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Science is the fuel required for lifting ecosystem restoration into the orbit of hundreds of millions of hectares

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Restoring the hundreds of millions of hectares of degraded ecosystems worldwide will require new approaches to raise the required funds and new systems to implement at the required scales. Two decades of large-scale restoration in the subtropical thicket biome in the Eastern Cape, South Africa, have generated valuable information for developing such approaches and systems. The successful upscaling of restoration in this biome can be attributed to four main actions. First, from the outset in 2003, peer-reviewed science was foundational to the entire restoration initiative. Second, also from the outset, there was a commitment to large-scale, long-term ecological research by the public sector (the then Department of Water Affairs and Forestry in South Africa), which resulted in what is to our knowledge the world's largest ecosystem restoration experiment, comprising 330 quarter-hectare plots distributed over ~75,000 km^2. Third, retrospective scientific description of previous restoration work — done by farmers in the 1960s and 1970s — provided valuable information on restoration's multiple benefits, without having to wait for the large-scale restoration experiment to yield results. Lastly, diverse and short-term scoping studies were undertaken to address questions that emerged during the large-scale implementation of restoration. These studies were vital for rapid adaptive management and planning new scientific experiments, filling a gap between long-term ecological research and retrospective science.

KEYWORDS

arid ecosystems, ecosystem restoration, land degradation, large-scale research, subtropical thicket

1 Introduction

The UN Decade on Ecosystem Restoration calls for investments of a trillion dollars into the restoration of hundreds of millions of hectares of degraded land across the globe by 2030 (UNEP/FAO, 2020). Two decades of restoration efforts in the subtropical thicket biome in the Eastern Cape, South Africa (Mills et al., 2015) have provided some of the most valuable information available internationally to assess the investment and implementation models for such large-scale ecosystem restoration. In 2003, restoration efforts in the thicket biome were catalysed by public-sector finance with the express purpose of raising private-sector funding to take restoration from a plot scale to a biome scale. Currently, there are at least eight private-sector companies, of which we are aware, that have formed to implement thicket restoration at the scale of tens to hundreds of thousands of hectares, leading to the creation of many hundreds of jobs, and the planting of many tens of millions of cuttings of the indigenous succulent tree 'spekboom' (*Portulacaria afra* L. Jacq., Didiereaceae) (Figure 1). In short, the vision for large-scale restoration funded by the private sector developed in 2003 (Mills et al., 2007) has materialised. Here, we provide a perspective on the four main actions — that could be replicated in other ecosystems worldwide — that led to this success. We end with an overview of how we think subtropical thicket restoration efforts could be optimised and further honed over the next ten years of this multi-decadal ecosystem restoration journey.

2 Actions of success to date

The first main action of success was ensuring that peer-reviewed science was foundational to the restoration programme. This required a commitment from the main stakeholders (the government department providing funding[1], research institutions, and consulting scientists) to publish peer-reviewed scientific papers that would provide a credible knowledge base upon which the entire restoration programme would be built. The rationale was that private sector funders would most likely only finance large-scale projects with budgets of tens or hundreds of millions of dollars if the technical approaches and investment benefits were well documented in peer-reviewed literature. This rationale appears to have been supported in that the public founding documentation of the various implementation companies and the Verra project documentation refer extensively to the published literature, especially papers such as Mills et al. (2005); Mills and Cowling (2006); Mills and Cowling (2010) and van der Vyver et al. (2013).

The second action was committing at the outset to large-scale, long-term ecological research rather than plot-scale, short-term experiments. This commitment, maintained for two decades[2], led to the establishment of what is, to our knowledge, the largest ecosystem restoration experiment in the world — 330 quarter-hectare fenced plots, distributed over the ~75,000 km^2 extent of degraded parts of the xeric succulent thicket biome (Mills et al., 2015), with 12 different restoration treatments in each plot. The success of these 'thicket-wide plots' (Figure 1) has also played a major role in convincing investors that large-scale restoration in the thicket biome is feasible.

The third action was identifying and studying several sites of restoration work implemented by farmers in previous decades. The retrospective scientific description of this uncoordinated restoration (e.g., Mills and Cowling, 2006; van der Vyver et al., 2013) provided sufficient insight and supporting data to interest investors and other scientists without having to wait a decade or more for the results from the thicket-wide plots. This action enabled momentum to be built within the investment community both in the private and public sectors (Mills et al., 2015) early on in the restoration journey, which was later accelerated as the results of the thicket-wide plots were published.

The fourth action ensuring success was undertaking diverse scientific scoping studies to fill specific, emerging knowledge gaps that became apparent during restoration implementation. We found that such studies (Table 1) were vital for maintaining the momentum of investment into restoration, generating the information needed for rapid adaptive management practices during project implementation, and for planning new, long-term scientific experiments.

3 Inevitable knowledge gaps

Large-scale restoration will, we suggest, always have the challenge of managing knowledge gaps, no matter how rigorous the long-term ecological research and retrospective science taking place in parallel. This is because many ecological factors influence the restoration of a natural ecosystem — many of which vary on monthly, daily or even hourly bases[3], and most of which will remain unmeasured, no matter how large the research budget. The consequence of so many unmeasured factors is that it is difficult to pinpoint which factors determine the success or failure of restoration in a particular long-term experimental plot, and whether success or failure in landscapes adjacent to the plot will be reproducible[4].

Although the problem of unmeasured factors and unpredictable events adversely affecting the restoration outcome[5] can never be fully overcome, we found that implementing diverse scoping studies

1 At the time, the Department of Water Affairs and Forestry in South Africa.

2 The Subtropical Thicket Restoration Programme (STRP) was established in 2004 by the then Department of Water Affairs and Forestry (South Africa). It was formed to catalyse public and private sector funding into restoration of the thicket biome. More than 10,000 hectares of degraded thicket have been planted with spekboom cuttings through this programme to date. Unfortunately, the momentum of this government-funded programme has subsided in recent years.

3 e.g., soil water content; soil temperature; soil oxygen status; soil microbial activity; abundance of soil meso- and macro-fauna; soil nutrient availability; herbivory pressure from insects, reptiles and mammals; health of parent plants from which cuttings are taken.

4 In 2021, we planted several hundred thousand cuttings near a thicket-wide plot with high survivorship (see Figure 1G). Most of these cuttings died. We formed the view that during some months of 2021 the soils were too wet for the planted cuttings, causing rotting and termite damage, and that in other months, conditions were too dry and windy, causing desiccation and extreme herbivory pressure. Presumably, the year in which that plot was planted was neither too wet nor too dry, but data on soil water content, soil microbial activity, termite activity and herbivore pressure was not collected; it is consequently not feasible to examine this hypothesis.

5 Referred to as non-demonic intrusions by Hurlbert (1984).

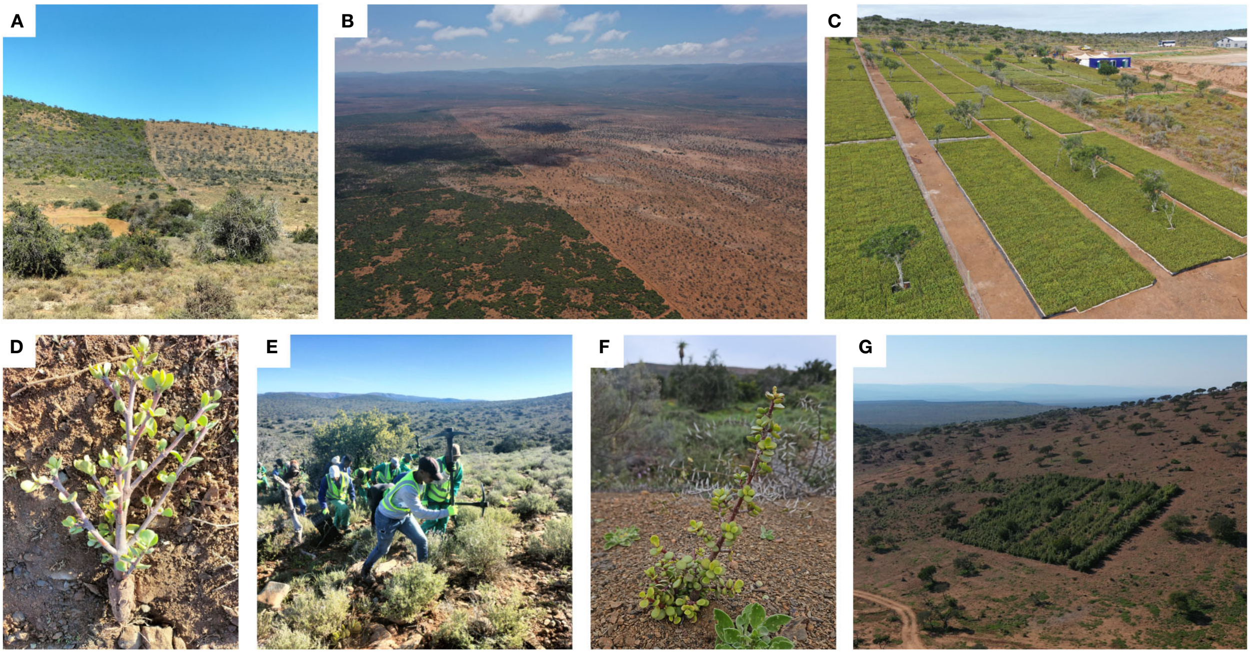

FIGURE 1
Ongoing subtropical thicket ecosystem restoration and research in the Eastern Cape, South Africa. **(A, B)** Fence-line contrasts showing intact versus degraded thicket. **(C)** A nursery in the Sundays River Valley in which spekboom (*Portulacaria afra*) cuttings are propagated *en masse* in seedling trays. **(D)** A cutting (with a well-formed 'root carrot') that is ready to be planted into the field. **(E)** A field team planting rooted cuttings into a degraded thicket landscape. **(F)** A recently planted rooted cutting. **(G)** A thicket-wide plot that had a high survivorship of planted cuttings.

(Table 1) and undertaking hourly monitoring of cuttings using camera traps provided valuable information for steering the large-scale implementation of planting tens of millions of cuttings over thousands of hectares. Scoping studies, for example, showed that pre-rooting cuttings before planting them resulted in vastly improved survivorship in both wet and dry periods. And camera traps showed which herbivores were causing the most damage to plants through uprooting and/or eating leaves, stems and bark (Table 1).

Budgetary constraints usually require prioritising certain scoping studies and monitoring procedures over others. Such decision-making is important, but our view is that the in-field brainstorming of ecologists to formulate new hypotheses and to design monitoring protocols for testing them is of even greater importance. We found that new ideas and hypotheses on how to improve the restoration process were easier to generate in the field than off-site. Without the range of competing hypotheses that were generated during weeks of observing restoration plots in a variety of landscapes, the scoping studies and monitoring we undertook would have had considerably less value[6].

6 For example, the root dynamics of planted cuttings had not been examined over the first decade of the restoration work in thicket. We found in our fieldwork that fungi and termites often damaged roots in wet soils shortly after planting unrooted cuttings, and that many old (>5 years) plants that had survived but not grown substantially often had small root masses. Understanding the dynamics of successful rooting became a major theme in our scoping studies.

4 Breeding further success

Looking ahead to the next ten years of subtropical thicket restoration, as the scale of restoration increases into the hundreds of thousands of hectares, we argue that all four actions described above need to remain front and centre, but with some modifications. For the first action, we encourage funders to hold scientists accountable and ensure that data is published in peer-reviewed literature rather than languishing in unpublished reports. A large proportion of the data collected over the past two decades in subtropical thicket, funded from South African tax revenue, has not been published and is unavailable to the public. The publishing of these data and their interpretation should not rely on the intentionality of individual scientists but rather should be required by funders, with major penalties for non-compliance.

For the second action, we would advocate fundraising to implement as many long-term, large-scale experiments as possible, but with the caveat that they are monitored frequently and adjusted early on based on the findings of concurrent scoping studies. In the case of the thicket-wide plots, major investment into maintenance of the plots and examination of the effects of 15 years of restoration in terms of biodiversity, carbon capture and hydrology is now required. This investment requires intensive coordination and management by either a new coordinating institution formed for this purpose or an existing institution[7].

7 e.g., the South African National Biodiversity Institute (SANBI).

TABLE 1 Scoping studies conducted in parallel with large-scale restoration of degraded subtropical thicket in the Eastern Cape, South Africa, over the period 2020–2023.

Directly affected restoration protocols	
Rooting of cuttings in a nursery prior to planting in field	This study showed that mortality of pre-rooted cuttings is negligible, even in intense droughts. Investors now consider rooting cuttings an insurance policy against droughts.
Camera traps for assessing herbivory effects on cuttings planted in field	In certain patches of the landscape, the majority of planted unrooted cuttings can die as a result of animals (e.g., impala, *Aepyceros melampus* Lichtenstein 1812; grey duiker, *Sylvicapra grimmia* L. 1758) pulling or defoliating freshly-planted cuttings out of the ground before they have had a chance to root. And in extreme drought, herbivory pressure from unexpected grazing animals (e.g., Cape hare, *Lepus capensis* L. 1758; common warthog, *Phacochoerus africanus* Gmelin 1788) occurred. Where there are large numbers of these small herbivores, established cuttings can remain 'bonsaied' (i.e., prevented from growing much larger than their initial size) for decades. Management of such herbivores is consequently now a major component of large-scale restoration initiatives. Before the information from camera traps was available, only greater kudu (*Tragelaphus strepsiceros* Pallas 1776), Chacma baboon (*Papio ursinus* Kerr 1792) and black rhinoceros (*Diceros bicornis* L. 1758, restricted to protected reserves) had been speculated to be potentially problematic for restoration using spekboom cuttings (Mills and Cowling, 2006; Powell, 2009; van der Vyver et al., 2021).
Parent plant health and vigour of cuttings	This work is ongoing, but early results suggest that if parent plants are drought-stressed, then cuttings are less likely to thrive in the field or in a nursery setting. Harvesting of cuttings is now only done when parent plants are not drought-stressed.
Timing of watering after planting affects root development in unrooted cuttings	Dry spells with extended periods of low soil moisture are common in the subtropical thicket. Not watering cuttings for 28 days after planting had minor effects on their growth. However, differences in health and condition of individual parent plants had an overriding influence on root growth (Galuszynski et al., 2023).
Soil type's influence on root development	In historical aerial imagery (~1939), many open areas in solid thicket (*sensu* Vlok et al., 2003) could be attributable to differences in soil type. Cuttings were grown in soil from degraded thicket and neighbouring, historically open areas, resulting in high and negligible rooting, respectively. The latter soil had a high calcium carbonate content, and such soils are expressly avoided for restoration operations.
No effects on restoration protocols to date	
Planting rooted cuttings on a monthly basis	Results from this study suggested that the timing of rainfall is more important than the time of year of planting. There is no evidence from the study to date that indicates planting of rooted cuttings should be stopped during certain times of the year. However, growth chamber experiments demonstrate that ambient temperatures typical of winter result in reduced rooting of unrooted cuttings. This effect may not have been apparent in a separate field study of unrooted cuttings because of the north-facing (i.e., relatively warmer) slopes of the study site.
Planting rooted cuttings at different depths	There is no evidence to date from this study that planting deeper than 5–10 cm is necessary.
Soil treatments	No strong evidence has emerged to date that adding compost, clay, waterbinding gels, mycorrhizae or nutrients to cuttings in the nursery or in the field has a marked effect on rate of rooting. This is work in progress and warrants further investigation. It is likely that optimising soil conditions will ultimately speed up rooting. It is, however, questionable as to whether a fast-rooting cutting in a nursery will be a drought-resistant, hardy cutting in the field.
Micro-cuttings	Mortality of rooted cuttings with a basal stem diameter of a few millimetres during a drought in the field was surprisingly low. The cost of using such cuttings for restoration is likely to be considerably less than using larger cuttings. However, this potential saving needs to be weighed up against the likelihood of slower accumulation of biomass in the field and the potential for greater rates of mortality in the nursery during hot spells.
Planting in nurse shrubs	Survivorship of rooted cuttings within thorny nurse shrubs is greater than in the open (i.e., outside of the shrubs) at many sites. It is not, however, known to what extent growth is inhibited by competition from these shrubs.

For the third action, we suggest that project developers and funders actively seek additional sites for retrospective study. This is in contrast to a more *ad hoc* approach[8] in which such sites are only studied if there happens to be a curious scientist involved who wants to embark on this type of work. Again, funders should hold contracted scientists accountable for publishing the data collected.

For the fourth action, we suggest that funders ensure that there is a substantial investment into applied research comprising small scoping studies that take place in parallel to the implementation of the large-scale restoration. Our experience is that there is no substitute for in-field discussions between multi-disciplinary scientists and restoration practitioners for generating worthwhile hypotheses, thought experiments, and new management approaches. We also found that scientific creativity in the field benefited greatly from certain rules of engagement: actively seeking new hypotheses to counter existing hypotheses with regards to the ecological processes at play and how restoration should be conducted; using a wide variety of thought experiments to debate the strength of the various countering hypotheses; and then using the outcome of the debates to set up scoping studies to test competing hypotheses.

Topics which we anticipate will lead to new scoping studies relate to *inter alia*: the facilitative role that the thicket ecosystem engineer 'spekboom' (*P. afra*) plays in promoting natural regeneration of indigenous thicket plants (Sigwela et al., 2009; van der Vyver et al., 2013); quantifying the return of bird and insect species in the thicket-wide plot experiments using eco-acoustics technology (Grant and Samways, 2016; Stowell and Sueur, 2020; Maeder et al., 2022); the considerable increase in herbivore carrying capacity once *P. afra* has established, and the establishment of

8 Which was the case in the STRP.

sustainable herbivory levels to prevent re-degradation; the potential to greatly expand the range available to black rhinoceros (*Diceros bicornis*) by planting *P. afra*; the potential for nurturing cuttings in a nursery environment (using, for example, shade, mycorrhizal inoculants, fertilizer and water) that ultimately do not thrive in the field; and how to manage herbivores, whether domestic or indigenous, to enhance rather than degrade the ecological function of restored thicket.

Lastly, we note that funders and investors should be prepared for some, or even many, of these scoping studies not to go as planned. Some may fail, or yield no results of consequence, while others may yield completely unexpected results. This is the nature of ecosystem restoration: success follows a pathway of failures and surprises. Preparing for failures and welcoming surprises should consequently be fully embraced by all stakeholders embarking on a new restoration journey. Although success breeds success in large-scale restoration, failure and surprise perhaps breed even more.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

Author contributions

AJM: Conceptualization, Writing – original draft, Writing – review & editing. RD: Writing – review & editing. RGL-O: Writing – review & editing. RvM: Writing – review & editing. AJP: Writing – review & editing.

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Conflict of interest

Authors RD and RvM were employed by company C4 EcoSolutions, supervised by AJM during the course of this research.

The remaining authors declare that this research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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