn et al., 2022).

Besides their commercial value, pines (mainly *P. radiata*) also provide windbreaks for fruit orchards and vineyards in the CFR (Richardson et al., 1994b). Agroforestry systems using tree windbreaks yield environmental benefits such as savings on irrigation water (by decreasing crop field evapotranspiration) (Veste et al., 2020).

Opinions on the aesthetic value of pines are divided, with many people (especially in urban areas) regarding them as enhancing otherwise treeless landscapes and providing shade and other recreational opportunities (van Wilgen, 2012). For example, the plantations and arboretum at Tokai (Cape Town) are used by people from the surrounding residential areas for horse riding, cycling, mushroom foraging, hiking, and picnicking (Ernstson, 2013). In recent years, South African National Parks began a rehabilitation programme to restore the highly endangered sand plain fynbos vegetation by removing Tokai's pine plantation (Hitchcock et al., 2012). Despite the conservation advantages of this project, many residents valued the forested landscape over fynbos, and resisted attempts to clear all the pines (Hitchcock et al., 2012). Due to the time that pine plantations have existed in the areas, some people also regard pines as culturally valuable as they grew up knowing only the transformed and afforested landscape (Ernstson, 2013). For example, some *Pinus* trees have been listed as "Champion Trees" in terms of the National Heritage Resources Act (Act No. 25 of 1999) based on their age and area of establishment and in these cases are exempt from being managed (Table 1).

4. The negative impacts of wilding pines in the Cape Floristic Region

4.1. Impacts on water resources

Invasion by wilding pines increases the height, above-ground biomass and leaf area index of the invaded fynbos (Versfeld and van Wilgen, 1986), which in turn leads to increased evapotranspiration and streamflow reduction. Le Maitre et al. (1996) and van Wilgen et al. (1996) used the results of catchment hydrological experiments, spread of trees after regular fires, and inter-fire growth of invading trees to estimate changes in runoff as the alien plants spread. They estimated that ongoing invasion by pines and other alien trees could reduce the water supplies to the city of Cape Town by 30%, and that effective clearing of these invasions would reduce the cost of delivering water. In the last decade, research has refined these models. Dzikiti et al. (2013) estimated that annual transpiration and evapotranspiration rates were higher in the riparian zone than in the non-riparian area for both *P. pinaster* (980 vs. 1417 mm) and *P. halepensis* (753 vs. 1190 mm). They concluded that wilding pines growing in riparian zones use at least 36% more water than those non-riparian pines. Le Maitre et al. (2016) then produced revised estimates of runoff reductions due to invasive trees (including pines) across South Africa. For the primary catchment areas in the CFR, reductions in runoff were 0.31% (Olifants River), 6.04% (Berg River), 6.11% (Breede River), 8.43% (Kromme River), 1.86% (Gouritz River) and 2.09% (Gamtoos River). Note that the upper catchments of the Olifants, Gouritz and Gamtoos areas are not as heavily invaded as the others.

A central question around the impact of wilding pines is whether the reduced streamflow will result in an inability of the dams and reservoirs to supply sufficient water to towns and cities in the CFR. Based on modelled estimates derived from historic records of rainfall and runoff, engineers assign a level of confidence that the water supply system will be able to meet a given level of demand. Le Maitre et al. (2019) predicted that the 98% assured total system yields in the Western Cape Province were ~ 580 million m^3/yr under a scenario of effective control of tree (mostly pine) invasions. This would reduce to ~542 million m^3 /yr under current levels of invasion and further reduce to ~ 450 million m^3/yr in 45 years if the invasions are not managed. They concluded that reductions in runoff due to invasion could have substantial impacts on the yields of large, complex water supply systems if the invading trees are not removed, increasing the likelihood that the system would fail to deliver sufficient water to meet demand in times of drought. Landscape-scale streamflow reductions by pine plantations (as opposed to wilding pines) are much lower (3 – 4%) because plantations have a mix of younger and older trees at any given time (Scott et al., 1998; Gush et al., 2002; Scott and Gush, 2017).

4.2. Impacts on biodiversity

Wilding pines have negative impacts on biodiversity, especially in the CFR. These include reductions in native plant cover, species richness, and density through direct competition, as well as reductions in the numbers and diversity of ant, bird and invertebrate species, as documented in a recent review by van Wilgen et al. (2022a). Galloway et al. (2017) also found that native plant species diversity, growth form density and overall plant density was lower under established pine plantations compared to reference fynbos sites. Mostert et al. (2017) found that native perennial plants showed better recovery after clearing of pines than after clearing of alien *Acacia* shrubs, although overstorey proteoid elements were lost from the pine site. This finding supports other evidence that the impacts of pines on fynbos vegetation are generally not as severe as the negative effects of nitrogen-fixing *Acacia* species but impacts under pines remain significant (Holmes et al., 2020). Recent studies on native animals in areas invaded by pines have documented further impacts. These included reduced richness, abundance, and diversity in areas invaded by pines compared to surrounding fynbos (Schreuder and Clusella-Trullas, 2016); reduced densities of the rough moss frog, *Arthroleptella rugosa* (Angus et al., 2023); negative impacts on other ectothermic species; and lowered species richness and abundance of ground-dwelling invertebrates, particularly fynbos-specialist invertebrates (Uys, 2012).

4.3. Impacts related to wildfires

The establishment of dense stands of wilding pines in the CFR increases the risk of damaging wildfires by increasing biomass and thus fuel loads compared to native vegetation. In the last decade the CFR has experienced increases in both fire frequency and severity, threatening ecosystem stability in many areas (Msweli et al., 2020; Manzano et al., 2023; Kraaij et al., 2024). The CFR is also experiencing increasingly hot, dry summers (Slingsby et al., 2017), which has further exacerbated fire events in invaded areas. For example, in June 2017 a series of devastating fires in the Knysna area resulted in the loss of 939 houses (Forsyth et al., 2019) and claimed the lives of seven people. Kraaij et al. (2018) estimated that more biomass was consumed in plantations, and in fynbos invaded by alien trees (about 50% of which were pines) than in adjacent uninvaded fynbos during the Knysna fires. Such increases in fuel consumption would have increased the intensity and severity of fires, making them more damaging and more difficult to control. The height of canopies in wilding pines further adds to the severity of the fires that are often then impossible to contain (Forsyth et al., 2019). Further research also found that *P. radiata* had the highest overall flammability score out of 30 selected woody native and alien species in the CFR (Kraaij et al., 2024).

5. The status of management of wilding pines

5.1. Policy, strategy and legislation

Policy, strategy, legislation and regulation are essential elements of a governance framework within which biological invasions should be managed. These elements are not the same thing, and it is important to understand the difference between them. Government policy sets out the principles, objectives, and guidelines, and should articulate the government's vision and intentions. Strategies should provide a plan outlining steps and resources to achieve objectives outlined in policies. Legislation can then be promulgated to provide a structured legal framework defining acceptable conduct and consequences for violations. Finally, regulations are rules and directives issued by government agencies to implement and enforce laws [see Lukey and Hall (2020) for a full explanation of these issues].

South Africa does not yet have a policy or strategy for dealing with invasive alien species. The country does however have laws, primarily in the form of the National Environmental Management: Biodiversity Act (Act 10 of 2004, NEM:BA), and Alien & Invasive Species (A&IS) Regulations that were published under that act in 2014, and revised in 2020 (Wilson and Kumschick, 2024). Species are listed under the regulations in different categories. Category 1 species must be controlled, and cannot be traded or otherwise allowed to spread, whereas Category 2 species are the same as Category 1 species except that permits can be issued for their cultivation and trade, subject to conditions that would include ensuring that the cultivated species do not spread.

Currently, eight species of pines are listed as invasive under the NEM:BA regulations. These include four species from Central and North America (*Pinus radiata, P. patula* Schltdl. & Cham., *P. taeda* L., and *P. elliottii* Engelm.), three European species (*P. canariensis* Sm., *P. pinaster*, and *P. halepensis*) and *P. roxburghii* Sarg. from the Himalayas. The two dominant species within the CFR (*Pinus pinaster* and *P. radiata*) are listed as Category 2 for plantations and windrows and Category 1 elsewhere (National Heritage Trees or National Monument Trees in terms of the National Heritage Resources Act, Act No. 25 of 1999, are exempted). Finally, all pines not in plantations and windrows with a circumference greater than 1.256 m at a height of 1m at the date of the first publication of the Notice (August 2014) are not listed for urban areas in Cape Town, the Overberg District Municipality and Winelands District Municipality, except when in a riparian area, or in a protected area or any property directly abutting a protected area, or where they are ruled to pose a wildfire risk, where they remain listed as Category 1. However, all specimens that had a smaller circumference in August 2014 are regarded as Category 1 regardless of where they occur. It is thus not necessary to control large pines in urban areas, or for the government to enforce compliance with such a regulation.

The Minister of Forestry, Fisheries and the Environment has exempted forest plantations that were established and operational before 1 August 2014 from the requirement to obtain a permit in terms of NEM:BA. The A&IS Regulations require conditions to be stipulated in these permits, including that the permit holder must take all necessary steps to prevent the spread of the species. While there is a general duty of care to control listed invasive species in NEM:BA, that responsibility only applies to owners of land on which the species is present. Commercial forestry companies that operate commercial plantations owned by the State therefore do not have that general duty of care to prevent spread. In those instances, the State bears that responsibility. In cases where commercial operators are required to obtain permits issued under the A&IS, it is also difficult to link these operations to invasive stands given the difficulty in obtaining evidentiary proof of the origin of invasive specimens. Thus, a substantial area of commercial forestry remains as an unregulated seed source for re-invading adjacent areas that have been cleared. This is being addressed by commercial forestry companies in the CFR, who are in the process of phasing out pine species (*Pinus pinaster*) and are experimenting with several hybrid pines that could potentially be less invasive.

The NEM:BA A&IS Regulations provide the basis for regulating alien and invasive taxa in South Africa. Initially, the taxa included on the regulatory lists were assigned by taxon-specific expert panels using a range of approaches. However, since 2017 a standardised approach using an internationally accepted Risk Analysis for Alien Taxa (RAAT) framework has been implemented and current regulatory lists revisited (Wilson and Kumschick, 2024). No *Pinus* species have yet been re-considered using the developed RAAT.

5.2. Planning

Planning is an important component of alien plant control operations. The first status report on biological invasions in South Africa identified the lack of adequate planning as a significant weakness (van Wilgen and Wilson, 2017). However, the situation has recently improved; the latest status report notes a marked increase in the adequacy of management plans for protected areas (Zengeya and Wilson, 2023). In the first report, plans for 98% of the area covered were assessed as inadequate. The current estimate is that planning in ~85% of the area was adequate, and ~15% was partially adequate, with less than 1% of the planning being scored as inadequate. Alien plant control management plans have been developed for all major protected areas in the CFR, including six National Parks and 18 Provincial Nature Reserve complexes covering 1 034 740 ha (for specific

National Park management plans see https://www.sanparks.org/conservation/management-plans/overview).

5.3. Government support for control operations

The government has provided support for the control of invasive alien plants to landowners since 1995 through its Working for Water (WfW) Programme (van Wilgen et al., 2022b). The bulk of this support in the CFR has gone to government entities at the national (South African National Parks, SANParks), provincial (CapeNature) and local (municipal) levels, mainly for control in protected areas. Spending on the management of invasive alien plants in the protected areas of the CFR between 2010 and 2022 amounted to ZAR 976 million (2022 values of ZAR), with 15% of this being spent on wilding pines (van Wilgen et al., 2025). Individual protected areas received between ZAR 1.3 and 367 million between 2010 and 2022, with over 90% being spent in five national parks. Over this period, spending fluctuated between ZAR 60 and ZAR 100 million per year, with spending on National Parks being sustained (and recently increased), while spending on the provincial nature reserves managed by CapeNature has declined to very low levels (zero in some recent years, van Wilgen et al., 2025). This discrepancy between the funding of SANParks and CapeNature can be explained, at least in part, by the rules under which WfW is required to disburse funding. CapeNature is required to tender annually for these funds, but this requirement does not apply to SANParks, which is an entity within the same department as WfW, allowing funds to be transferred to them without the need to tender, which considerably facilitates the flow of funds.

5.4. The Greater Cape Town Water Fund

The water for the Greater Cape Town Region comes from a catchment area covering 170,000 hectares that supplies five major dams (Stafford et al., 2018). The Greater Cape Town Water Fund (GCTWF) was launched in 2018 to address the threats posed by invading alien trees to water security at their source, almost all of which is outside of Cape Town's municipal boundaries, which in turn prevents the municipality from spending funds there. The fund was based on a feasibility study (Turpie et al., 2017) and business case (Stafford et al., 2018) which showed that removing invasive trees from Cape Town's water catchments could generate annual water gains of 55 billion litres within six years, equivalent to one-sixth of the city's current supply needs (Stafford et al., 2018). The project can potentially prevent the loss of 100 billion litres of water annually within 30 years. The GCTWF estimated that this approach was significantly more cost-effective than other water supply augmentation options (e.g. building more dams, or commissioning desalination plants).

The GCTWF receives support from public and private institutions, led by The Nature Conservancy, a global non-profit environmental organisation. The GCTWF has estimated that it would require ZAR 720 million to bring invasive alien trees under control over the next 20 years in the priority catchments identified. Of this, ZAR 372 million will be needed for initial clearing, and ZAR 348 million for ongoing maintenance. The Fund has raised ZAR 313 million to date, of which ZAR 125, 118 and 69 million was obtained from the City of Cape Town, philanthropists and foundations, and business corporations respectively. Spending on control began in 2020, when ZAR 9.9 million was spent (a further ZAR 91.6 million was spent between 2021 and 2023, and the budgeted amount for 2024 is ZAR 103.8 million). In addition, the City of Cape Town is decommissioning its own pine plantations and has pledged to release R 75 million over the next three years to sustain and expand these clearing efforts (du Toit, 2023).

5.5. Payments for ecosystem services

The WfW programme has provided almost all the funding for wilding pine control efforts in the CFR since 1995, as conservation agencies do not have adequate funds for this purpose. To address this reliance on WfW, van Wilgen and Richardson (2012) recommended making effective use of payments for ecosystem services (PES) to sustainably fund control operations. The National Water Resource Strategy outlines water charges set by the Department of Water and Sanitation and how this collection of payments should be used to fund rehabilitation and maintenance initiatives (Cumming et al., 2017). The Department of Water Affairs and Sanitation also requires a water resource management fee in their water tariffs that goes towards managing water supply systems including the clearing of invasive alien plants. Although between R23 million and R48 million per annum was collected from these tariffs up to 2008 (Turpie et al., 2008), there is no evidence that these funds have yet been utilised for the control of alien plants in catchment areas. Thus, although there is an intent to utilise PES, this has not been implemented (DEA-SANBI, 2012). Stakeholders often do not understand the concept of PES (Sitas et al., 2014) and without this understanding, moving towards defining the services and attaching values to them has proved difficult.

5.6. Volunteer groups

Volunteer individuals, groups, and organizations also contribute to the control of wilding pines in the CFR. These volunteers cleared approximately 5300 ha of land per year over the past 20 years in the CFR with an estimated labour value of R5.1 million annually (Jubase et al., 2021). Most volunteers were also engaged in detecting and reporting IAPs, which is another valuable contribution to their management. In one case, a volunteer group in Greyton (Wild Restoration) secured funding from the European Outdoor Conservation Association, enabling it to clear about 100,000 pine trees from a 280-ha area using helicopters to place chainsaw operators in inaccessible areas (Vivier, 2023). Volunteer groups maintain more than four percent of Table Mountain National Park (Huntley, 2005), and there are at least 52 such volunteer groups in the CFR (Jubase et al., 2021).

5.7. Phasing out of pine plantations

Plantation forestry in the CFR has faced more challenges than elsewhere in the country. Frequent wildfires, and low returns on investment resulted in many planted areas not being economically viable (van Wilgen and Richardson, 2012). A recommendation was therefore made to phase out some plantations in the CFR. This came into effect in 2001 when Cabinet approved the decommissioning of 45,000 of the 70,000 ha of commercial plantations across the Western Cape Province (VECON, 2006; Ministry of Public Enterprises, 2000). The Table Mountain National Park also undertook to remove all pine plantations within its boundaries (van Wilgen, 2012).

In 2001, Mountain to Ocean (MTO) Forestry won the bid to operate state plantations in the CFR. One of the conditions of the lease was that MTO would implement the government's strategy and exit 45,000 ha of plantations by 2020 (Wood Southern Africa and Timber Times, 2015). Government would then decide who the appropriate managing agent of the exited land would be - either South African National Parks or the provincial conservation organization Cape Nature, depending on the location. Shortly after MTO's take-over, market conditions improved. This, coupled with fires in the Tsitsikamma areas that destroyed over 16,000 ha of plantations, resulted in a timber shortage, threatening sawmilling and timber-related businesses (Wood Southern Africa and Timber Times, 2015; SA Forestry, 2023). In 2005, MTO began to reassess the viability of the exit areas and made representations to the government requesting the reversal of the exit policy, arguing that there were broader socioeconomic impacts, such as job losses and negative economic implications (De Beer, 2012; De Beer et al., 2014). As a result, Cabinet approved that 22,500 ha of exited land be replanted for timber production (Ministry of Public Enterprises, 2000; VECON, 2006), but due to delays and indecision, the areas have not been replanted and are becoming increasingly degraded (Mathews, 2024).

5.8. The forest industry

The forestry sector in South Africa acknowledges the historical contribution of plantations to the spread of pine invasions and is seeking effective strategies to address the issue. They have increased the planting of *P. elliottii* which produces very few seeds in the CFR (Poynton, 1977). *Pinus elliottii* produces an economically viable crop in the CFR, and it is the species of choice on the hydromorphic soils of the Tsitsikamma region and some southern Cape plantations (du Toit, 2012). Further plantings of *P. pinaster* have been suspended and the boundaries of *P. pinaster* compartments adjacent to natural vegetation have (since the late 1990s) been planted with *P. elliottii* to reduce seed dispersal. The area under *P. pinaster* in South Africa has been also reduced from approximately 10 000 ha in 2010 to 301 ha to 2019 (DFFE, 2020). Since 2000, several experiments testing pine hybrids have been established in the CFR, to determine the commercial potential and invasive tendencies of these hybrid alternatives (MTO, 2023), but only early-stage growth results are currently available.

5.9. Control on privately-owned land

Large tracts of land in the CFR that are invaded by alien plants are in private ownership (van Rensburg et al., 2018). An insight into the operations of private landowners can be obtained from the case at Vergelegen Wine Estate, where a reduction of IAP coverage from an initial 73% (over 2300 ha) to 8% was achieved over ten years (van Rensburg et al., 2017). However, the cost of the operation was eventually 3.6 times more than was originally estimated (ZAR 43.6 vs 12.19 million, van Rensburg et al., 2017). Reporting of management on privately owned lands is limited, preventing an accurate estimation of their contribution to the overall management of wilding pines in the CFR. Very few private landowners can afford similar control projects (Vergelegen is owned by a wealthy mining company).

5.10. Management of pines for recreational and aesthetic purposes

Pine trees are widely planted in gardens and streets in the CFR, and pine plantations are frequently used for recreational activities. There is therefore a tension between the desire to retain pines, and the need to remove them as a source of seeds that could spread to other areas. Gaertner et al. (2016) proposed a framework for the management of invasive alien plants in the City of Cape Town and divided species into three categories; 1) species that should be tolerated due to low impacts; 2) those that require active engagement due to conflicting opinions on their value) and 3) those that provide few or no benefits and should be priorities for control. They suggested that *P. pinea* should be tolerated as it is not a major invader, and that *P. pinaster* and *P. halepensis* should be priority species for removal due to their low commercial and aesthetic value. For *P. radiata*, they suggested that there should be wider consultation about their management to raise awareness and avoid unnecessary conflict. There is also a requirement under the NEM:BA I&AS regulations for smaller individuals of listed pine species in urban areas to be removed. This regulation was intended to allow large pines in gardens and parks to remain, thus removing a significant obligation on municipalities to enforce their removal. However, it was also intended for authorities to require the removal of smaller specimens, but there are no records that this was ever done. Over the past 10 years these smaller trees would have grown, and it would be difficult to accurately identify the individuals that should have been removed. These regulations also only apply to eight *Pinus* species, and over 80 *Pinus* species are present in South Africa, of which 57 are potentially invasive (van Wilgen and Richardson, 2012). These unregulated species can legally continue to be sold and planted across the country.

5.11. Biological control

Currently, there are no biological control options for use against invasive pine trees in South Africa. A program that sought to find, evaluate and deploy seed-feeding biological control agents against pines was initiated in 2000 (Moran et al., 2000). A cone-boring weevil (*Pissoides validirostris*) was identified as a potential biological control agent (Fig. 3), but it was not released due to concerns that the agent may increase the risks of ingress by the pine pitch canker fungus *Fusarium circinatum* (Lennox et al., 2009). Later, this decision was questioned by Hoffmann et al. (2011) but the programme was not pursued for the next twenty years. Subsequent engagement with the forest industry has reduced these concerns, and funding from the Nature Conservancy (a NGO based in the United States of America) have led to a rejuvenation of the programme.

6. Management of pines - challenges and opportunities

6.1. Balancing conservation and economic benefits

A conflict between the needs of the forest industry and the goals of conservation efforts exists in the CFR (Anon, 2012; De Ronde, 2012; Genis, 2012). The forest industry points to economic contributions, while conservationists highlight the impacts of invading pine

Fig. 3. Adult *Pissoides validirostris* followed by a time series of a *Pinus pinaster* cone being damaged by *P. validirosrtis* larvae in Portugal 2010 (Photos: Alain Roques).

trees on water resources, biodiversity and fire risks. In response, a meeting was convened by WWF (South Africa) to explore issues and to initiate a dialogue aimed at finding mutually acceptable and sustainable solutions (van Wilgen, 2015). The meeting ended with proposals for three possible solutions. These called for (1) a collaborative management initiative, involving foresters and conservation agencies, to be trialled on a small scale; (2) forest companies to lease land from the state, with a portion of the lease fees to be used to control invasions in adjacent protected areas or catchments; and (3) a thorough, participative, scientific assessment, as was done when the South African government was faced with the development of an acceptable policy for managing elephants (Scholes and Mennel, 2008). To be legitimate, such an assessment would need to be initiated and endorsed by the government. To date, none of these proposals have been implemented.

6.2. Monitoring, adaptive management, and agility

Our understanding of the dynamics and responses of complex ecosystems to management is not complete. Management also needs to respond to unexpected events (such as wildfires), unintended outcomes of interventions, or failure to make sufficient progress towards desired goals. Adaptive management is defined as an intentional approach to making decisions and adjustments in response to new information and changes in context. Monitoring progress towards the achievement of goals set out in management plans is an essential input to being able to manage adaptively. However, although the planning of wilding pine control operations is adequate, there is still no monitoring; this is a serious shortcoming in the current management approach (van Wilgen et al., 2020). Alien plant control teams must also be able to respond quickly to unplanned events such as wildfires, which are a common feature of the CFR's ecosystems. Follow-up weeding should ideally focus on recently burnt areas to remove post-fire seedlings before they grow to a size where removal otherwise becomes prohibitively expensive. To do this, management would have to be flexible and agile, and able to redirect resources to recently burnt areas as these opportunities arise. Unfortunately, the control programmes in the CFR generally operate in a bureaucratic environment which does not allow for flexibility.

6.3. Integration of control with prescribed fire

Prescribed burning can be effective for managing wilding pines, as well as promoting the regeneration of native flora in the CFR (van Wilgen et al., 1992; van Wilgen, 2013), and managers have employed fire to control the spread of wilding pines in the CFR with varying levels of success (van Wilgen and Richardson, 2012). Most current management plans prescribe burns at intervals of between 12 and 15 years in the CFR. Best practice for managing wilding pines involves felling trees at 12–18 months before scheduled burns, allowing release of seeds from the serotinous cones (Richardson and Nsikani, 2021). Because the trees have been felled, the seeds are released close to the ground and are less likely to disperse over long distances. In addition, over the next year or two, many of these seeds are consumed by rodents (cf. Bond 1984). Some seeds will still germinate, and the appropriate response would be to burn the area as scheduled 1 – 2 years later, which will kill pine seedlings before they mature and produce the next crop of seeds. This technique can be very successful, but its use is constrained by risk-averse fire legislation which would hold managers liable in the event of a prescribed fire escaping. As a result, currently over 90% of the CFR's protected areas burns in unplanned wildfires (van Wilgen et al., 2010), which may result in the proliferation and spread of pines in some cases. Prescribed burning needs to be more widely used, and integrated with invasive pine control efforts, if these efforts are to become more efficient.

6.4. The Veld and Forest Fire Act

The Veld and Forest Fire Act (Act No. 101 of 1998) [Clause 5(1) (c)] states that Fire Protection Associations (FPAs) must make rules to bind their members and further states [Clause 5(4) (c)] that this can include the use of fire to conserve ecosystems and reduce fire danger. We reviewed these rules for six FPAs in the CFR (the Cape Peninsula, Greater Cederberg, Greater Stutterheim, Sarah Baartman West, Southern Cape, and Winelands FPAs). All recognised the need for removal of invasive alien plants, and noted in varying forms that prescribed burning could be used for this. For any landowner to obtain permission to conduct a prescribed burn, however, certain conditions need to be adhered to, including applying for a permit, providing relevant information and a motivation, obtaining written permission from neighbouring properties, and ensuring that firebreaks are in place. While there is recognition of the importance of prescribed burning it is seldom used (pers. comm. Dirk Smith, Southern Cape FPA).

6.5. Implementing biological control

Biological control should be a component of the management of wilding pines in South Africa. Past efforts that targeted at the Iberian ecotype of the cone-feeding weevil *Pissodes validirostris* Gyll. (Coleoptera, Curculionidae) for use against three Mediterranean pines (*P. pinaster, P. halepensis* and *P. pinea*) are currently being resurrected. These species are only of minor importance in commercial forestry in the CFR (Hoffmann et al., 2011). *Pissodes validirostris* is the only species of *Pissodes* that does not feed on the cambium and phloem of Pinaceae; it feeds only on the cones and seeds of *Pinus* trees and the whole life cycle occurs in the same host species (Lennox et al., 2009; Fig. 3). Roques et al. (2004) have confirmed that the Iberian ecotype of *Pissodes validirostris* is specific to *Pinus pinaster, P. pinea* and *P. halepensis* as their larvae only survived to maturity on these closely related pine species. The damage inflicted by the weevil is significantly higher on *P. pinaster* when compared to the other two species. This host specificity limits control to *Pinus pinaster, P. pinea* and *P. halepensis* while other problematic species, notably *P. radiata*, would remain without biological control (Hoffmann et al., 2011).

6.6. Planting less invasive species or hybrids

Planting less invasive *Pinus* species could potentially alleviate current problems. Progeny trials for *P. elliottii* were predominantly planted in the northern KwaZulu-Natal Province under subtropical climatic conditions in the past. In KwaZulu-Natal, *P. elliottii* is invasive in subtropical grasslands (Henderson, 2020). Similar trials with *P. elliottii* were planted in the Western and Southern Cape forestry regions (i.e. in the CFR), but these displayed very poor cone and seed development (A. Nel, SAPPI Southern Africa, pers. comm.). Poynton (1977) noted that *P. elliottii* produced "heavy crops" of seed in northern KwaZulu-Natal, but that it was a "relatively shy bearer" in the former Cape Province. Hybrids of *P. elliottii* and *P. caribaea* are now also being trialled in the CFR. These hybrids again display high seed production in northern KwaZulu-Natal, but poor seed production in Mpumalanga, and it is hoped that the plantings in the CFR will display similarly poor seed production.

New plantings in the CFR make use of the ramets of hybrid pines, and inbreeding between these ramets could reduce invasive tendencies. Where ramets pollinate each other, it is effectively self-pollination. This leads to inbreeding and results in a non-competitive offspring in the F2 generation. There is a large body of evidence that inbreeding depression occurs in conifers in general and pine species in particular (Savolainen et al., 1992; Nikles et al., 1996; Williams and Savolainen, 1996; Kuang et al., 1998, 1999; Koelewijn et al., 1999; Sorensen, 1999; Williams, 2007; Williams, 2008; Pâcques, 2019).

Chancerel et al. (2013) identified a genomic region associated with inbreeding depression in *Pinus pinaster*. Inbreeding depression can manifest in several life stages of the plant, namely embryonic death or non-development in seeds (Savolainen et al., 1992; Sorensen et al., 1999; Williams, 2007; Williams, 2008), low germination percentages in seedlings (Kuang et al., 1998; Sorenson et al., 1999; Koelewijn et al., 1999), low survival rate of young trees in field and poor reproductive ability in mature trees (Nikles et al., 1996; Sorenson et al., 1999). Replacement of pure pine species that are invasive with ramets of interspecific hybrids thus has the potential to significantly reduce invasive potential of commercial pine plantations.

6.7. Cost-effective use of herbicides

Herbicides could be used to improve the efficiency of wilding pine control, but the best ways of doing this are not yet clear. Two herbicides, Paraquat and Diquat, have been tested on pines in the CFR with unsatisfactory results (Donald, 1982). Currently, Glyphosate is the recommended herbicide for integration with ringbarking on *P. pinaster,* while tebuthiuron is registered as a soil-applied herbicide for the control of standing trees, but this non-selective residual herbicide is not ideal for use on a large scale nor in the CFR. However, new application techniques have been developed, including the Aerial Basal Bark Application (ABBA) and tree injection known as drill-and-fill (De Lange et al., 2022). These two techniques are applied in New Zealand with ABBA adopted for management of large-scale pine invasions (Gous et al., 2014). The ABBA method, which makes use of helicopters to deliver herbicides using hand-held lances may be effective, but it is expensive relative to other methods in accessible terrain, and juvenile trees could be missed from the air. The drill-and-fill technique requires less equipment which would be an advantage at high altitudes. However, there is still no information on the performance of the various doses in relation to tree size and the doses used in New Zealand are deemed to be too high (Rolando et al., 2021).

The Fertilizer, Farm Feeds Agricultural and Stock Remedies Act 36 of 1947 governs herbicide applications in South Africa. This act requires thorough testing of herbicides before they can be used locally. In 2018, trials of herbicides for use against invading pines were started in the CFR by the Department of Forestry, Fisheries and the Environment, including foliar sprays, ABBA and drill-and-fill methods. Foliar and drill-and-fill trials followed practices developed in New Zealand (Gous et al., 2014). There have been numerous setbacks in these trials, including destruction of trial sites by fire, but the results from New Zealand are promising particularly for herbicides used in the drill-and-fill and foliar sprays. These herbicides are expected to become available in South Africa after the required testing and registration.

Unmanned aerial vehicles ("drones") could also potentially be used for aerial herbicide applications. Although technological development continues to narrow the gap in terms of functional substitutability between helicopters and drones, drones are currently still unable to substitute for helicopters when using the ABBA method (De Lange et al., 2022). Drones may be used for mapping invasions, and post-treatment surveillance, but weight limitations prevent effective use in heavy crosswinds.

De Lange et al. (2022) designed a model that uses site conditions such as density, slope, surrounding obstructive vegetation, and remoteness to examine the relative effectiveness of these different control methods. This model predicted that the drill-and-fill teams would consistently outperform chainsaw operations across all cover and slope classes and on-site conditions. Although chainsaw teams could fell more trees per day, they employed more people and required heavier equipment, so the drill-and-fill teams were more cost-effective. The only circumstances in which the ABBA method was more cost-effective was when invading pine densities were low (one stem per ha or less) and ground team access was difficult. Under these conditions helicopters were able to reach and treat many more trees than ground teams, compensating for their relatively high cost (De Lange et al., 2022).

6.8. Prioritization and triage

An assessment of the prospects of gaining control of invasive alien plants in the protected areas of the CFR concluded that "only substantial increases in annual funding under a scenario of low spread (4%), and removal of some taxa from the control programme would allow for control to be achieved in $<$ 20 years" (van Wilgen et al., 2016). They therefore proposed that management should focus efforts on priority areas and species, as attempts to achieve control of all species and over large areas would simply dilute scarce funds to a level where they would not be sufficient to gain effective control. This is in line with an assessment made by Wicht (1945) over 80 years ago, where he advised that "it would be a more practical and realistic policy to destroy them [i.e. invading alien plants] only on selected areas, such as proclaimed Nature Reserves, and to take no action elsewhere." A proposal by van Wilgen et al. (2016) envisaged re-directing available funds to priority areas and priority species. Criteria for the selection of priority sites would include whether they fell within strategic water source areas (Le Maitre et al., 2018), biodiversity hotspots, or protected areas. For priority species, it was proposed that funding should be directed towards pines, given that they posed the largest threat because of their ability to spread over large distances by means of wind-dispersed seeds, and they would ultimately come to occupy the largest area. The other two genera where most funding is currently being spent (*Acacia* and *Hakea*) pose less of a risk as they have effective biological control in place (Esler et al., 2010; Moran and Hoffmann, 2012; Impson et al., 2024). Implementing triage will not be easily achieved, and this further underscores the importance of finding effective biological control agents for pines.

6.9. Recovery of cleared sites

The removal of pines from an area does not necessarily result in the full recovery of natural vegetation (Fig. 4). Legacy effects may inhibit autogenic recovery making restoration difficult or even impossible (Holmes et al., 2020). Fill et al. (2018) compared areas where invasive pines in the Berg River catchment had been cleared with nearby uninvaded benchmark sites and showed that fynbos vegetation did not fully recover 13 years after the removal of pine invasions. A comparison of 50 m^2 plots found lower native species numbers and cover in the cleared plots (21 vs 32 species/plot, and 94 vs 168% cover respectively). On the other hand, In the eastern parts of the CFR, Baard et al. (2024) reported relatively good passive recovery of native vegetation following the removal of pine, where cleared plantations supported 91% of the native species found in adjacent (unplanted) fynbos. They concluded that the restoration potential of the eastern (with a comparatively higher proportion of grasses) fynbos was superior to that previously documented in western proteoid fynbos. In general, the chances for successful restoration after clearing invasive pines are improved if action is taken when infestations are at low densities and at early stages of invasion (Galloway et al., 2017; Sapsford and Dickie, 2023).

7. Opportunities

7.1. Broaden sources of funding

The Working for Water programme (WfW) has been the major, and in many areas the only, source of funding for controlling invasive pine trees in the CFR over the past three decades. Recently, this funding has declined markedly, especially in provincial protected areas managed by Cape Nature, starkly illustrating the risks involved in

Fig. 4. Teams clearing dense stands of invasive *Pinus pinaster* trees in the upper catchments of the Theewaterskloof Dam (-33.952, 19.3892) in the Cape Floristic Region. Control operations in dense stands such as this will not necessarily be followed by complete recovery of native vegetation, especially if the invasions have been present for a long time (Photo: Sharon McComb).

relying on a single source of funding (van Wilgen et al., 2025). The situation has improved somewhat with the establishment of the Greater Cape Town Water Fund, but this currently has a limited footprint, and further diversification will be needed for the necessary funding to be reliable and sustainable. Funding schemes based on payments for ecosystem services (primarily the provisioning service of water) offer substantial promise in this regard but have been under-utilised to date. It would also be necessary to ringfence funds raised in this way to ensure that they are used for the purpose of controlling invasions in strategic water source areas and not for other purposes. The funding model that supports the Greater Cape Town Water Fund could also be replicated in other parts of the CFR. The impetus for the development of the Greater Cape Town Water Fund was provided by Cape Town's water crisis in 2018, and other cities and large towns in the CFR face similar threats to water security. For example, residents of the city of Gqeberha faced a similar situation in 2013 and 2022 to the water shortages that existed in Cape Town in 2018 (Brown, 2022). The WfW Programme is run by the national Department of Forestry, Fisheries and the Environment. They disburse funds to a range of implementing agencies, mainly government conservation bodies and municipalities. This adds complexity as the disbursements need to be tendered for and approved, resulting in interruptions in the flow of funds, and adding overhead costs amounting to 22.6% (van Wilgen et al., 2022b). By granting funds directly to the government implementing agencies, these problems could be avoided. Implementing any or all these proposals would not be easy, but they would substantially increase the chances of reducing invasions to manageable levels, with attractive returns on investment.

Including value-added industries (projects set up to utilize the biomass generated by clearing invasive alien plants) in the control programme also needs to be carefully considered. The rationale for these projects has been that, by using a resource that would otherwise have gone to waste, it would be possible to generate further employment opportunities, produce useful products, reduce the risk of damaging wildfires fuelled by increased dry biomass in the field, and offset control costs. This is also recently receiving renewed attention due to the potential climate impacts of leaving biomass in the field to decay (Pirard, 2023). Several studies have indicated that including value-added products into control programs would theoretically deliver higher, and positive, returns on investment (e.g. Vundla et al. 2016, Pirard 2023). However, this is not how it works in practice (van Wilgen et al., 2022b). Value-added projects have been run independently from the control projects themselves, and they use material from a range of sources in addition to invasive alien plant control operations. The value-addition projects would need to be clearly linked to the goals of gaining control over invasive plants in priority areas, and if value-addition is not viable under such circumstances, it could be discontinued to free up funding for control and restoration in priority areas (Wilgen et al., 2022b).

7.2. Integrate control practices

The integrated management of alien plant invasions requires the coordinated use of a variety of control methods, thereby increasing the chances of successful control. Integrated alien plant management programs require long-term planning, knowledge of the target species' biology and ecology and the effective use of all available practices in appropriate combinations (Hobbs and Humphries, 1995; Flint et al., 2012). Currently, the management of wilding pines in the CFR is heavily reliant on mechanical clearing alone, in the form of ground-based teams that clear relatively accessible areas, and high-altitude teams that work in more difficult terrain. The effectiveness of these efforts could potentially be substantially improved if they were to be augmented by, and integrated with other techniques, including the use of biological control, herbicides, fire, and remote sensing.

The effective use of herbicides could also considerably cut the costs and increase the efficiency of control operations. De Lange et al. (2022) estimated that traditional felling was prohibitively expensive because of the need to equip, train and supervise chainsaw operators and ensure their safety, and because reaching the sites took a lot of time due to long distances carrying heavy equipment over rugged terrain. In most cases, the drill-and-fill method proved to be more cost-effective, while the aerial basal bark application, using helicopters, would be cost-effective in sites with isolated pines on steep slopes surrounded by dense natural vegetation. Removal of these isolated pines would be vital, because they would otherwise remain as an ongoing seed source for re-invasion of cleared areas.

Prescribed fire to kill seedlings could be more widely used, and it would replace the current dominant practice of repeatedly revisiting cleared sites annually to manually remove seedlings, bringing about further cost savings. Reinstating a program of prescribed burning and integrating it into alien plant control programs (e.g. Richardson et al. 1994a) offers benefits in terms of increasing control effectiveness, and several factors would need to be considered. Days with suitable and safe weather during ecologically acceptable times of the year are rare, reducing the number of opportunities to safely implement burns (van Wilgen and Richardson, 1985). Van Wilgen et al. (2016) proposed a trade-off between restricting the use of fire to ecologically acceptable seasons, for reasons of biodiversity conservation, and allowing fires at other times of the year to enable the effective reduction of pine invasions. An insistence on restricting fires to seasons that would best suit pristine fynbos means that there are fewer opportunities to burn, and consequently a greater area burnt in wildfires. Ultimately, a wildfire-driven fire regime could result in greater levels of invasion, and a greater loss of biodiversity, than judicious burning to contain invasions. Finally, van Wilgen (1984) noted that the cost per ha to conduct prescribed fires declined exponentially with increasing size of the area burnt, suggesting that it could be more cost-efficient to burn fewer but larger areas rather than many smaller areas.

Monitoring is an essential input for effective management, but a formal system monitoring is typically absent from current wilding pine control projects. There have been considerable advances in the detection and classification of pines using remotely sensed imagery. Images can be acquired from satellites (Rebelo et al., 2021; Duncan et al., 2023), manned aircraft and unmanned aerial vehicles (Dash et al., 2019) and can be used for monitoring the distribution and spread of IAPs (Mtengwana et al., 2021; Müllerová et al., 2023). The recent advent of hyperspectral sensors has improved the ability of imagery to detect spectral patterns that may be diagnostic and allow greater classification accuracy (Arasumani et al., 2024). Regular processing of remotely sensed data to produce maps of the extent of pine invasions will greatly facilitate quantitative monitoring of pine invasions.

7.3. Accommodate the need for commercial forestry

Commercial forestry is an important economic activity in the CFR, and any holistic approach to managing invasive pines would ideally be based on interventions that are mutually acceptable to both the forest industry and those tasked with managing invaded areas. The forest plantations and natural vegetation both occur in predominantly mountainous water catchment areas in the CFR. These areas deliver different benefits at different levels to different groups of people (cf. Bardgett et al. 2021), so an ideal configuration of land uses would be one that delivers the highest net economic benefit (i.e. the value of all benefits minus the value of all negative impacts). Such estimates have been made for invasive alien trees that also have benefits in South Africa [see De Wit et al. (2001) for *Acacia mearnsii*, and Wise et al. (2012) for *Prosopis* species], but this has not yet been formally done for *Pinus* species in the CFR. In the CFR, most of the area invaded by pines is outside of the land managed by foresters, and where the industry probably cannot affordably assist with their management. The issue therefore would be for parties to agree on what steps would be acceptable to maximise benefits and minimise impacts of pines. In the case of biological control by means of seed-attacking agents for commercially unimportant pine species, there is already broad agreement that it would be an acceptable practice. Planting different species or hybrids that would be less invasive is also being investigated. Withdrawing from areas where commercial forestry is no longer financially viable is still under debate, and it would be important to get consensus on where these areas should be. Finally, whether, or to what extent, the forest industry should be expected to contribute to control efforts beyond the boundaries of their land needs to be negotiated. A strong argument could be made that current invasions originate from State-funded plantings over 100 years ago, and expecting relatively recently commercialised operations to carry this cost would be unreasonable. On the other hand, current plantations of invasive pine species will for some time still exist as a substantial source of propagules, and there should arguably be some level of contribution made towards controlling ongoing invasions that arise from this source. This question needs to be resolved, with one of the key issues being whether such contributions would be affordable. Currently, forestry operations are required to pay levies for streamflow reduction activities. This is widely seen by the industry as unfair, as no other water-consumptive forms of crop production are subjected to this requirement. It could be jointly argued by both parties that these levies could be directly used to augment the control of wilding pines, thereby not adding any additional financial burdens on the industry.

7.4. Use scarce funds more effectively

Funding for the control of wilding pines will always be limited, and for this reason it would be important to focus that funding on priority areas, rather than to dilute it by spreading it across many areas. Allocating insufficient funding to any area would mean that rates of spread would be more rapid than rates of clearing, and invasions would simply continue to grow (van Wilgen et al., 2016). Sites could be prioritised in terms of their importance as strategic water source areas, protection status (funds should first be directed to protected areas), and funds can be allocated to the sites with highest priority. A second and equally important criterion would be whether the funds would be sufficient to achieve a desired level of control within a stipulated timeframe. If such a goal is not attainable, it would arguably be more efficient to allocate those funds to other priority areas so that effective control could be achieved there.

7.5. Improve awareness

Many people regard trees as beneficial, regardless of whether they have negative impacts. This has led in many cases to vigorous resistance to efforts to remove invasive pines and plantations (van Wilgen, 2012). However, if the goal of phasing out invasive pine species in gardens, municipal parks, and protected areas is to be achieved, then the responsible municipalities will have to adopt a much more proactive approach to implementing the required actions and enforcing the legal obligations in terms of the NEM:BA I&AS regulations. If progress is to be made it will be necessary to raise awareness of the consequences of not phasing out the invasive trees.

8. Conclusions

Our review has suggested that the future of the CFR, and the goods and services that it provides to society, are at a critical point. A scenario of business as usual will result in ongoing spread of wilding pines, with associated impacts, and continued conflict between stakeholders with interests in commercial forestry and conservation. On the other hand, making use of the opportunities arising from recent experience and advances in understanding provides hope for gaining control of the situation by maximising benefits and minimising harm (Fig. 5). The consequences of not effectively making use of these opportunities are serious. Invasive pines threaten to occupy large proportions of the strategic water source areas that supply major cities and towns in the CFR. For example, Le Maitre et al. (2019) predicted that yields from dams in the CFR could be reduced by 22.4% (from ~ 580 million to ~ 450 million m^3/yr) if all invasive

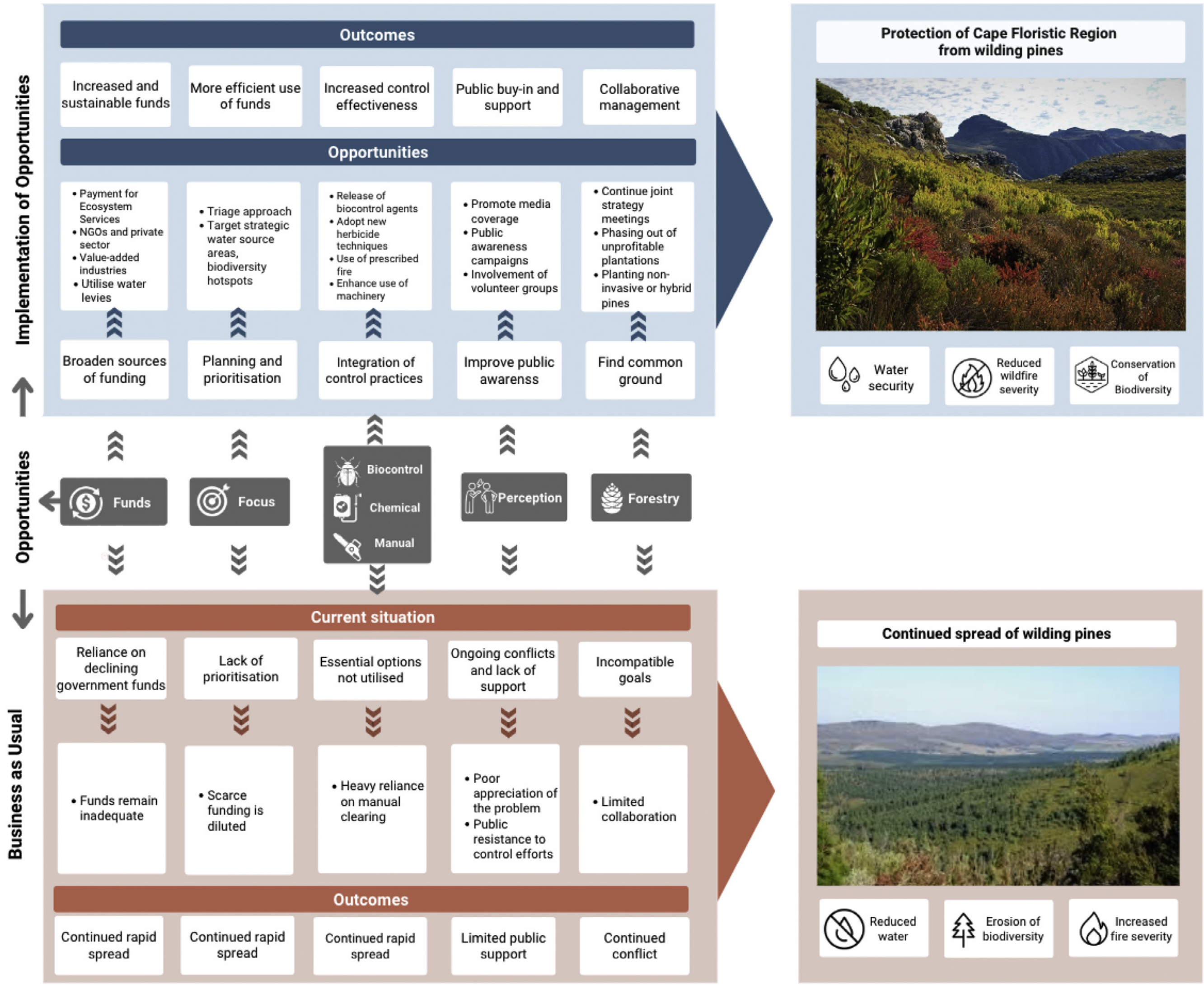

Fig. 5. An illustration of the potential outcomes that would be associated with (a) a scenario of business as usual in which invasions continue to spread and impacts increase (lower panel) or (b) a scenario in which stakeholders collaborate to make full use of several opportunities that in combination could result in bringing invasions under control (upper panel).

species in these catchments (including the pines) are not managed, thereby reducing water supplies and impacting substantially on local economies and quality of life. Losses of the CFR's unique biodiversity will escalate steeply, and damage from wildfires will increase across the CFR. It is an issue that deserves priority attention from government at national, provincial and local levels, the private sector, and society at large.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

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