Local and national stakeholders collaborate to take on *Prosopis* invasions with biological control and biomass use in South Africa

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DATES:
Received: 13 Feb. 2024
Revised: 06 Jun. 2024
Accepted: 07 Jun. 2024
Published: 26 Sep. 2024

HOW TO CITE:
Ivey P, van Staden G, Harding G, Oosthuizen D, Hoft E, van Staden P, et al. Local and national stakeholders collaborate to take on *Prosopis* invasions with biological control and biomass use in South Africa. S Afr J Sci. 2024;120(9/10), Art. #17928. https://doi.org/10.17159/sajs.2024/17928

ARTICLE INCLUDES:
☒ Peer review
☐ Supplementary material

DATA AVAILABILITY:
☐ Open data set
☐ All data included
☐ On request from author(s)
☒ Not available
☐ Not applicable

EDITORS:
Teresa Coutinho
Lindah Muzangwa

KEYWORDS:
invasive species, *Prosopis*, collaboration, biocontrol, community of practice, integrated management

FUNDING:
South African National Research Foundation (84643); South African Department of Forestry, Fisheries and the Environment; Swiss National Science Foundation and the Swiss Agency for Development and Cooperation (400440_152085).

Research that directs the way stakeholders act and how they collaborate is essential when addressing complex environmental challenges in the field of sustainability science. For example, researchers attempting to manage *Prosopis* invasions through biological control in South Africa have historically faced challenges from stakeholders. In this study, we illustrate the importance of stakeholder engagement and social learning by outlining the collaborative efforts of various stakeholders to promote effective, integrative and sustainable management of *Prosopis* invasions in the Northern Cape, South Africa. Through a community of practice approach, stakeholders worked together over the past half-decade in an attempt to develop a National Strategy for *Prosopis* management and improve its control. This strategy aimed not only to emphasise the need for integration of biomass use (aimed at offsetting the costs of mechanical clearing and necessary herbicide use) but also to underscore the significance of biocontrol alongside other management approaches. Stakeholders also identified that adequate farm-scale planning is necessary to provide a sense of purpose and assist in monitoring of progress. We worked alongside land managers and experts to develop such plans. The engagement of local champions played a crucial role in facilitating collaboration and learning among stakeholders, emphasising the significance of inclusive approaches in addressing complex sustainability challenges. In addition, we gained an understanding of how to develop the community of practice to enhance collaboration that ensures the implementation of plans to better manage *Prosopis.* Our findings underscore the necessity of meaningful stakeholder engagement and collaboration in effective invasive species management. By promoting understanding and involvement of diverse stakeholders, initiatives can have a greater impact in addressing broader sustainability issues.

Significance:

Our findings highlight the fundamental role of stakeholder collaboration in addressing environmental challenges (e.g. biological invasions), promoting sustainability and fostering social learning. Collaboration facilitates exchange of knowledge, promotes social learning and allows stakeholders to make informed decisions when addressing sustainability issues. Collaborative approaches promote the effectiveness of a community of practice in managing *Prosopis* invasions in South Africa. Local champions played a pivotal role in facilitating collaboration, bridging communication gaps and promoting inclusive approaches. Sustained stakeholder engagement, transdisciplinary collaborations, effective biological control and market development for biomass products will be essential to improve the sustainable management of *Prosopis*.

Introduction

To address sustainability issues through science, Brandt et al.[1] stress the importance of transformative research and collaboration. This includes promoting stakeholder engagement in co-design and co-management of action-orientated research as well as social learning.[2-4] Collaboration is needed in all domains of environmental management and conservation, including forestry and agroforestry, but many challenges remain in integrating collaborations and sustainable practices.[5]

Collaborative research is, however, challenging, and there is a risk that stakeholders might feel like subjects rather than true collaborators, leading to potential conflicts. This is common in invasion science[6], and in particular, the management of invasive plants arising from forestry and agroforestry practices, such as *Prosopis* species[7,8]. For example, in South Africa, Harding[9] and Shackleton et al.[10] surveyed landowners' opinions about *Prosopis* management but lacked consideration of other stakeholders and did not offer avenues of more collaborative processes moving forward. They merely consulted local actors through one-way dialogues which had limited effects on social learning and the initiation of actions to sustainably control *Prosopis*. Poor collaboration has likely allowed invasions to spread and impacts to continue to rise, and steps need to be taken to correct this. This disconnect between stakeholders, research and implementation[11] is well illustrated by the biocontrol community's response to the Harding[9] study. The majority of landowners favoured removal of *Prosopis* and more effective management thereof[9], but researchers, in order to avoid perceived conflicts of interest, focused their efforts on seed-eating weevils and, initially, did not consider natural enemies that damage seedlings or the whole plant. Similarly, Shackleton et al.[12] published co-created guidelines for *Prosopis* management in the peer-reviewed literature (a process driven by scientists), which have not been implemented. A reason for this was that there were not, and still are not, processes in place to ensure that government officials and other relevant stakeholders consider or implement the findings of the research (in many cases, such work is even sponsored by government departments but never adequately considered or acted upon). In an effort to make research findings more accessible, the biological control research community provides annual reports on the progress of government-funded projects to officials and managers who occasionally attend annual research meetings. These awareness-raising and capacity-building efforts appear insufficient to make findings and recommendations accessible to managers and policymakers.

When managing invasive species through collaboration, it is essential to recognise complexities, like different needs and conflicts, and the legal frameworks.[8] For example, in South Africa, legislatively the onus of invasive species management, including *Prosopis*, is on private landowners[13], but the government is responsible for public areas and communal lands. Despite government efforts, such as the Working for Water (WfW) programme, allocating substantial funds to manage invasive species on public and private lands, the effectiveness of management remains limited, with WfW targeting only 4% of the area invaded by *Prosopis.*[14] Scientists attribute this failure to various factors, including a lack of prioritisation, misguided success metrics and insufficient funding. Overall, one option to encourage the sustainable management of *Prosopis* and other plant invasions in the country is to promote collaboration and introduce integrated management, including the introduction of biological control agents.[15,16] However, this has at times been controversial, suffers from funding issues and requires coordination among stakeholders[17,18].

Management of invasions using biological control may be slow and sometimes less effective than expected; therefore, the biocontrol community has legitimate concerns about managing the expectations of stakeholders.[19,20] These concerns should, however, not hinder mutually beneficial relationships between land managers (responsible for the control of *Prosopis*), landowners, biological controllers or other relevant stakeholders. Ultimately, it is necessary to develop partnerships, which will ensure a virtuous cycle of information sharing between farmers, researchers and managers. An effective way of supporting such collaborations and expansive learning between relevant stakeholders is through an insider interventionist researcher who links communities to information[21]; this person can also act as a champion for collective learning[22]. However, this is not always easy to do.

This paper explores our efforts over the past half-decade to establish a community of practice that engages different stakeholders in partnerships to achieve the goal of effective management of *Prosopis* invasions in the Northern Cape, South Africa (see Box 1). We review the process followed, the promising outcomes and developments as well as some key successes and challenges faced.

Box 1: *Prosopis* species found in South Africa[23]

- *Prosopis chilensis* (Molina) Stuntz[9] – naturalised, may form hybrids
- *Prosopis glandulosa* J. Torrey [24]
- *Prosopis glandulosa* var. *glandulosa* J. Torrey[9,24] – naturalised
- *Prosopis glandulosa* var. *torreyana* (L. Benson) M.C. Johnston[9,24] – most problematic, forms hybrids readily
- *Prosopis juliflora* (Swartz) DC[9] – naturalised
- *Prosopis pubescens* Benth.[9,24] – naturalised
- *Prosopis tamarugo* F. Philippi[25]
- *Prosopis velutina* Wootan[9,24] – most problematic, forms hybrids readily

Prosopis invasions: History and management

Numerous species from the genus *Prosopis* were introduced from the Americas into arid regions of South Africa in the late 1800s to act as fodder, shade and fuelwood trees.[23-25] These *Prosopis* species, and hybrids thereof[23], are now invasive in arid areas of the country, with several negative social-ecological impacts[26-33]. Like many useful invasive species, during the early stages post-introduction, the benefits of *Prosopis* were positive, and increased initially.[7,26] However, once *Prosopis* populations got too dense, the supply of benefits dwindled and negative impacts arose. Ecological impacts of *Prosopis* invasions include reductions in insect, bird and plant diversity[27-29], increased mortality of native tree species[30], loss of scarce groundwater resources and grazing potential[31,32]. Social impacts include negative effects on local economies[26] and people's livelihoods[29,33]. With time, the net value of the *Prosopis* trees in South Africa becomes negative as the cost of managing the invasion and its negative impacts far outweigh any positive values. With the fall of benefits and rise in costs, most landowners in the Northern Cape now perceive the cost of *Prosopis* invasions outstrips the benefits of the plant.[10] Due to increased impacts and loss of benefits, many countries globally, including South Africa, are regulating and managing *Prosopis* invasions using various methods.[34-36]

Prosopis management in South Africa has initiated interactions between government officials, forestry and agricultural researchers, and landowners from the time of the first introduction of the species to the present. Between 1880 and 1960, the community was focused on establishing *Prosopis* populations (Figure 1) as forestry officials facilitated the planting of *Prosopis* on private and public land. Essentially, there was a 'community of practice' that worked together to promote *Prosopis* in arid areas. Van den Berg et al.[37] estimated that by 1974, *Prosopis* infested up to 127 thousand hectares in the Northern Cape Province (Figure 1).

Between 1960 and 1987, a new 'community of practice' took shape to understand the extent of unwanted *Prosopis* invasions and how best to manage the growing problem (Figure 1), of which biological control was considered the most sustainable solution. Biological control researchers in South Africa discussed the status of *Prosopis* at their annual research meetings and agreed that a researcher visit the Northern Cape to '*gauge the pest status of the species*'[38]. In order to understand the issue better, Harding[9] surveyed 175 landowners' opinions about *Prosopis* control. There was a strong response in favour of control of *Prosopis* with 51% calling for eradication and 24% suggesting a level of management to prevent further impact[9,23]. Even with this show of support for eradication, the research community 'erred on the side of caution' and chose to focus on biological control agents that damaged dry seeds in an attempt to reduce germination and did not consider natural enemies that might damage vegetative parts of the plants and kill either seedlings or adults. We might consider this a 'failure' of the community of practice at the time as researchers 'chose' to act contrary to the expressed view of the landowners (the most important and legitimate stakeholders). In all likelihood, the approach adopted by biological control researchers was motivated by the paper, 'Tactics for Evading Conflicts in the Biological Control of South African Weeds'[38,39]. This motivates for selection of a biological control agent that could reduce the spread of the plant but protect the pods used as animal fodder.[23,39] In 1987, after thorough research to confirm that three species of weevils (*Algarobius prosopis* (LeConte), *A. bottimeri* Kingsolver and *Neltumius arizonensis* (Schaeffer)) ate only seeds of *Prosopis*, managers released these weevils in large numbers across the Northern Cape. It was found that weevils could destroy up to 92% of seeds in ideal environmental conditions, but the 8% of seed remaining in the environment continued the spread of *Prosopis*.

From 1988 to 2002, the community gained insights into the impact of biological control and considered other approaches for the management of *Prosopis* (Figure 1). Even though the seed-feeding biological control agents appeared to be failing to halt the spread of *Prosopis*, there was an optimistic outlook for its management, a 2001 workshop proposed, that: '*in 20 years from now, invasive Prosopis in Southern Africa will be under control and confined to areas where it can be managed to deliver sustainable benefits*'[40]. Unfortunately, 23 years on, the optimism of this workshop has not delivered this vision; despite much further work, South Africa is far from reaching the goal of having *Prosopis* under control, and currently, invasions are estimated to be over 6 million hectares.

Establishing a collaborative *Prosopis* management initiative

In July 2018, researchers from the Agricultural Research Council – Plant Health and Protection and the Centre for Biological Control (CBC) met with the Natural Resources Management Committee of Agri Noord-Kaap (Figure 2). At this meeting, the biological controllers presented information

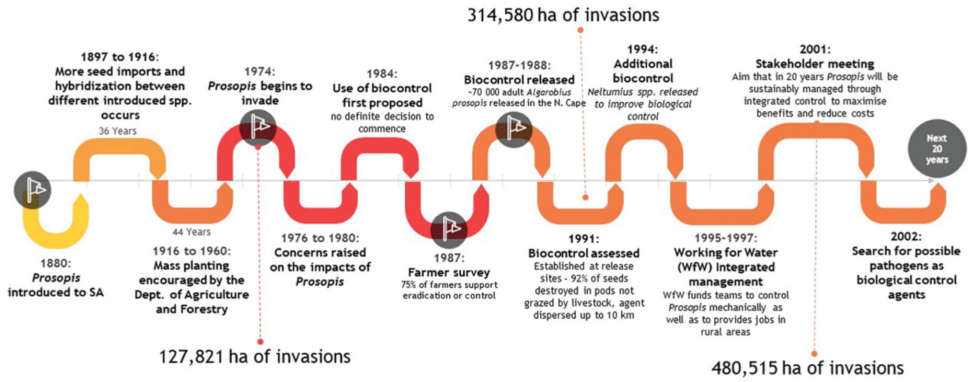


Figure 1: A visual description of the history of *Prosopis* in South Africa (1880–2002). Data were drawn from different sources referenced in the text and from notes of biological control meetings held during the period 1976–2002. The extent of *Prosopis* invasion as estimated by van den Bergh et al.[35] appears in 'ha of invasion'.

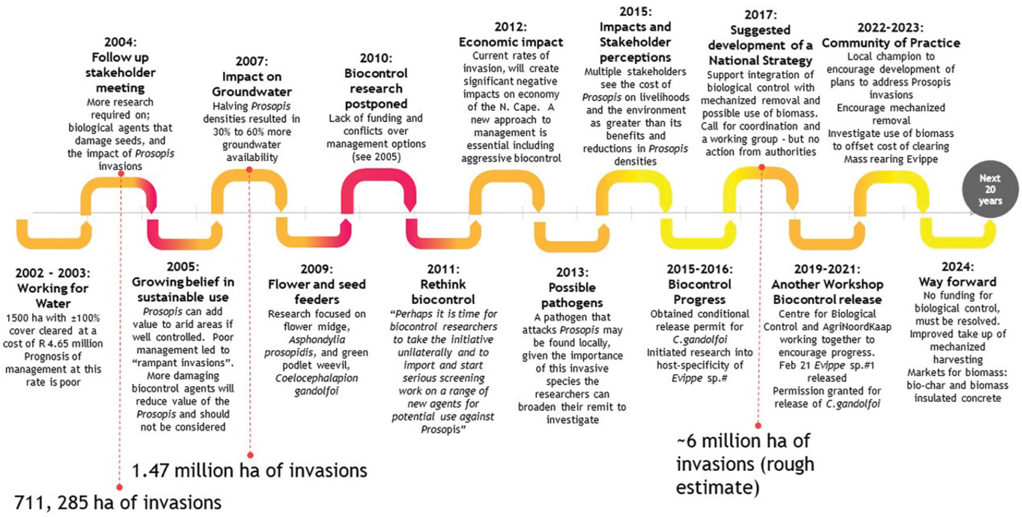


Figure 2: A visual description of the history of *Prosopis* in South Africa (2002–2024).

on the management of both *Prosopis* and cacti. After this initial meeting, Agri Noord-Kaap, in partnership with the CBC, co-ordinated and facilitated a workshop to discuss *Prosopis* management in February 2019. At this meeting, stakeholders from multiple backgrounds and institutions formed a working group to develop 'A National Strategy for Management of *Prosopis*'. Participants at the meeting developed the ultimate goal of promoting sustainable management of invasive *Prosopis* to protect lives, livelihoods and biodiversity. The partnership developed several drafts of the National Strategy, but there were numerous reasons why it went no further: COVID, drought, fire, locusts and the threat of land expropriation without compensation preoccupied many important stakeholders' minds more than the need to manage *Prosopis*. In 2021 and 2022, to promote momentum, champions focused on promoting further collaboration and learning initiatives.[22] In particular, a young researcher originating from a Northern Cape farming community co-ordinated awareness-raising initiatives and sustained interactions between different stakeholders. At a workshop in June 2022, farmers raised concern that the focus of management was too biased towards biological control, '*Ons het vergaderings, en jy bring net goggas en nog goggas*' (We have meetings and you just bring bugs and more bugs). In response to this, a roadshow was arranged (October–November 2022) where experts presented on invasive plant management, biomass use and use of *Prosopis* pods. The content from these roadshows was well received and slowly cooperation improved. The primary local 'champion' has now moved on, but the established networks and relationships continue, and new leaders in the collaborative network have taken up tasks.

Promoting sustainable *Prosopis* management

Through a series of meetings and workshops involving numerous stakeholder groups, we explored intermediate and final goals, including behaviour changes and actions required to achieve 'the Sustainable management of invasive *Prosopis* to protect lives, livelihoods and biodiversity' (Figure 3). We explore these intermediate outcomes below.

Farm-scale plans for *Prosopis* management

The proposed National Strategy for *Prosopis* management[12] which was co-developed by stakeholders from various backgrounds recommended the development of a manual for private landowners outlining best practices for farm-scale management of *Prosopis*. This was important to promote local support, which was necessary to effectively manage *Prosopis* invasions. Subsequent to the 2019 stakeholder meeting, the working group considered this and proposed targets for farm-scale plans:

- Engage experts to develop a template for *Prosopis* management plans.
- Encourage each landowner to produce a management plan.
- Aim for 300 plans by December 2025.
- Encourage 300 plans annually thereafter.
- Encourage landowners from adjacent farms to work concurrently to enable expert to visit groups of farmers at one time.
- All 3600 Agri Noord-Kaap registered farmers to have plans in 12 years.

To achieve the proposed targets, the CBC engaged a private company to develop a template and work with 30 farmers, to prepare plans that included not only an emphasis on biological control but also guidance on herbicide use and post-clearing follow-up (company's expert knowledge). Despite the development of the template and promotional roadshows in October and November 2022, attracting over 150 stakeholders, farmer

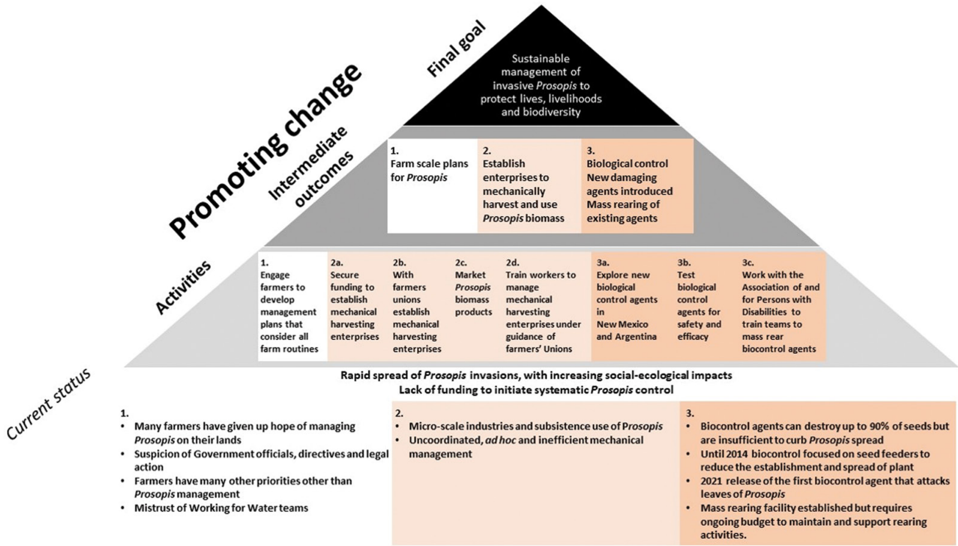


Figure 3: Changes in behaviour and actions required to reach the final goal of 'Sustainable management of *Prosopis* to protect lives, livelihoods and biodiversity'.

responses to date have been low, suggesting that despite successful awareness raising and outreach at the time, behaviour change and acceptance of a different approach can be challenging. In February 2023, the consultancy company that developed the plan reported that they, were '*battling to get farmers to come forward and join for management plans to be drawn up for their property*'. They attributed these challenges to the following factors: (i) farmers fear that a management plan of this nature would lead to the Department of Forestry, Fisheries and the Environment issuing 'directives' that force them to clear their land or face legal proceedings, and (ii) some farmers have a lack of knowledge of, and fear of, technology, which hampers their use of tools such as Google Earth to map the populations of invasive alien plants on their properties. This highlights the importance of ensuring trust, clarity and transparency as well as inclusivity by ensuring the accessibility of tools and technologies and knowledge for all when developing collaborative environmental management initiatives.

To this end, 13 farms were selected for the development or review of their invasive species management plans: three in the Groblershoop area (owned by a single family), two in the Carnarvon area and eight farms in the Brandvlei area. In order to encourage more farmers to make use of the offer of assistance to develop and review plans, we circulated messages on community communication groups, after which a further nine farmers from various parts of the Northern Cape indicated an interest in the development of plans. Of these, four were able to host a visit from the consultant during April 2023. The following useful insights have been gained to date:

- Farmers focus on dense stands of *Prosopis*, feeling helpless. As such, we need to change mindsets to start small and grow with time and show examples that exist where dense invasions have been removed and emphasising the benefits of clearing less dense infestations first.
- There are negative perceptions of WfW's effectiveness (poor work ethic, long travelling times that limit the number of hours of effective work on site and these, at the hottest part of the day). As such, better strategies should be developed collaboratively between farmers and government-managed programmes to improve efficiency.
- Choice of what herbicide to use is sometimes poor and based on what is already available on the farm or the WfW store and not what is most effective.
- The available labour force on farms is low and limits the ability for physical control. This supports the need for better biological control initiatives.
- A 9-year drought has had major impacts on grazing and farmers' finances to fund control initiatives. This highlights that plans need to be cost-effective and adaptive when other priorities become more important.
- The value of land (ZAR300–ZAR1000/ha) is lower than the mean costs of *Prosopis* management ($\geq$ R6000/ha). As a result, farmers are not inclined to invest in clearing *Prosopis* and will rent land for grazing rather than address the invasion. This suggests that cost-effective strategies such as biological control or cost-saving/mitigation strategies are needed (e.g. use of biomass).

Options for management

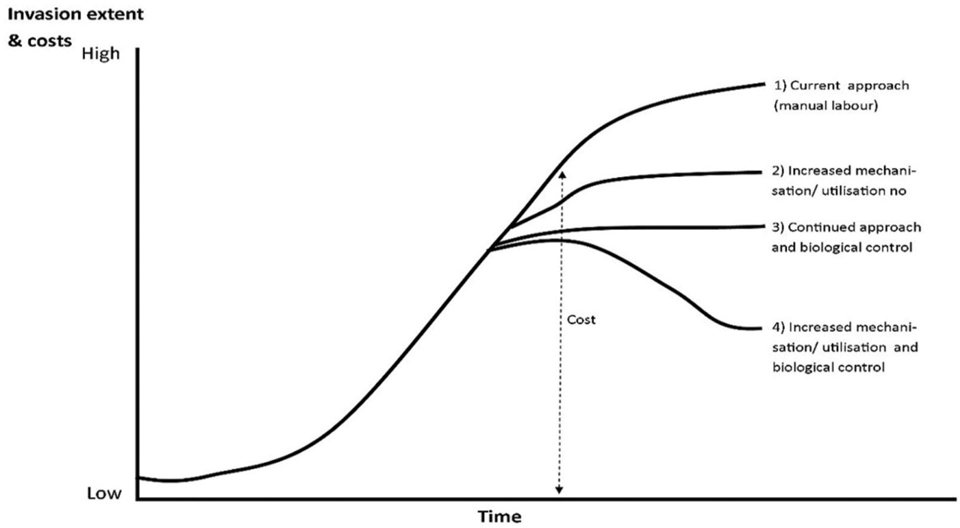
Effective management strategies are crucial to reduce the impacts of *Prosopis* invasions, and integrated approaches are likely to achieve the best results. Based on previous collaborative work and the opinions of stakeholders at a facilitated workshop, we consider four different scenarios[12] (Figure 4):

- Current approach: Maintaining the status quo (uncoordinated manual clearing) would lead to increased invasion extent and management costs.
- Increased mechanisation: Enhancing mechanical control and the use or sale of biomass to manufacture higher value products to offset costs.
- Biological control: Investigating and introducing biological control agents that damage plants and not only seeds.
- An integrated approach: Integrating increased mechanisation, use of *Prosopis* biomass and employing more damaging biological control agents together.

While efforts in Kenya to limit *Prosopis* spread through utilisation have not been effective[36], South Africa's unique context, including landownership and an existing biological control programme, suggests that the fourth scenario, with careful planning and effective biological control, could potentially curb *Prosopis* spread.

Mechanical harvesting and utilisation of biomass

The cost of clearing *Prosopis* trees is high, so the working group investigated options to utilise biomass to cover the costs of control. Marais et al.[41] estimated that the initial clearing of *Prosopis* cost on average ZAR1730/ha. Almost two decades later, Shackleton et al.[12]



Source: Shackleton et al.[12] (reproduced with permission)

Figure 4: Scenarios of the potential extent of *Prosopis* invasion and associated costs over time based on different control options, combinations of options and their potential effects on invasion extent.

estimated the costs of labour-intensive clearing with chain saws and brush cutters to be ~ZAR9000/ha and the costs of mechanised clearing to be ~ZAR10 000/ha. A way of 'subsidising' these costs through potentially using biomass is needed. There might be competing interests between those who have developed income-generating industries around the exploitation of a resource[42], such as *Prosopis*, which land managers want to remove from the landscape. The greatest benefit of *Prosopis* management is the restoration of access to groundwater and grazing and not any income generated from use of the biomass. Therefore, restoration of ecological infrastructure is the ultimate aim of *Prosopis* management, and utilisation is a means to minimise initial costs. Furthermore, encroaching indigenous tree species such as Swarthaak, *Senegalia mellifera* (M. Vahl) Seigler & Ebinger has impacted the quality of grazing and can potentially provide biomass to ensure the sustainability of biomass businesses.[43] The working group identified several possible uses of *Prosopis* biomass, including firewood, charcoal/briquettes, biogas and biomass-insulated concrete materials.

Firewood: Farm managers believe the market for firewood from *Prosopis* to be saturated and that many users prefer to use wood from indigenous trees.[33] The costs of both production (controlling *Prosopis* and preparing firewood) and transporting firewood to market makes this use of biomass uneconomical.

Charcoal and briquettes: Low-input technology (200-litre iron drums) can produce charcoal from *Prosopis* that is suitable for restaurant's barbeque fires and pizza ovens. If there is a local market and other activities carry the cost of transport, then production of charcoal may defray some of the expense of *Prosopis* control. For example, over four months, the cost of managing *Prosopis* and producing the charcoal was ZAR120 000, and the income was ZAR60 000 for 7200 kg, thus covering half of control costs. Charcoal production results in smaller pieces that the farmer cannot sell. One option is to manufacture briquettes from these pieces, but this requires special machinery.

Boskos fodder: To manufacture a cost-effective and abundant fodder, some farmers mill *Prosopis* leaves and branches to which they add sources of protein and energy as necessary. This allows farmers to address the specific nutritional needs of their livestock. This fodder source is both economical and readily accessible and offers a solution for emergencies such as droughts or providing sustenance to animals after wildfires, when natural grazing is scarce. Fodder 'recipes' must comply with current legislation and must be registered accordingly. Further research is required to determine the feed composition for different seasons to ensure consistent nutritional values, and this presents a further avenue for collaboration between academics and farmers moving forward.

Biogas: Engineers have investigated the production of biogas from *Prosopis*. While the technology is currently unproven, it has the potential to supply both heat and electricity for agro-industrial processes (possibly even for export to Europe). This form of electricity generation is appealing given the uncertainty of electricity supply from the national grid. Again, more collaborative and transdisciplinary work is needed on this.

Biomass-insulated concrete construction: This approach aims to improve the thermal and noise insulation qualities of buildings, replace sand and stone aggregate with biomass (possibly invasive alien plants) and reduce greenhouse gas emissions from the combustion of biomass by fixing carbon in building structures.[44] Researchers combined fine biomass chips with fly ash, cement and chemical binders to prepare a sample, which proved that *Prosopis* is acceptable for biomass-insulated concrete construction. The CBC and the Association of and for Persons with Disabilities (APD) required an office and a store at the biological control mass-rearing facility in Upington, which were built using *Prosopis* biomass-insulated concrete techniques (Figure 5). Relevant stakeholders can see this construction technique by visiting these two units. By creating a market for this construction method, farmers will be able 'sell' *Prosopis* biomass to construction companies, enabling them to get some reimbursement for the control costs.

Biological control research and implementation

A core avenue for management identified in the collaborative workshops was the use of biological control.[12] This approach has caused controversy that has limited its use, as *Prosopis* was seen as beneficial by some landowners in the 1980s.[9,45] As such, only agents that ensured the continued supply of *Prosopis* benefits (fuel/fodder) were considered. In 1984, the Plant Protection Research Institute initiated research to introduce seed-feeding insects that are specific to *Prosopis*. After extensive testing of the host-specificity of *Algarobius prosopis* (60 different species of legumes were tested), the government authorities deemed this species safe for release in South Africa.[23] Even though this seed-feeding agent can destroy up to 92% of seeds under optimal conditions, and is able to spread rapidly[23], it is estimated that the size of the *Prosopis* invasion continued to grow from 127 000 ha in 1974 to over 314 000 ha in 1990[37] (Figure 1).

Between 1999 and 2011, the biocontrol community restricted research to two species of natural enemy, one that damaged flower buds (*Asphondylia prosopidis*) and the other that targeted seeds in the green pods (*Coelocephalapion gandolfoi*) (Figure 2).[46] From 2014, biocontrol research began on natural enemies that damaged the whole plant with research into the suitability of *Evippe* sp. #1 for South African release.[47] The aim of biological control of *Prosopis* is not to eradicate but to reduce the density, spread and impact over time, to a level at which the plants do not have a significant negative impact on the environment (Figure 6). In September 2020, the Department of Agriculture granted permission for the release of *Evippe* sp. #1, and the first releases were made in February 2021. Likewise, in 2019, researchers completed the final testing required for the release of *C. gandolfoi.* Finally in November 2021, with the help of farmers who found sites with *Prosopis* that had suitable green pods, *C. gandolfoi* was released.

After the Department of Agriculture granted permission to release additional biocontrol agents, mechanisms to promote equity inclusion and social justice in the programme were also considered. There are extremely few work opportunities for the approximately 45 000 persons with disabilities in the Northern Cape.[48] Much of the population of this region is rural, and this can further entrench persons with disabilities in poverty, as transport distances and costs restrict access to work opportunities and health care.[49] To this end, the CBC engaged organisations (particularly the APD) that support persons with disabilities and those living in poverty to see if the rearing of biological control agents could be an avenue to create meaningful work for them[50,51] and work towards the goals of the APD, which is to empower, uplift and assist the disabled person in such a manner that they will be able to function independently and earn their own income or at least have funds supplementary to their social grant. The CBC further has collaborated academically with biokineticists to develop biocontrol facilities that provide suitable work environments for persons with disabilities.[52]

With co-funding from the Department of Forestry, Fisheries and the Environment and private entities, the CBC and APD erected a mass-rearing nursery tunnel, offices, storeroom and ablution facilities (all with wheel chair access) at the APD premises in Upington and a team including persons with disabilities has been created (Figure 7). Long-term funding remains essential for this project to succeed, and funding from different sources is vital, as central government funds appear unreliable. Without sponsorship, it would be impossible for APD to provide services and help or assistance to the members of the workshop. This highlights the importance of sustained co-funding to ensure the success of early investments and the sustainability of the whole programme.

Figure 5: Clockwise from top left. *Prosopis* invasion in Groblershoop area, illustrating absence of grass and shrubs for grazing, felled biomass, biomass chips for biomass-insulated concrete construction, different aggregates in 'concrete', *Prosopis* biomass building in Cape Town and completed buildings made from *Prosopis* biomass-insulated concrete at APD Upington.

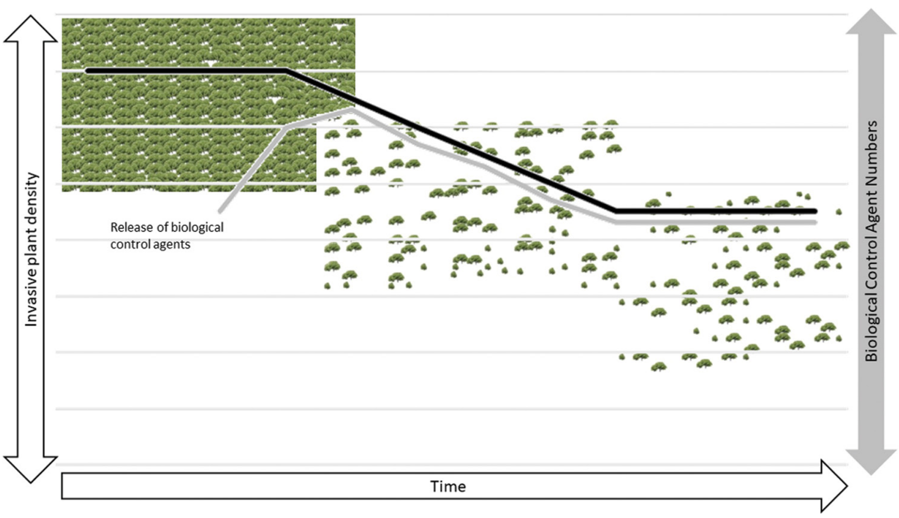


Figure 6: The desired outcome of biological control of *Prosopis* over time.

Figure 7: Training day: Hennie le Roux, Montell Solomon, Anika Coetzee, Steven Sifumba, Johnie Jafta, Rebecca Saulse, Geraldine du Raan, Erin-Pearl Tyers, Corné le Roux, Christopher Strauss, Vuyani Ntlanganiso, Katrina Maklaro, Thabelo Khoele and Philip Ivey.

Discussion and way forward

It remains essential to establish meaningful engagement, co-management and learning, and reduce research-implementation gaps to ensure the successful management of biological invasions.[8,11,53] With regards to the management of *Prosopis* in South Africa in the past, there has been some engagement[12], but the continuity has been lacking, and most research to date has rather treated people as research subjects[10] and not collaborators working together to address shared problems. Realising these past limitations, the CBC has aimed to promote collaborative research and management for *Prosopis* over the past half a decade. Since 2019, the collaboration among stakeholders for the management of *Prosopis* has made good progress. On reflection, the following lessons have been learnt through the process:

- Finding an initial champion to act as an insider researcher and lead collective learning in the Northern Cape community, which has a small number of people spread over a large area, was challenging, but it helped us progress. Forming this community of practice, through the identified champion, better enabled stakeholders (including farmers and researchers) to communicate with one another and share challenges, which has been extremely beneficial. In addition, this collaboration has led to the emergence of new champions in different institutions, which has and will promote continued collaboration into the future.
- Stakeholders are keen to better manage *Prosopis* on their properties but are overwhelmed by the problem and often have more important farming issues to address, even though *Prosopis* invasion can destroy livelihoods if not addressed. Finding adaptable methods to manage multiple stressors simultaneously was identified by stakeholders as a key entry point to promote sustainable management.
- The management planning approach collaboratively developed by scientific experts and land owner experiences aims to make the farm more manageable by focusing operations to open roads, water points and fences, and then to target areas where success can be achieved. Success in this has been demonstrated and promoted in workshops and roadshows to help landowners overcome a sense of helplessness. Although awareness has been raised, more work is needed to promote buy-in and behaviour change and for landowners to adopt and implement plans.
- Through engagement and social learning processes, biocontrol is now better understood and accepted by the stakeholders. This is best illustrated by the assistance received by local stakeholders in identifying sites for the release of *C. gandolfoi*; this has allowed landowners to co-own the post-release research and be part of the research process. In addition, this improved understanding and acceptance, which has even led to co-funding mechanisms in biological control facilities which would have never previously been thought of. More work is required to raise understanding of stakeholders of concepts such as host-specificity and establishment of founder populations, but the foundations are established for this collaborative learning. One approach might be to develop a biocontrol monitoring programme managed by stakeholders.
- Collaborations between academics and non-governmental organisations (NGOs) have identified and developed ways to ensure that the mass rearing of biological control agents to target *Prosopis* can provide meaningful work for people living with disabilities.[53] In addition, engagement has led to the successful co-funding between various public and private institutions to erect needed facilities. Sustained funding is required to support this initiative, which remains a challenge, but through further co-financing by various stakeholders, it could be achieved. This will require maintained regular engagement and collaboration into the future.
- There are several ways in which *Prosopis* biomass can be processed into products, including biochar and biomass-insulated concrete construction. This would benefit many stakeholders through covering control costs, establishing new industries and promoting job creation. Working together various stakeholders need to collaborate to build the market for these products.

Overall, we suggest that moving forward, research on controlling plants like *Prosopis* should be less about 'studying what the farmer and other stakeholders want' but about how the 'researcher becomes more part of the farmer's/stakeholders' reality' and developing a sustainable partnership between all the stakeholders with a joint mission. We illustrate in this study that this is possible and believe this should become a common practice to reduce research implementation gaps into the future.

Acknowledgements

We acknowledge the insights on persons with disabilities from Vanessa Tyers. Any opinion, finding, conclusion or recommendation expressed in this material is that of the authors. We acknowledge contributions to this paper by students and colleagues of the authors.

Funding

This work is based on the research supported in part by the National Research Foundation of South Africa (grant number: 84643). Other funding was provided by the Department of Forestry, Fisheries and the Environment. R.S. was partially funded by the Swiss National Science Foundation (SNSF) and the Swiss Agency for Development and Cooperation (SDC) as part of the Swiss Programme for Research on Global Issues for Development (r4d), for the project 'Woody invasive alien species in East Africa: Assessing and mitigating their negative impact on ecosystem services and rural livelihood' (grant number: 400440_152085).

Data availability

The data supporting the results of this study have not been made available by the authors in any format.

Declarations

We have no competing interests to declare. MS Word – review tools (https://www.microsoft.com), Google Scholar (https://scholar.google.com), ChatGPT (https://chat.openai.com), Crossref (https://search.crossref.org) and MS Power Point (https://www.microsoft.com) were tools used to check summaries and improve language, collate and compile references in journal format, identify links with SDGs, and prepare diagrams.

Authors' contributions

P.I.: Conceptualisation, data collection, writing – the initial draft, writing – revisions, project leadership, funding acquisition. G.v.S.: Conceptualisation, data collection, writing – the initial draft, project leadership, funding acquisition. G.H.: Writing – the initial draft, project leadership. D.O.: Data collection, writing – the initial draft. E.H.: Writing – the initial draft, funding acquisition. P.v.S.: Data collection, writing – the initial draft. E.A.: Writing – the initial draft, funding acquisition. K.W.: Conceptualisation, funding acquisition. M.H.: Conceptualisation, project leadership, student supervision. R.S.: Conceptualisation, writing – the initial draft, writing – revisions. All authors read and approved the final manuscript.

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