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A conceptual framework for understanding ecosystem trade-offs and synergies, in communal rangeland systems

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ABSTRACT

Communal rangelands are a global resource of significant benefit to society through the provision of critical ecosystem goods and services such as carbon sequestration, water and livestock forage. The relative importance of the ecosystem goods and services provided by communal rangelands is driven by the social and environmental priorities of a range of different stakeholders at the local, regional and national level. Understanding the potential ecosystem service trade-offs (and synergies) is vital for making informed and inclusive decisions as part of the process of stakeholder engagement, both in goal setting as well as evaluating the appropriateness of outcomes in rangelands. However, application of trade-offs approaches to communal rangelands, has frequently been limited by a lack of adequate stakeholder engagement to help define important factors such as the diverse objectives of end users and the broader institutional and policy environments that frame them. To help address this, we propose a framework that conceptualises the links between different actors and trade-offs at three key levels, using communal rangelands in South Africa as a case study. Firstly, we explore environment trade-offs between key ecosystem services, largely determined through public sector engagement in the formulation of environmental policy. Secondly, we examine the potential for environmental policies to create community-environment trade-offs between the needs of local communities and those of society more broadly. Thirdly, we consider community trade-offs reflecting the many different social and economic priorities of people living in communal systems. We suggest that the framework will find greatest application in the initial process of determining potential ecosystem service trade-offs and associated land use scenarios with key stakeholders, and then subsequently in connecting the trade-offs back to these stakeholders, following analysis, as part of a 'discussion support' process. We also discuss the broader applicability of this approach to rangelands systems outside of South Africa.

1. Introduction

Rangelands are primarily natural grasslands, scrublands, woodlands, wetlands and (semi-) deserts (Alkemade et al., 2013) and are the dominant form of ice-free land cover on the planet (Godde et al., 2020; Reid et al., 2014). They are of significant benefit to society through their provision of critical ecosystem services in the form of climate regulation, water, livestock forage, and other local products such as timber and fuel (Godde et al., 2020; Herrero et al., 2009; Sayre et al., 2013). Importantly, they are also home to some of the poorest and most marginalised people in the world, who depend on them for their livelihoods, often through extensive livestock grazing (Reid et al., 2014). These marginalised peoples exert rights over rangelands and the beneficial ecosystem services that derive from them on a community basis, hence the frequent

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designation of these areas as communal rangelands (Palmer and Bennett, 2013).

Ecosystem services in communal rangelands, as elsewhere, are the flows of value to human societies derived from the condition and quantity of their natural capital (MEA, 2005; TEEB, 2010). They incorporate different combinations of processes, structures and traits that define their potential to provide services, which fall into four broad categories: regulatory, provisioning, cultural and supporting (MEA, 2005). The concept of ecosystem goods and services provides a basis for assessing the benefits derived from communal rangelands (Sala et al., 2017). The relative importance of these ecosystem goods and services in communal rangeland systems is driven by the interests of a range of different stakeholders, including at the national level, policy makers in the public sector, and at the local level, the communities who are land stewards (Briske et al., 2020). As such, there is considerable ambiguity and potential for conflict of interest as to which land use goals and practices can most effectively provide the range of ecosystem goods and services required by these different stakeholders (Briske et al., 2020; Sala et al., 2017). Thus, establishing a consensus on ecosystem service delivery in communal rangeland systems requires an inclusive approach that can capture all of these differing and frequently antagonistic land use objectives and examine how the different ecosystem services associated with them can be balanced against each other. One way to approach this is by analysing the trade-offs and synergies between these ecosystem services (Bennett et al., 2009; Bradford and D'Amato, 2012).

Trade-offs are antagonistic interactions between ecosystem services that involve diminishing or losing one service in return for gains in another (Bennett et al., 2009; Cavender-Bares et al., 2015; Dade et al., 2019; Favretto et al., 2016). In agricultural systems, trade-offs incorporate consequences related to different time scales (short versus long-term productivity effects), spatial scales from field to landscape, and social and environmental land use objectives (Klapwijk et al., 2014). For example, tree planting in native grassy biomes may sequester carbon (regulating service) but would constitute an undesirable trade-off between climate mitigation and local biodiversity and ecosystem functioning (supporting services) as well as to provisioning services associated with grassy biomes such as ecotourism or livestock farming (Bond et al., 2019). In contrast, synergies in ecosystem services involve situations in which both sets of services increase or decrease (Bennett et al., 2009; Dade et al., 2019). For example, rehabilitation of a degraded grassland system through reseeding to increase biodiversity has also been shown to improve soil fertility (Furrey and Tilman, 2021). Understanding the trade-offs and synergies at these different levels will be important in making more effective land use decisions at the local scale and also, more broadly, in formulating policies to guide land use, particularly in communal rangelands which are socially and environmentally heterogeneous (Palmer and Bennett, 2013).

To date, the analysis of trade-offs in environmental systems has tended to rely on models to assess ecosystem service flow and trade-offs, for example InVEST (Kareiva et al., 2011) and a number of others based on spatial or Bayesian probabilistic networks (see Crossman et al., 2013 and Balbi et al., 2015). However, as highlighted by Klapwijk et al. (2014), many of these trade-off models are limited by a lack of stakeholder engagement, to help define important factors, particularly the diverse objectives of end users and the broader institutional and policy environment that frames them. A key challenge in addressing these limitations, is to find ways to ensure that both stakeholder input into trade-offs analyses and evaluation of outcomes encompasses as wide a range of societal actors as possible (e.g., farmers, scientists, policy-makers). This is particularly true of communal rangeland systems where only limited trade-offs analysis studies have been undertaken, primarily involving either modelling without any stakeholder input (Petz et al., 2014) or engagement of community-level actors only (Favretto et al. 2016; Tebboth et al. 2020).

A useful starting point in addressing such a challenge can be the development of a conceptual framework which enables clear relations between stakeholders and potential ecosystem service trade-offs to be established (Fisher et al., 2014). Turkelboom et al. (2018), for example, developed a conceptual framework in relation to spatial planning that put stakeholders at the centre of the trade-offs analysis, enabling effective connections to be made between stakeholders at all levels ranging from land users to government organisations, their land use choices and the direct and indirect impacts of these on ecosystem services. Building on the utility of this approach, and drawing on our understanding of communal rangeland systems in South Africa, this paper advances a novel, conceptual framework that: (i) gives consideration to the full range of societal stakeholders who need to be involved in the process of formulating and evaluating ecosystem trade-offs; and (ii) reinforces this process by connecting these stakeholders to the range of ecosystem service trade-offs that will pertain under different management scenarios within communal rangelands.

In developing this framework, we do not attempt to explore and evaluate the many practical methods through which stakeholders can be more effectively engaged to participate in trade-offs analyses in communal rangelands. Rather, given the nascent stage of trade-offs work in communal rangelands, we focus not on the 'how' but the 'who' and 'why' and present the conceptual framework as a starting point to guide more systematically the process of stakeholder engagement in communal rangelands. We begin with a brief overview of communal rangelands systems in South Africa to understand the importance of the different types of ecosystem services they provide, and the main threats they are currently facing in delivering these. We then set out our conceptual framework for understanding ecosystem service trade-offs in communal rangelands and conclude by suggesting how this framework can be applied in South Africa as well as more broadly.

2. Communal rangelands in South Africa

2.1. The value of communal rangelands

In South Africa, rangelands which include grassland, savanna, thicket, and karroid shrubland vegetation, cover 70 % of the land surface (Mucina and Rutherford, 2006). In common with other rangeland systems in South Africa, communal rangelands provide a number of critical ecosystem services (Turpie et al., 2017). For example, they can potentially play an important role in provision of regulating services such as carbon sequestration and related mitigation of climate change, with broader public benefits (Palmer and Bennett, 2013; Stringer et al., 2012). Likewise, many communal rangelands form part of critical watersheds, supplying water to key river systems, which service urban areas, particularly in Eastern Cape Province and KwaZulu-Natal (Lannas and Turpie, 2009; Zunckel, 2013). Some are also located in wetlands and other biodiversity hotspots, giving them strategic value through the supporting services they can provide from a conservation perspective (Owethu-Pantshwa and Buschke, 2019). At a local level, communal rangelands also represent a critical resource base for smallholder farmers, through provisioning services in the form of livestock production, and goods such as timber, fuelwood, thatching grass and wild foods and medicines (Cousins, 1999; Shackleton et al., 2001; Turpie et al. 2017). Finally, communal rangelands also have cultural importance to local communities by providing sacred places such as indigenous forests, rivers and pools, which are seen as giving a connection to ancestors and nature as well as having broader spiritual significance (Cocks et al., 2012).

2.2. Factors affecting the productivity of communal rangelands

The productivity of South African communal rangelands is, however, compromised both by their inherently low forage quality and degradation due to a combination of often interacting factors, primarily overgrazing (Palmer and Bennett, 2013) and woody plant encroachment by indigenous and invasive alien plant (IAP) species (O'Connor and van

Wilgen, 2020). Overgrazing is known to reduce biodiversity and carbon sequestration (Petz et al., 2014) while biological invasions are widely recognized as the second-largest global threat to biodiversity, after direct habitat destruction (van Wilgen and Richardson, 2014). Prominent IAPs in South African communal rangelands include Australian wattles (*Acacia dealbata and A. mearnsii*) along with species from the genera *Eucalyptus* (e.g., *Eucalyptus grandis*), *Opuntia* (e.g., *Opuntia ficus-indica*) and *Prosopis* (e.g., *Prosopis glandulosa*) (O'Connor and van Wilgen, 2020). The impact of this IAP proliferation on ecosystem services and associated livelihoods in communal areas is widespread. For example, an earlier study by Shackleton et al. (2007) reported that 15 of the 24 ecosystem goods and services in South Africa were in a state of decline due to IAPs. In particular, IAPs replace palatable grasses in wetlands and other riparian areas, thereby, dramatically reducing the capacity of rangelands to support livestock production (van Wilgen and Richardson, 2014; Gwate et al., 2016). For example, Yapi et al. (2018) have shown that total basal grass cover is reduced by up to 42 % in South African communal rangelands densely invaded by *Acacia mearnsii* (wattle) resulting in a reduction of up to 72 % in their grazing capacity. Wattle species also reduce water supply and run-off to storage reservoirs throughout South Africa (Le Maitre et al., 2020). Consequently, there have been considerable efforts at a national scale to control wattle and other woody IAPs, most notably as part of the Working for Water (WfW) Programme (Le Maitre et al., 2020; van Wilgen and Wannenburgh, 2016).

However, it has also become clear that IAPs generate conflicts of interest between different sets of stakeholders (particularly policy makers and local communities) as several studies have underlined the importance of IAPs such as wattle species to local people in communal rangelands as a source of timber and fuelwood (Shackleton et al., 2007; Zengeya et al., 2017). Another avenue of conflict is between policy makers and conservationists, as the WfW Programme has been criticised for a historical focus on job creation over actual IAP eradication (van Wilgen and Wannenburgh, 2016). Conflicts such as these further emphasise the importance of trade-offs approaches in unpacking the costs and benefits of IAPs for different ecosystem services in communal rangelands (Shackleton and Gambiza, 2008). Similar conflicts of interest over IAPs have been reported in Ethiopia with *Prosopis juliflora* (Tebboth et al., 2020) and in Kenya for *Opuntia stricta* (Shackleton et al., 2017). Furthermore, within the broader context of governance of natural resources, with communal or customary tenure being the dominant form of tenure over 78 % of Africa (Alden Wily, 2018), there are different interests and conflicts across community actors, for example between women and men, and between the older and younger generations. This is largely linked to structural and gender inequalities and related power dynamics regarding access to resources and decision-making power (Lemke and Claeys, 2020; Errico, 2021).

3. A conceptual framework for unpacking the trade-offs and synergies in ecosystem services in communal rangelands

In applying a trade-offs lens to communal rangelands systems, it is fundamental to understand them as part of a broader people-environment nexus which recognises the importance of both the social and natural environmental dimensions of rangeland stewardship (Sayre et al., 2013). Our framework builds from this in its approach to conceptualising trade-offs and synergies in these systems in terms of the ecosystem services they provide and how these are negotiated between different sets of actors and stakeholders at different positions in society. Firstly, we consider the range of possible trade-offs and synergies between the four sets of ecosystem services described in Section 2. In simple terms, this can be expressed in a 4x4 matrix, as outlined in Table 1.

Combining the four sets of ecosystem services in Table 1 results in 10 different potential combinations of trade-offs to be considered in the framework. Whether all of these combinations are relevant in every situation will need to be determined in relation to specific scenarios and drivers of change in communal rangelands (see Section 4).

Table 1
Possible combinations of ecosystem service trade-offs and synergies.

	Regulating	Supporting	Provisioning	Cultural
Regulating	✓	–	–	–
Supporting	✓	✓	–	–
Provisioning	✓	✓	✓	–
Cultural	✓	✓	✓	✓

Secondly, if it is to have practical application, the framework also needs to recognise the different types of stakeholders involved in trade-offs decisions and, importantly, to try and connect the specific types of trade-offs outlined in Table 1, directly and meaningfully to the most relevant stakeholder groups (Crane 2010; Klapwijk et al., 2014; Ruckelshaus et al., 2013). These stakeholders may be direct beneficiaries of these ecosystem services, such as smallholder farmers within local communities, or governmental bodies representing broader public interests at a national scale. An indication of the types of stakeholders who will be important in framing these decisions in communal rangelands in South Africa is provided in Table 2.

These stakeholders frame the situational decisions regarding how quantities and qualities of different ecosystem services are accorded relative value and thus how the trade-offs between them are determined. In relating potential ecosystems trade-offs to different sets of stakeholders it is important to initially identify where the main interactions between these different sets of stakeholders in Table 2 are likely to occur. Drawing on published studies from the international and local literature as well as experience of stakeholder engagement around ecosystem services in South Africa (Bennett et al., 2021), we suggest that in general there are three critical points of engagement between different stakeholders that are pertinent to the trade-offs process in communal rangelands in South Africa (Fig. 1). Importantly, these points also represent the different scales at which trade-offs around communal rangelands occur from national down to local.

The first point of engagement is between different institutions in the public sector (e.g., government departments) whose primary focus is on protecting environmental services in communal rangelands and formulating appropriate environmental policy to achieve this. In reality, this process of policy formation in South Africa is increasingly bottom-up in approach, drawing on input from those outside the public sector such as academics, NGOs and local community groups (Reed et al., 2018; Republic of South Africa, 2020), as represented in Fig. 1. The environmental policy that results from this engagement process is itself therefore the result of a series trade-offs between the interests of national actors in different departments and those of other non-governmental stakeholders (Nilsson and Weitz, 2019).

The second key point of stakeholder interaction framing trade-offs and synergies in communal areas is potentially the most complex, representing the nexus between environmental policy and the people and organisations it directly affects. These include local communities

Table 2
Stakeholders with an interest in ecosystem services at different scales in communal rangeland systems in South Africa (after Sala et al. 2017).

Stakeholders	Spatial scale Local	National/regional	International
Individual	Small-holder farmers	Researchers and practitioners	Researchers and practitioners
Commercial entity	Local traders and entrepreneurs	National companies *	International companies*
Public sector	Local government	National and regional government	International community

* These are included for the sake of completeness, although they have a fairly limited role in most communal areas in South Africa outside of mining areas.

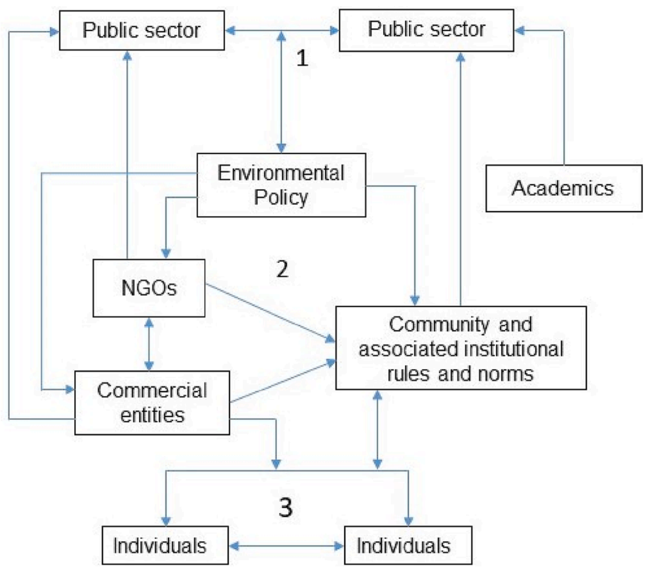

Fig. 1. Conceptual framing of key areas of interaction between different stakeholders and associated governance mechanisms in determining ecosystem service trade-offs and synergies for communal rangelands in South Africa, identified as: 1) Between different governmental (public sector) and non-governmental (academics, NGOs and commercial sector) stakeholders for determining environmental policy; 2) Translating policy into practice in communal rangelands; 3) Within and between community institutions (e.g. traditional leaders) and individuals (e.g. men, women, youth) within communities.

themselves and the commercial entities and NGOs who are actively involved with them, all of whom interact in making use of the natural environment to support local livelihoods and businesses as well as cultural needs. Local communities are key to the delivery of environmental goals in communal areas, as decentralised governance approaches in South Africa effectively make local communities stewards of communal rangeland resources. However, meeting immediate livelihood needs may result in local people failing to comply with environmental regulation (e.g., through overstocking or failing to rest rangeland; see Palmer and Bennett, 2013), resulting in trade-offs between regulatory or supporting services and provisioning services. This framing of the interaction between policy and people does not assume that local communities in communal areas are incapable of collectively managing the natural resources they govern (see Bennett and Barrett, 2007 for evidence to the contrary) nor that all relationships between environmental policy and communities will necessarily be antagonistic. Rather, it acknowledges the reality that there remains a strong disconnect in South Africa between broader environmental policy and how this can practically be realised in communal areas (Vetter 2013). NGOs in South Africa frequently play a critical 'bridging' role in this respect by interfacing between communities and government to work out how to practically deliver key national environmental initiatives such as the WfW programme (Turpie et al., 2008). Commercial entities such as local companies may also be an important part of the dynamic between environment and people through their extraction of local resources such as minerals, aggregates and timber, which in turn influences the ecosystem services available to local communities and associated community rules and norms about resource access and use (Mnwana 2016).

Finally, trade-offs are a necessary part of the everyday interactions between different groups of local community actors (point 3 in Fig. 1). Use of natural resources by local communities may potentially conflict with that of commercial entities, e.g., livestock production versus mineral extraction (Mnwana, 2016). Moreover, it is widely recognised that communities themselves in rural South Africa are increasingly heterogeneous (Shackleton and Luckert, 2015) and consequently that individuals and groups afford different priorities to the type and extent of services they need rangelands to provide, which may be conflictual (Klapwijk et al., 2014; Tebboth et al., 2020). For example, women in communal areas are recognised to prioritise rangeland for collection of firewood (Kirkland et al., 2007) whereas men prioritise livestock production (Hall and Cousins 2013). This has to be understood in light of the fact that women have often limited and unsecured access to land and livestock and are largely excluded from decisions concerning these (Errico, 2021).

Combining the three key points at which stakeholder interaction is hypothesised to occur in trade-off decision making (Fig. 1), with the ten different sets of ecosystem service trade-offs that can potentially occur (Table 1), enables the identification of three broad categories of trade-offs that can be used to conceptually frame the analysis of ecosystem trade-offs in communal rangeland systems:

1. **Environment** trade-offs and synergies within and between different regulating and supporting services in communal rangelands determined primarily by public sector bodies in relation to different sets of national policies and legislation;
2. **Community-Environment** trade-offs and synergies between the regulating and supporting services demanded by the broader public sector and the provisioning and cultural services required by local communities and commercial entities.
3. **Community** trade-offs and synergies, between local actors in the types of provisioning and cultural services required by different communities and commercial entities and by different individuals/ social groups within these communities.

Each category is defined by a combination of the scale at which the trade-offs occur, in terms of the geographical extent of the ecosystem services themselves, and the level of interaction of the stakeholders involved in negotiating them, with environment being broadest and community most local. It is acknowledged that the terms environment and community embody a range of contested social and natural scientific meanings (Carlon 2021; Schröter et al., 2014) and that deploying them in this primarily utilitarian manner constrains a more critical exploration. However, the categorisation does enable systematic capture of the relevant sets of ecosystem service trade-offs at these different scales.

4. Applying the framework to communal rangelands in South Africa

We demonstrate the potential utility of this conceptual framework by applying it to the widespread scenario of IAP-infested rangelands in communal areas of South Africa, with a particular focus on the most widely distributed invasive trees, *Acacia dealbata and A. mearnsii* (O'Connor and van Wilgen, 2020). An important first step in doing this is to identify and represent the range and extent of typical ecosystem services within a particular system, before the potential trade-offs between them can then be considered. One way of expressing the relative value of ecosystem services under specific land use scenarios is to use the flower diagram approach developed by Foley et al. (2005) and subsequently applied in analyses of ecosystem trade-offs in grassland systems (Fan et al., 2019). We use this to represent typical ecosystem services under two different land use scenarios related to IAP invasion in communal rangelands of South Africa (Fig. 2).

In Fig. 2, eight typical ecosystem services associated with communal rangelands in South Africa are presented. These have been identified qualitatively from Turpie et al. (2017) and other published sources, as indicated below. They are designed to be representative of all four categories of ecosystem service, with regulating services represented by water and carbon sequestration (Lannas and Turpie, 2009); supporting services by biodiversity and soil fertility (Owethu-Pantshwa and Buschke, 2019); provisioning services by animal/livestock production,

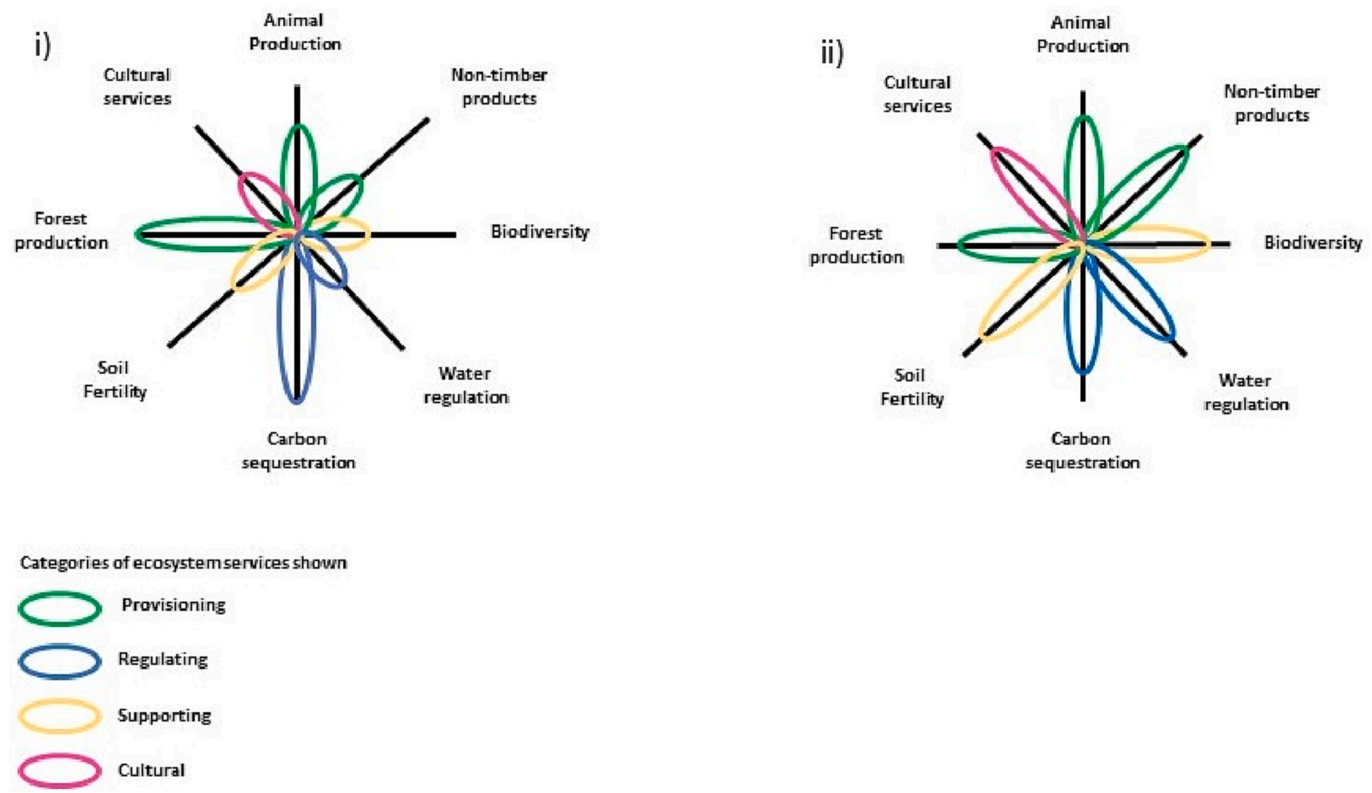

Fig. 2. Typical ecosystem services associated with communal rangelands under two land-use scenarios (i) current IAP invasion and skewed ecosystem services and (ii) reduction of IAPs to achieve greater balance in the range of services provided. Different categories of ecosystem services are illustrated by different colours.

forest production and non-timber production (Shackleton et al., 2001; Ngorima and Shackleton 2019) and cultural services (Cocks et al., 2012) represented generically. Although the extent of each of these eight services has been arbitrarily defined for each of the two land use scenarios, they could be more precisely defined through empirical measurement or modelling. The first scenario represents the current status quo in many communal areas of South Africa subject to IAP invasion, with high levels of IAP "forest" production and potential carbon sequestration but at the expense of important services such as biodiversity, water regulation, and local livelihood priorities such as livestock production (Fig. 2i). In the second hypothetical scenario, a reduction in IAPs enables greater balance between these ecosystem services, reflecting the needs of a broader range of local and national stakeholders. This requires several important ecosystem trade-offs at different levels to be made and also leads to the creation of new synergistic relationships (Fig. 2ii). Whilst hypothetical, this scenario reflects alternative management goals identified by local stakeholders in South Africa through land use partnerships such as Umzimvubu Catchment Partnership Programme (UCPP) (https://umzimvubu.org).

The conceptual framework enables movement between these two scenarios by encouraging systematic consideration of the range of stakeholders that need to be consulted in this process and the types of ecosystem trade-offs and synergies that are likely to be important in the interactions between them. Table 3 and Fig. 3 summarise the application of the conceptual framework to identify the main trade-offs at different levels required in moving from scenario (i) to scenario (ii) in Fig. 2.

5. Discussion of utility of framework

5.1. Application to local context in South Africa

The framing in Table 3 and Fig. 3 provides a foundation for analysing ecosystem trade-offs and synergies associated with IAP invasion in South Africa. Collectively they capture all ten sets of potential trade-offs between the key groups of ecosystem services and help map these to the sets of stakeholders who will be responsible for interpreting them in policy and practice. This framing is useful in two key ways.

Firstly, as a means of systematically capturing and presenting the full range of potential ecosystem trade-offs and synergies within the system. Whilst many other studies have proposed approaches for conceptually analysing these relationships (e.g., Bennett et al., 2009, Crossman et al., 2013; Petz et al., 2014), we build from these to suggest a convenient means of 'bundling' these trade-offs under the categories of 'Environment', 'Community-Environment' and 'Community'. Within these bundles, we also provide a systematic approach to analysing all possible relationships between ecosystem services. The Environment 'bundle' of trade-offs and synergies includes those between regulating and supporting services in all combinations and thus bundles together those services with indirect use value (Defra, 2007; Pagiola et al., 2004). At the other end of the scale, the Community bundle of trade-offs and synergies between ecosystem services includes those combinations within and between provisioning and cultural services, which have direct use (consumptive and non-consumptive respectively) to local communities (Defra, 2007; Pagiola et al., 2004). These are important to recognise, as differences between groups of actors within communities in their relative ability to access to key resources has received relatively little attention in studies considering relationships between ecosystem services (Fisher et al., 2014; Felipe-Lucia et al., 2015). In particular, very few studies recognise the potential for local trade-offs between provisioning and cultural services within communities, which the current framework enables us to highlight. Importantly, it also facilitates clear identification of the Community-Environment trade-offs that address the divide between the direct ecosystem service needs of local rangeland users and the broader, more indirect ecosystem service needs of society as a whole. Typically, this positions key local cultural services and provisioning services such as livestock production against larger scale

Table 3
Potential Ecosystem Trade-offs in an Invasive Alien Plant (IAP) infested communal rangeland.

Form of ecosystem service trade-off	Primary level(s) of stakeholder involvement	Category of ecosystem service trade-off	Examples of potential ecosystem trade-offs (+/-) and synergies (+/+) and (-/-).	Relevant supporting literature
Regulating-Regulating	Public sector	Environment	Carbon sequestration vs regulation of water flow (+/-).	De Wit et al., (2001) and Gibson et al., (2018) identify positive role of *A. mearnsii* and other IAPs in carbon sequestration and negative in reduction of stream flow in South Africa. Carbon water trade-offs also identified by Korchani et al., (2022) for revegetated former agricultural lands in Spain and Kim et al., (2016) for woody encroached grasslands in USA and Argentina
Regulating-Supporting	Public sector	Environment	Carbon sequestration vs biodiversity (+/-).	Nunes et al., (2021) identify the C sequestration potential of early growth stands of *A. dealbata* with implied trade-offs for biodiversity. De Wit et al., (2001) in addition to C sequestration show negative impact of *A. mearnsii* on native plant diversity in South Africa.
Regulating-Provisioning	Public sector and commercial or community	Community-Environment	Carbon sequestration vs livestock production (+/-)	Petz et al., (2014) suggest higher carbon sequestration in Southern Africa with low grazing intensity. Yapi et al., (2018), demonstrate that dense areas of *A. mearnsii* infestation (thus increased potential carbon sequestration) in South Africa are associated with lowered grazing capacity.
Regulating-Cultural	Public sector and community	Community-Environment	Carbon sequestration vs engagement with indigenous forest for cultural purposes (+/-)	See references above for C sequestration potential – Ngorima and Shackleton (2019) show negative impacts of invasive *A. dealbata* on traditional cultural services in forest areas in South Africa.
Supporting-Supporting	Public sector	Environment	Maintenance of biodiversity and soil fertility currently (-/-) but with potential for (+/+) with wattle removal	De Wit et al., (2001) summarise negative consequences of *A. mearnsii* for both biodiversity and soil fertility, while Furey and Tilman (2021) identified a strong synergistic relationship between increasing plant diversity in a restored landscape and an increase in a range of soil nutrients.
Supporting-Provisioning	Public sector and commercial or community	Community-Environment	Preservation of biodiversity and habitat vs use of forest for timber or fuelwood (-/+)	De Wit et al. (2001) identify negative impacts of *A. mearnsii* on biodiversity. Carpentier et al., (2017) highlight trade-offs between timber production and biodiversity in North America.
Supporting-cultural	Public sector and community	Community-Environment	Biodiversity and engagement with landscape for cultural purposes currently (-/-) but with potential to shift to synergistic (+/+) relationship (as in Fig. 2 (ii)) with wattle removal.	Negative consequences of IAPs for biodiversity and cultural services in South Africa already suggested above. Potential to shift to a more synergistic relationship between biodiversity and cultural services demonstrated in several studies such as Pena et al., (2018) in Spain.
Provisioning-Provisioning	Commercial and community	Community	Livestock production vs use of forest for timber or fuelwood (-/+).	Ngorima and Shackleton (2019) suggest primary benefit of *A. dealbata* to local communities in South Africa is timber and fuelwood but with costs in terms of reduced forage availability for livestock. Bennett et al. (2021) show that trade-off may be gendered within communities, with men primarily focusing on livestock production and women on fuelwood provision.
Provisioning-Cultural	Commercial and individual	Community	Use of forest for timber or fuelwood vs engagement for cultural purposes (+/-)	Trade-off not directly identified in the literature but implied in study by Ngorima and Shackleton (2019).
Cultural-cultural	Community	Community	Maintenance of cultural sites and engagement with ancestors (-/-) at present but with potential for synergies (+/+) with wattle removal	Ngorima and Shackleton (2019) identify negative implications of *A. dealbata* for important cultural sites such as graves and ability to engage with ancestors in invaded areas. Pena et al., (2018) suggest that in environments with increased biodiversity synergies between different cultural services emerge.

regulating and supporting services such as carbon sequestration or water provision (Sala et al. 2017; Sayre et al. 2013). This is particularly important from the perspective of communal rangeland systems, where local actors continue to be heavily dependent on the direct provisioning services they supply, but mechanisms to encourage them to have agency and stewardship over broader-scale environmental services remain relatively undeveloped (Briske et al., 2020).

Secondly, the greatest utility of the conceptual framework is in helping to make clearer connections between potential trade-offs and the actors who will be most closely involved in helping to clarify and resolve them. Bennett et al. (2021), for example, used a nascent version of the framework to work back from a set of hypothesised trade-offs to the actors most closely connected with them, in order to identify key stakeholders to attend a workshop on trade-offs in communal rangelands in South Africa. The framework was also of importance during a subsequent workshop undertaken as part of the same study (Bennett et al., 2021). The hypothesised trade-offs it helped to generate acted as a starting point for prioritisation of their relative importance to different actors through a co-construction process between academic convenors, local NGOs, national and local governmental actors and local communities. Importantly, this process also enabled some of the initially hypothesised relationships between ecosystem services to be reframed, as greater awareness of current management practices became apparent. For example, the relationship between livestock production and thatching grass was initially hypothesised to be synergistic but in reality was a trade-off, as unregulated grazing by livestock prevented its accumulation. Subsequently, some of the trade-off priorities established in the workshop became the focus of more detailed empirical data

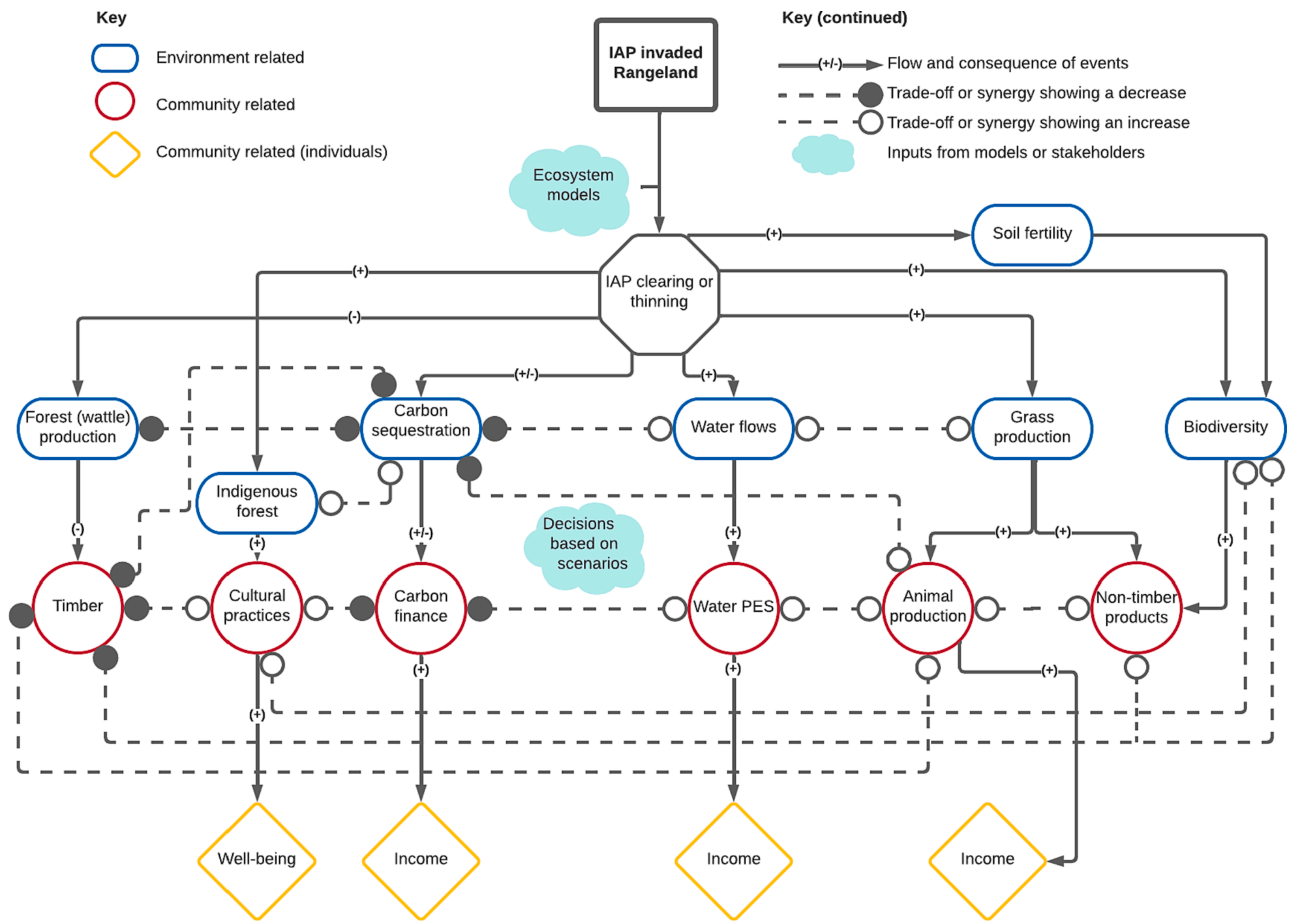

Fig. 3. Potential trade-offs (and synergies) between environment, community-environment, and community categories on a hypothetical rangeland that is being cleared of invasive alien plants. Each relationship could be discussed at any of the three stakeholder levels (see Fig. 1), although this will be more likely to occur at some levels than others (see text and Table 3).

collection in a related project (https://www.coventry.ac.uk/cawr-tocasa). This included a trial involving thinning of wattle (as opposed to recommended clear felling) to better balance to the range of ecosystem services available. This underlines how the conceptual framework was able to provide a foundation for two important approaches to trade-offs analysis: participatory methods and empirical analysis (Klapwijk et al. 2014), and how one was able to inform the other.

There is also an important role in this conceptual framing for linking the subsequent outcomes from trade-offs analyses back to appropriate stakeholders. Once trade-offs have been prioritised and appropriate analyses undertaken to quantify them, the outcomes need to inform policy and practice (Ruckelshaus et al., 2013). They should form the basis for interactive discussion support with actors at all levels, involving different 'what-if' scenarios (Klapwijk et al., 2014) based, for example, on the outcomes of livestock production or wattle growth modelling under different management practices or future climate scenarios. For larger scale environmental trade-offs such as those between carbon and water, these discussions will need to occur primarily between public sector actors with responsibility for policy making, where the outcomes may help to reformulate policy priorities. In the case of South Africa, such engagement should be focused on key government departments such as Department of Environmental Affairs (DEA), who are central to policy-making on water, as well as coordinating domestic policy on climate change. In contrast, community-environment trade-offs such as between carbon sequestration and livestock production will require careful consideration of trade-off outcomes by an inherently broader cross-section of stakeholders, potentially involving public sector policy makers such as DEA as well as local communities and associated NGOs. As part of this it will be important to find ways to communicate modelling outcomes for livestock production and carbon sequestration under different 'what-if' scenarios (e.g., more or less invasive trees, grass vs tree sequestration potential, etc.) to local stakeholders in a clear and accessible way. Exploring potential resolution of identified community level trade-offs such as those between livestock production and provision of fuelwood or thatch grass, will need to be undertaken sensitively to avoid aggravating community relations, as these often reflect skewed power relationships within communities between dominant actors (male livestock owners) and the more marginalised (women, often without livestock) (Lemke and Claeys, 2020).

Within these different contexts, the conceptual framing provided above can only be viewed as a starting point in the process of working through the different sets of trade-offs with appropriate stakeholders. Whilst it provides a useful basis for linking categories of stakeholders with defined sets of trade-offs and synergies, an exact understanding of the most appropriate stakeholders to engage in this process will require detailed local knowledge (Bennett et al., 2021; Tebboth et al. 2020). Likewise, the detail of which platforms and methods are appropriate to engage stakeholders both in the formulation of trade-offs and in the translation of analysis outcomes into practice must be defined in an appropriate way by those responsible for brokering the trade-offs process. The literature provides appropriate examples from which to draw (e.g., see Tebboth et al., 2020 for Favretto et al., 2016 for Botswana).

There are also several examples of methods and approaches for quantifying trade-offs relevant to communal lands (e.g., Crossman et al., 2013; Klapwijk et al., 2014; Favretto et al., 2016; Fan et al., 2019).

5.2. Broader utility of the framework

The conceptual framework has the potential for broader application in a number of different ways. Firstly, it has potential for greater understanding of trade-offs in IAP infested communal rangelands. Invasive IAPs are widespread within communal rangelands in South Africa, impacting not only more mesic systems through invasion by *Acacia* spp., but also more arid systems subject to extensive invasion by alien plants such as *Opuntia* spp. and *Prosopis* spp. (O'Connor and van Wilgen, 2020). Invasive plants in communal rangeland systems also frame ecosystem trade-offs in many other parts of the world, most notably the horn of Africa where both *Prosopis juliflora* and *Opuntia stricta* severely encroach rangeland but have also found widespread use amongst local people (Tebboth et al., 2020; Shackleton et al., 2017; Strum et al., 2015). Moreover, the trade-offs approach that we have outlined could easily be extended beyond invasive plants to encompass other key drivers of environmental change in communal rangelands such as erosion (often critical in more mountainous systems) and lack of water.

Likewise, there is the potential to adjust the range of stakeholders who link to the different sets of trade-offs established. Our current analysis largely omits commercial entities given the relatively limited role they play in most communal systems in South Africa. However, there are strong commercial interests in similar systems in other parts of the world, for example where mining of natural resources such as precious metals or oil conflicts with local land use by pastoralists (e.g. see Dalaibuyan, 2022 for Mongolia) or where land grabs are taking place to facilitate commercial agriculture (e.g. see Ndi, 2017 for Cameroon). Indeed, the conceptual approach might even be extended to include commercial rangelands systems. Here many of the same environmental issues including climate change and woody plant encroachment pertain (Sayre et al., 2013) but social composition at the local level will likely be more homogenous, leading to less opportunity for community-level trade-offs between commercial ranchers.

More broadly, the conceptual framework we present here can play an important role in the overall process of analysing relationships between ecosystem services with stakeholders (Fig. 4). The process might involve, as a first step, using flower diagrams (Foley et al., 2005) or similar conceptual approaches, to frame the key ecosystem services associated with a particular system and how these might be expected to change between two or more alternative land use scenarios. Critical here will be an ability to draw on information from published studies and to elicit input from informed stakeholders in the process of formulating alternative land use scenarios. The second stage will be to identify more clearly the specific sets of trade-offs that the land use scenarios demand, through interactive stakeholder engagement, most likely as part of workshops. Both of these stages find strong support in the approaches to analysing trade-offs in IAP-infested rangelands adopted by Tebboth et al. (2020) and Bennett et al. (2021). It is also in these two stages that the conceptual framework we present is likely to find greatest application. Firstly, through its ability to systematically identify potential sets of relationships between ecosystem services and then by connecting these to the groups of stakeholders most appropriate to identifying and refining them. The conceptual framework will also find application at stage 4 of the process by helping to reconnect the stakeholder audience to the outcomes of the trade-offs analysis (stage 3), as a basis for potentially reframing land use and management priorities to achieve alternative ecosystem service outcomes. As such the overall process forms an iterative loop involving ongoing exchange of information available from informed trade-offs analyses with key stakeholders and incorporation of their feedback to refine land use decisions in response to changes in local social-ecological drivers.

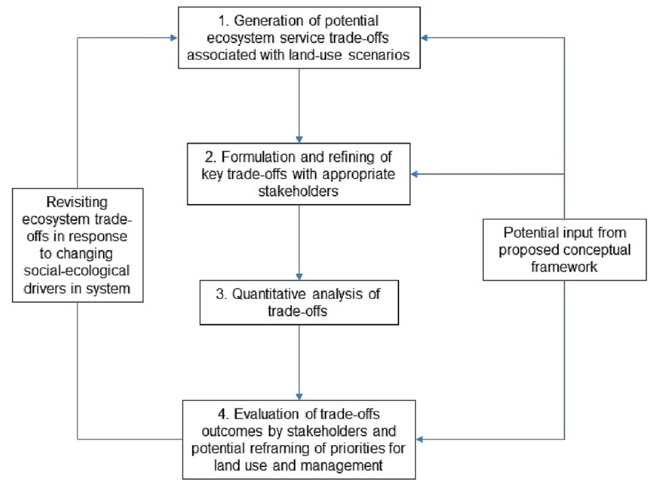

Fig. 4. Proposed role for the conceptual framework in the overall process of formulating and analysing ecosystem trade-offs with local stakeholders.

6. Conclusion

The conceptual framework presented here provides a novel approach to understanding trade-offs in communal rangeland systems. It enables clearer connections with relevant stakeholders and associated trade-offs to be made by focusing analysis on three levels of stakeholder-ecosystem service interactions. It also proposes a systematic approach to working through potential trade-offs between all categories of ecosystem services. Its application to a hypothetical scenario of IAP-invaded rangeland in South Africa demonstrates its utility in identifying the potential sets of trade-offs and synergies within the system and mapping these to appropriate sets of stakeholders. Subsequently, it will be important to test the framework in other communal rangelands systems, particularly those with different primary drivers of environmental change, to explore its wider utility and enable its refinement.

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.

Data availability

No data was used for the research described in the article.

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