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Prosopis juliflora management and grassland restoration in Baringo County, Kenya: Opportunities for soil carbon sequestration and local livelihoods

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Abstract

1. Climate change, land degradation and invasive alien species (IAS) threaten grassland ecosystems worldwide. IAS clearing and grassland restoration would help to reduce the negative effects of IAS, restore the original vegetation cover and sustain livelihoods while contributing to climate change mitigation, but uncertain financial benefits to local stakeholders hamper such efforts. This study assessed where and when net financial benefit could be realized from *Prosopis juliflora* management and subsequent grassland restoration by combining ecological, social and financial information.
2. Impacts of *Prosopis* invasion and grassland degradation on soil organic carbon (SOC) in nine sublocations in Baringo County, Kenya, were evaluated. Then the financial impacts of *Prosopis* removal and grassland restoration in the area were calculated and spatially explicit management scenarios for each sublocation modelled, combining geographical information derived from satellite images taken in different years of the invasion with SOC data and socio-economic data collected in the sublocations.
3. The expanding *Prosopis* distribution and density since 1995 have increased cumulated SOC storage on former bare land or degraded grasslands. On former pristine or restored grasslands, however, *Prosopis* invasion has reduced total SOC storage.
4. *Prosopis* removal and grassland restoration are predicted to yield financial benefits through charcoal made from removed trees, increased cattle numbers and carbon credits. However, a trade-off between increased SOC and net financial benefit was found. The predicted net SOC increase would contribute around one-tenth, at most, to the net financial benefit.
5. The available budget, based on Baringo households' average willingness to pay, would enable removal, on average, of one-fifth of *Prosopis* per sublocation in a

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single year. A larger area can be cleared if *Prosopis* is sparse than if it is dense. The analyses show that in some sublocations, households' annual investments could result in restoration of all former grassland areas.

6. *Synthesis and applications*. This study shows how integrating and linking detailed ecological, social and financial geodata to develop accurate and realistic invasive alien species management scenarios can illustrate costs and benefits of management interventions in a spatial context. Such scenarios should be used more extensively to support land management decisions.

KEYWORDS

carbon credits, Kenya, optimal management scenarios, pastoralist communities, *Prosopis juliflora*, return on investment, soil organic matter, spatially explicit management

1 | INTRODUCTION

Climate change, land degradation and invasive alien species (IAS) are three major threats to peoples' livelihoods in arid and semi-arid areas (Bekele, Haji, Legesse, Shiferaw, et al., 2018; Kassahun et al., 2008). Each of these factors has a negative influence on ecosystem services, including vegetation biomass, which is a prime resource for pastoralists and agro-pastoralists. Overgrazing has led to degraded grasslands (Doran et al., 1979), and invasive alien plant species are adding to degradation by reducing the abundance and quality of available grassland, as well as access to it (Kassahun et al., 2008; Linders et al., 2019). Climate change may further exacerbate the problem—for example, if changing rainfall patterns lead to unreliable fodder availability (McPeak, 2003). The reduced availability of grazing land and other natural resources, along with the associated changes in peoples' livelihoods, has increased the likelihood of social conflicts and deterioration of cultural values in several regions (Baka, 2014; Kassahun et al., 2008; Rogers et al., 2017). IAS clearing and grassland restoration would help reducing the negative effects of IAS, restore the original vegetation cover and sustain livelihoods while contributing to climate change mitigation. However, the benefits to local stakeholders may be uncertain and context-dependent.

Some stakeholders derive significant benefits of IAS (Bekele, Haji, Legesse, Shiferaw, et al., 2018) and management strategies should be holistic to reduce its negative impacts while maintaining some of the benefits. Management strategies and costs may differ depending on specific aims and local conditions. For example, areas where the IAS is sparse may be easier and cheaper to clear than areas where it is dense, and biodiversity restoration in these areas may be more successful if the invasion is relatively recent and the seed bank is sufficiently intact to allow native species to re-establish. Similarly, gains in cattle carrying capacity are likely larger after clearing dense IAS infestations and sowing grasses than after clearing sparse IAS infestations because IAS cover and grass cover are negatively related (Kiage et al., 2007; Linders et al., 2019). However, gains in soil organic carbon (SOC) content are likely lower after removal of dense invasions (Mbaabu et al., 2020). An increase in cattle numbers would provide financial benefits in the form of increased capital and income from sales, and increases in SOC could translate into financial value in the form of carbon credits in payment-for-ecosystem-services schemes (Follett & Reed, 2010).

Prosopis juliflora (Sw.) DC. (from now on *Prosopis*), a tree or shrub species native to parts of Central and north western South America where it occurs in thorn scrublands (Kaur et al., 2012), was introduced to and has become invasive in many countries (Shackleton et al., 2014). In Baringo County, Kenya, *Prosopis* was introduced in the 1980s, and the Kenyan government promoted its use to improve livelihoods by providing wind breaks and a source of timber, fuelwood and charcoal (Mwangi & Swallow, 2008). Given the generally disturbed status of habitats in Baringo County (Dregne, 2002; Linders et al., 2019), it can be expected that establishment of the highly productive *Prosopis* tree is increasing the organic carbon content in soils (Moradi et al., 2017), thereby contributing to climate change mitigation. Furthermore, production of charcoal from *Prosopis* wood provides income for local communities and a livelihood diversification strategy for pastoralists and agro-pastoralists (Andersson, 2005; Bekele, Haji, Legesse, & Schaffner, 2018). However, while *Prosopis* does provide these benefits, it has also spread rapidly across a large area, leading to a loss of native vegetation, agricultural areas and grazing land (Mbaabu et al., 2019). These changes are primarily driven by *Prosopis* invasion, along with human activities such as deforestation, land clearing, overgrazing and climate change (Kiage et al., 2007; Linders et al., 2019). The decrease in available grazing land may lead to a reduced potential for accumulating wealth, since livestock herds serve as a 'store of wealth' for many Eastern African pastoralists and agro-pastoralists (Doran et al., 1979).

By 2005, *Prosopis* invasion had intensified, and pastoralists now began to see it as the cause of grassland loss (Mbaabu et al., 2019). This prompted a legal suit between the local pastoral community and the Kenyan government (Little, 2019). In response, the government launched a sensitization programme, in which the affected communities were trained in managing *Prosopis* through manual or physical removal and subsequent reseeding of cleared areas with native perennial grasses. Pastoralists gradually adopted this practice as a new way of enhancing fodder availability for their livestock while generating income from commercial grass seed production and the number of grass fodder farms in the area has since increased (Lugusa et al., 2016). However, an effective and coordinated *Prosopis* management strategy is currently lacking in Baringo, where the physical removal did not result in a reduction of the spread or abundance of *Prosopis* (Mbaabu et al., 2019), as well as in other invaded areas in Kenya.

Prosopis also obstructs access to water sources due to its long thorns, and causes costs to small-scale farmers for clearing invaded cropland. This has heightened social tensions between agro-pastoralists in the region (Anderson & Bollig, 2016; Mbaabu et al., 2019). Other well-documented negative impacts of this species include reduced vegetation diversity and cover (Linders et al., 2019), and reduced groundwater availability (Dzikiti et al., 2013). Impacts on stakeholders differ, depending on their main livelihood and on the ecosystem services they rely on. However, by reducing the availability of grassland, *Prosopis* invasion is threatening the traditional way of living of large numbers of people (Linders et al., 2020). These and other trade-offs associated with *Prosopis* invasion must be considered when assessing its impacts and implications for its management and related policies.

An important factor in assessing the net impacts of *Prosopis* invasion across stakeholders is SOC, as carbon sequestration is an important ecosystem service (Nelson et al., 2008). Although *Prosopis* establishment may contribute to increases in SOC (Bhojvaid & Timmer, 1998), this must be balanced against its negative effects on grasslands, which are among the vegetation types with the highest SOC contents (Jackson et al., 2002; Jobbágy & Jackson, 2000), reaching levels similar to—or, as some studies suggest, higher than—*Prosopis* stands (Mbaabu et al., 2020). Moreover, the stated differences in SOC content under these vegetation types are per unit area and calculations of the net effect of Prosopis on SOC in an area should take the area covered by different vegetation types into account.

The results of two recent studies suggest that restoration or protection of grasslands is likely to benefit SOC content, fodder availability and biodiversity, and, consequently, peoples' livelihoods (Bekele, Haji, Legesse, Shiferaw, et al., 2018; Linders et al., 2020). The studies further revealed that people were very willing to invest money or time in managing *Prosopis* (Bekele, Haji, Legesse, Shiferaw, et al., 2018). To date, only few studies have integrated ecological, social and financial aspects in the development of IAS management plans that consider spatial variation, which are key to sustainable and, particularly important in developing countries, financially feasible management. Based on a combination of land use and land cover (LULC) maps for different years with ecological and socioeconomic geodata, this study presents an integrated analysis of the effects of grassland degradation and IAS invasion on SOC and selected livelihood aspects, to assess where and when net financial benefit could be realized from IAS management and subsequent grassland restoration, using *Prosopis* in Baringo County, Kenya, as an example. This method may help stakeholders plan IAS management to maximize economic as well as environmental and social benefits.

2 | MATERIALS AND METHODS

2.1 | The study area and its *Prosopis* invasion history

The study area consists of nine sublocations in the 'Njeps flats' around and between Lakes Baringo and Bogoria in Baringo County, Kenya. Its average altitude is 1,000 m a.s.l. The flats are dominated by rangeland and deciduous shrubland—a woody mixture of indigenous *Vachellia* species and exotic species. The main livelihood strategies in the study are pastoralism, agro-pastoralism, farming and charcoal production (Linders et al., 2020).

Prosopis currently dominates the lowland flats extending south of Lake Baringo and towards the northern tip of Lake Bogoria (Figure 1; Mbaabu et al., 2019; Ng et al., 2017). It was introduced in the area in 1982–1983 as part of the Fuelwood Afforestation Extension Project (Little, 2019). *Prosopis* trees were planted at more than 20 sites, originally covering an area of over 250 ha (Andersson, 2005). By 2016, *Prosopis* had invaded 18,792 ha of land in the lowlands of Baringo County (Figure 1; Mbaabu et al., 2019). *Prosopis* density has also increased over the years.

2.2 | Impacts of *Prosopis* invasion and grassland degradation and restoration on soil organic carbon

To understand the impacts of *Prosopis* invasion, land degradation and grassland restoration on SOC, LULC maps for the years 1995, 2002, 2009 and 2016 were analysed, along with a detailed map of *Prosopis* fractional cover in 2016. The LULC maps were generated earlier for another study (Mbaabu et al., 2019). For the present analysis, the relevant original LULC classes were regrouped into the following five categories: (a) degraded grassland, (b) pristine grassland, (c) restored grassland, (d) sparse *Prosopis* (Ps) (<50% coverage) and (e) dense *Prosopis* (Pd) (>50% coverage). A number of assumptions were made, based on the study area's LULC and land degradation history. Thus, areas originally classified as 'bare' were considered to be degraded grassland. Areas classified as 'grassland' were considered pristine grassland if they had been 'grassland' since 1995. Restored grassland comprises areas that had been classified as 'grassland' in the LULC maps of 2002, 2009 or 2016 but had belonged to a different LULC class before that (Eschen et al., 2021). Areas invaded by *Prosopis* were categorized as Ps when the invasion was <7 years old, and as Pd if *Prosopis* had been present for at least 14 years. For the 2016 categorization, Ps (<50% coverage) and Pd (>50% coverage) were differentiated using a detailed and accurate *Prosopis* fractional cover map generated following the approach recently published by Shiferaw, Bewket, et al. (2019) and Shiferaw, Schaffner, et al. (2019). All other, less relevant LULC classes were grouped and called 'Other'. Then the total area for each LULC type in each of the regrouped LULC maps was calculated.

Cumulative SOC content in the top 1m was determined in 10–17 plots in each of the five LULC categories (63 plots in total) as described by Mbaabu et al. (2020; Appendix S1 in Supporting Information for details). In short, four 1-m deep soil cores were

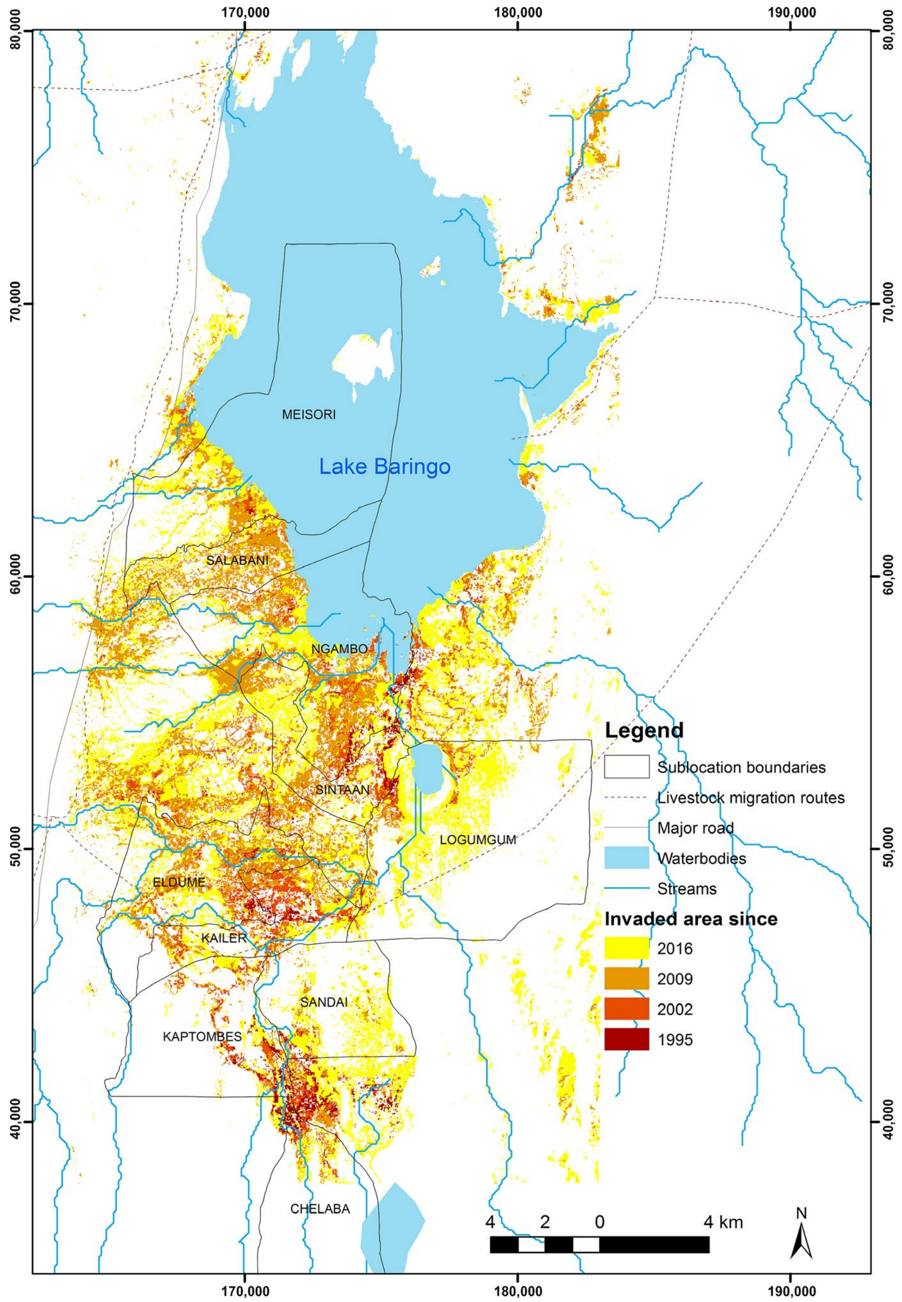

FIGURE 1 *Prosopis* invasion between 1995 and 2016 in nine sublocations in Baringo County, Kenya

TABLE 1 Mean and standard error (*SE*) of SOC measured to 100 cm depth (Mbaabu et al., 2020) in five habitat categories. Letters indicate significant differences among means ($p < 0.05$)

Categories	Mean SOC ± *SE* (t/ha)
Prosopis, dense	40.05 ± 1.28^{abc}
Prosopis, sparse	36.99 ± 2.51^{ab}
Pristine grassland	49.76 ± 2.28^{c}
Restored grassland	44.68 ± 3.77^{bc}
Degraded grassland	31.52 ± 3.04^{a}

taken in one 15 × 15 m plot per location (Kutsch et al., 2009; Lal, no date). To assess bulk density, soil cores were taken from the walls of a pit at the centre of the plot. SOC concentration (%) was assessed colorimetrically (Robinson, 1993) and converted to ecosystem estimates of organic carbon stocks per unit area (t C/Ha; Hoyle, 2013). The amount of category-specific SOC per unit area was assumed to remain constant over time, and the average SOC content (Table 1) was multiplied by the area covered by each LULC class without considering any accumulation or depletion factors.

2.3 | Calculation of costs and benefits of *Prosopis* management in nine sublocations in Baringo

The costs of manual *Prosopis* removal and grassland restoration by sowing of native grasses, as well as the resulting benefits in terms of changes in SOC and cattle number and income from charcoal production, were calculated for each sublocation. The full description of the calculations is presented in Appendix S2 in Supporting Information. The individual budget available for *Prosopis* control and grassland restoration, USD 37.74 per person, was based on a choice experiment to determine willingness to pay for *Prosopis* management among 250 households in Baringo (Bekele, Haji, Legesse, & Schaffner, 2018). Land size was not considered in the budget as land tenure in the region is mixed and many households do not own, use or manage a defined piece of land. The individual budget was multiplied by each sublocation's population size (Linders et al., 2020), as the budget for each sublocation. It was assumed that this budget would be used for a single intervention (i.e. clearing, sowing and follow-up weeding over the subsequent 2 years) and that it was available only once.

The benefits in terms of SOC of clearing *Prosopis* and establishing grassland were calculated as the difference in mean SOC per hectare between the cleared type of *Prosopis* (Pd or Ps) and restored grassland (Table 2), which was assumed to be accumulated over a period of 30 years, as this was the age of the restored grasslands where SOC was measured and roughly the number of years since the invasion started (Mbaabu et al., 2020). A one-off, immediate financial benefit of clearing *Prosopis* is the income generated from charcoaling the cut and uprooted trees. Increases in the number of cattle per ha following management were calculated as the difference between the current herbaceous biomass values, which depend on current *Prosopis* density, and the assumed values after removal of *Prosopis* and restoration of grassland (Mbaabu et al., 2020), divided by the average annual amount of biomass required per cow.

The costs and benefits of managing Ps and Pd areas were assessed using the available budget for each sublocation and the parameters in Table 2. The net financial benefit of managing Ps and Pd in each sublocation was calculated as the difference between the available budget and the monetary benefits of implementing *Prosopis* management (in USD). How the area treated and the net benefits are affected by the fractions of the budget allocated to treating Ps and Pd was assessed by performing the calculations with the relative budget allocation to Ps ranging from zero to one hundred per cent in increments of ten per cent. The return on investment was calculated as the ratio between willingness to pay per inhabitant and net financial benefit divided by population size in each sublocation.

2.4 | Modelling and evaluation of spatially explicit management scenarios

Uniform management of all invaded areas is too labour-intense and expensive to be realistic. Moreover, local people prefer prioritizing certain areas over others. For the calculations, areas that had been covered with native flora (grassland, native mixed vegetation consisting of trees, bushes and forests) before they were invaded by *Prosopis*, as well as areas invaded more recently over those invaded earlier were prioritized. This assumed that restoration of original plant and tree species is most likely to succeed in areas where stumps or seeds of native trees or grasses are still present. Invaded areas that had formerly been categorized as grassland, native bush- or shrubland, or natural forests were derived from the LULC categorizations for 2009, 2002 and 1995 (Mbaabu et al., 2019). If the available budget per sublocation exceeded the cost of treating these areas, it was assumed that further invaded areas (Ps or Pd not previously covered by grassland, native bush- or shrubland, or natural forest) would be treated until the entire budget was spent, prioritizing larger over smaller patches. Clearing *Prosopis* from the islands in Lake Baringo that belong to Meisori sublocation was not considered a priority. This process resulted in many differently sized fragments of invaded priority areas to be cleared. The fragments to be cleared were selected based on their size, starting with the largest.

Three management scenarios were defined: (1) The entire budget is used to treat Pd; (2) the entire budget is used to treat Ps and (3) half of the budget is used to treat Pd and the other half to treat Ps. The calculations for the nine sublocations are provided in Appendix S5 in Supporting Information. Once the available budget and the respective scenarios for each of the nine sublocations were calculated, the three *Prosopis* management scenarios for four selected sublocations were mapped.

3 | RESULTS

3.1 | Changes in LULC categories and SOC

Prosopis invasion affected the five LULC categories differently over time. While the area of dense *Prosopis* continually increased from 331 to 8,403 ha, that of sparse *Prosopis* decreased slightly after 2009 to 7,048 ha in 2016. The overall invaded area grew at the cost

TABLE 2 Parameters used to assess costs and benefits associated with *Prosopis* clearing and grassland restoration in sparse and dense *Prosopis* stands in Baringo

	Parameter	Ps	Pd
Costs	Clearing + 8 person days weeding (USD/ha)	231.67	299.55
	Sowing (USD/ha)	175.00	175.00
Benefits	Charcoaling cleared *Prosopis* (USD/ha)	475.06	1,391.90
	SOC carbon credit, low (USD/ha)	64.60	38.89
	SOC carbon credit, high (USD/ha)	172.26	107.94
	Increase in herbaceous biomass (t/ha)	6,138.04	6,667.93
	Increase in cattle carrying capacity (no/ha)	2.49	2.69

of grasslands. Pristine grassland areas radically declined (798 ha in 1995; 21 ha in 2016). Restored grasslands, after shrinking in 2002, grew after 2009 (321 ha in 2009; 684 ha in 2016). Degraded areas decreased due to *Prosopis* invasion. But other LULC classes also shrank at the cost of both sparse and dense *Prosopis* (see Appendix S3 in Supporting Information).

The LULC changes also affected SOC and thus carbon sinks in the area (Table 3). While the shares of SOC stored by the three grassland categories and the category 'Other' decreased, those stored by the two *Prosopis* categories increased. Since the overall invaded area grew, the total amount of SOC stored also grew. In other words, the invasion has increased overall carbon sequestration/SOC stored in invaded areas increased by 387%, or 474,554 tonnes in 2016, whereas the loss of restored and pristine grasslands released 76,222 and 38,600 tonnes of carbon (72% and 97%), respectively.

3.2 | Costs and benefits of *Prosopis* management

On average, the available budget enables treatment of 19.5%–22.8% of the entire invaded area in a sublocation in a single year (see Appendix S5 in Supporting Information). With increasing budget allocation to treating Ps, the treatable area of Ps increased and the treatable area of Pd decreased; the maximum fraction of treatable Pd was larger than that of Ps (60.7 ± 7.8 and 47.8 ± 2.8% of the total Ps and Pd areas in the sublocations, respectively). In Meisori sublocation, the available budget is enough to treat the entire Pd area and almost a third of the Ps area in a single year. None of the other sublocations have enough budget to treat either of the *Prosopis* categories entirely.

Analysis of the effects of the fraction of the budget spent on treating Ps and Pd revealed that augmenting the investment in clearing and sowing Ps linearly increased the average total amount of SOC added in a sublocation from 668 to 1,289 tC (Figure 2). Our calculation of the mean difference between *Prosopis* and restored grassland indicates that this was due to the larger increase in SOC achieved when sparse *Prosopis* is replaced with grassland than when dense *Prosopis* is replaced with grassland (7.69 vs. 4.18 tC/ha).

The increase in SOC accounted for 1.7%–12.5% of financial benefits, depending on whether we applied the high or the low SOC value and whether we assumed treatment of Ps or Pd. The

TABLE 3 Total SOC (tonnes) stored in the soil of each LULC category, cumulated across the study area, estimated for 1995, 2002, 2009 and 2016

	SOC (t)			
	Year			
Categories	1995	2002	2009	2016
Prosopis, dense	13,234.6	76,942.5	175,787.8	336,495.1
Prosopis, sparse	109,386.2	217,580.6	314,686.2	260,679.8
Pristine grassland	39,703.7	5,382.8	7,021.8	1,043.4
Restored grassland	106,796.7	28,336.8	14,327.2	30,574.2
Degraded grassland	415,666.3	306,901.9	256,033.4	234,477.3
Other	1,918,949.3	1,957,463.5	1,868,192.2	1,809,242.9
Total	2,603,736.8	2,592,608.1	2,636,048.7	2,672,512.9

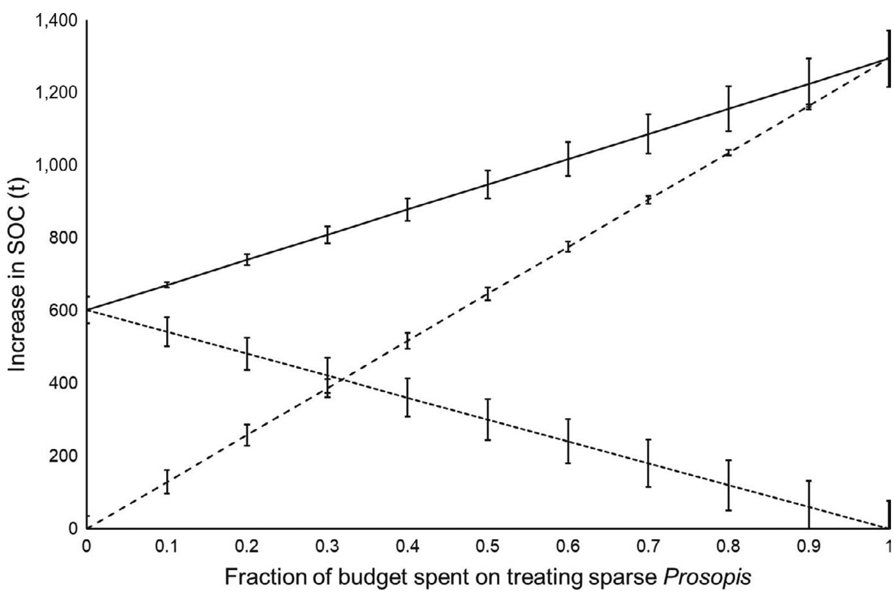

FIGURE 2 Estimated increase in SOC (average of nine sublocations) following *Prosopis* removal and grassland restoration, as a function of the fraction of the budget spent on treating Ps and Pd (long and short dashes, respectively). The solid line indicates the combined increase. Error bars indicate one Standard Error

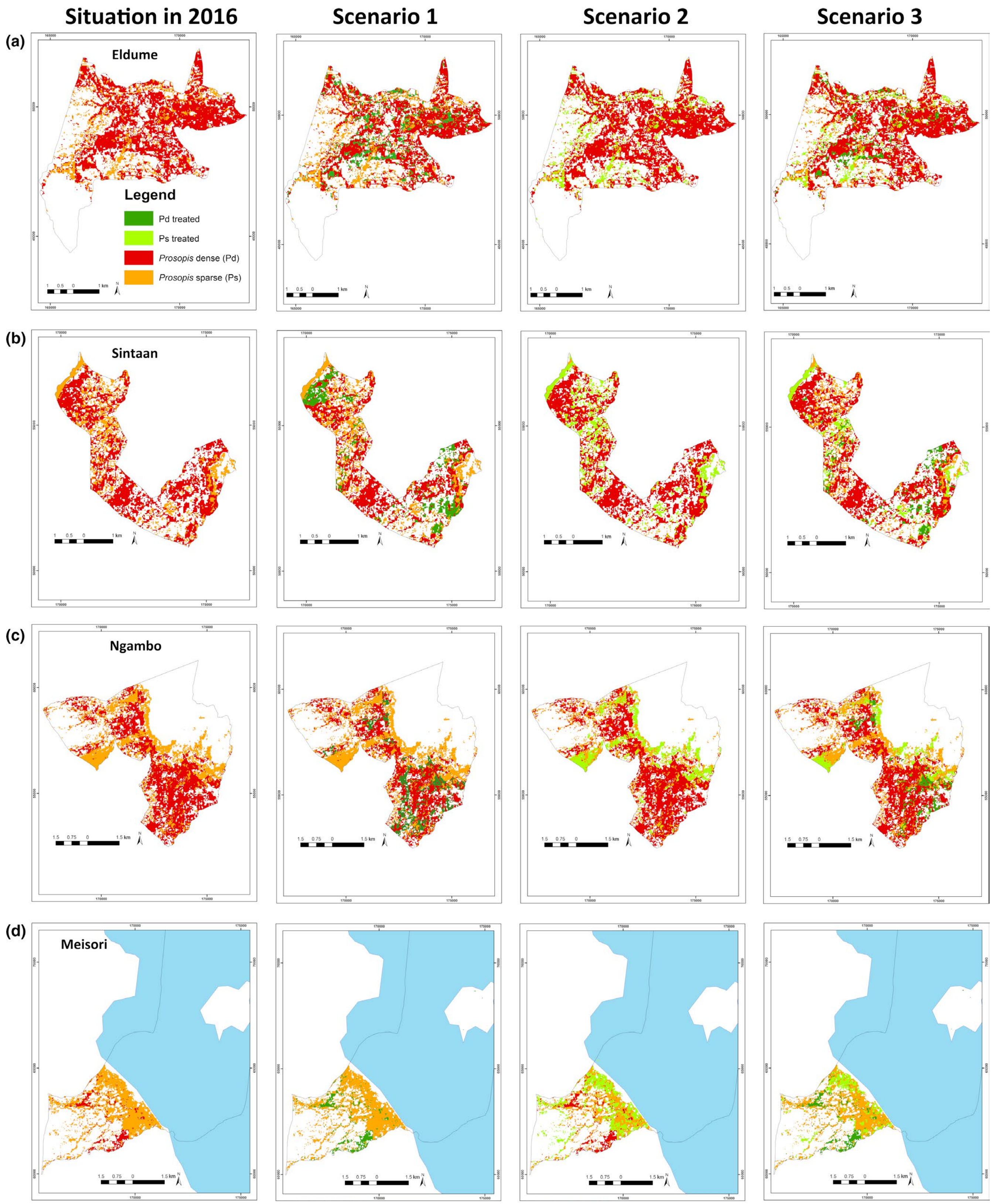

FIGURE 3 *Prosopis* invasion in 2016 and three management scenarios for each of the four sublocations Eldume (a), Sintaan (b), Ngambo (c) and Meisori (d). Areas invaded densely in 2016 are shown in red, sparsely invaded ones in orange. Scenario 1 allocates the entire available budget to treating areas of dense *Prosopis* (dark green). Scenario 2 allocates the entire budget to treating areas of sparse *Prosopis* (bright green). Scenario 3 allocates half of the budget each to treating areas of dense and sparse *Prosopis*. The legend in the top left map applies to all maps

immediate financial benefit from charcoal production made up 33.2%–62.2% of financial benefits, the percentage being higher when assuming treatment of Pd. The contribution of cattle value increased from 35.1% to 60.5% if we assumed treatment of Pd rather than Ps. Hence, the bulk of financial benefits that can be accrued over 30 years was made up from income from charcoal and an increase in capital in the form of cattle. The net financial benefit was inversely and linearly related to the fraction of budget spent on treating Ps.

Our analysis shows that clearing *Prosopis* and restoring grassland would provide financial gains to all sublocations: Every situation assessed would result in a positive return on investment in all sublocations. The return of investment was independent of population size and ranged from USD 2.12 per dollar invested when allocating the entire budget to treating Ps and assuming the lower SOC value, to USD 3.85 when allocating the entire budget to treating Pd and assuming the higher SOC value.

3.3 | Spatially explicit management scenarios

Figure 3 shows the *Prosopis* management maps for four out of the nine sublocations. Eldume sublocation is heavily affected by *Prosopis* invasion, with 38.6% of its area covered by Pd and 11.6% by Ps (totalling 1,299 ha of invaded area). Eldume's budget would enable treatment of 20.6% of Pd (Figure 3a; Scenario 1) or 80% of Ps (Scenario 2). While Scenario 2 would enable treatment of all sparsely invaded areas formerly covered with grassland and native flora, implementation of Scenario 1 would leave 21.8 ha of heavily invaded such areas untreated. The situation in Sintaan is even worse, with 60.5% of the sublocation's area being invaded (42% Pd, 18.5% Ps). This includes 120 ha of areas formerly covered with grassland and other native flora. Sintaan's budget would enable treatment of 26.7% of Pd (Figure 3b; Scenario 1) or 70.9% of Ps (Scenario 2). Scenario 3 would enable almost all areas formerly covered with grassland and native flora to be treated. At 1,716 ha, Ngambo has the largest invaded area, although it covers 'only' 46% of the sublocation. It also has the largest population. However, its budget would only suffice to treat 26.1% of Pd (Figure 3c; Scenario 1) or 44.4% of Ps (Scenario 2). Nonetheless, both scenarios would enable treatment of all areas formerly covered with grasslands and native flora. The situation in Meisori is slightly different from the other sublocations, as a smaller share of its area is invaded (6% Pd and 32% Ps). Meisori's budget would suffice to treat all Pd (Figure 3d; Scenario 1) and about 100 ha of Ps.

4 | DISCUSSION

Our results show that the one-off budget based on the average willingness to pay expressed by inhabitants of Baringo (Bekele, Haji, Legesse, Shiferaw, et al., 2018) would suffice to manage a considerable area of *Prosopis* in Baringo in a single year, and that the conversion of invaded areas into grassland would provide significant financial benefits. A sustained effort over several years might enable sustainable management of a large part of the areas invaded with *Prosopis* in most sublocations. The results also indicate what generates the financial benefit which areas could be prioritized for treatment.

4.1 | Costs and benefits of *Prosopis* removal

Although *Prosopis* management is expensive, our results suggest that a large part of the costs in Baringo can be offset by immediate financial benefits from the sale of charcoal. This is important, because the affected communities have limited human and financial resources for environmental management. Although income from charcoal production covers only part of the cost of *Prosopis* removal and grassland restoration, the immediate financial return may be a motivation to manage *Prosopis*, and it could support agro-pastoralist and pastoralist households during the reversion from charcoal-based to traditional pastoralist livelihoods. We are not aware of any studies quantifying the costs and benefits of making charcoal from *Prosopis*. Accordingly, trials are needed to demonstrate the feasibility and the financial and ecological benefits of *Prosopis* management in affected agro-pastoral communities. In addition, the immediate benefits of charcoal making may vary among countries. For example, in other countries where *Prosopis* is used for charcoal, such as Ethiopia and India, similar benefits may be gained, but not in countries where Prosopis is invasive but not used, such as Australia.

The cost of clearing *Prosopis* requires further investigation, as it strongly depends on the method used. Uprooting is particularly expensive and labour-intensive, but yields more charcoal than chemical management methods like herbicide treatment of the basal bark or cut stumps. However, if the aim is to establish grassland, tree stumps may not need to be removed, and a less labour-intensive method of treating cut stumps with herbicide may be more adequate. The cut stump method, which is comparatively quick and cheap, would make *Prosopis* management across large areas more feasible and might result in a better cost–benefit ratio than what we estimated. However, the lack of tools (chain saws) and acceptance of herbicide use by local communities make application of this method on a large scale currently practically impossible. Manual uprooting, while more labour-intensive, does not require special tools, chemicals or skills and can therefore be done by unskilled workers.

4.2 | Financial and immaterial benefits of restoring grasslands

Grasslands might establish within <30 years (Mureithi et al., 2014), especially if they are not overgrazed (Mureithi et al., 2010). Accordingly, part of the benefits from grassland restoration could be realized within <10 years; only the full accumulation of SOC would require 30 years. However, the financial benefit of grassland restoration elsewhere has been variable and depends on the cost of the restoration techniques that were used (e.g. Xu et al., 2019). Similarly, the benefit in terms of SOC sequestration increase over time and are higher if the restored vegetation is species rich, which adds to the costs (Yang et al., 2019). Yet, the long-term financial benefits from having restored grassland and keeping more cattle are likely underestimated in our study, as they can be derived repeatedly. The larger cattle numbers represent increased capital but also yield income from cattle-based products like meat and dairy, and from cattle sales. Finally, grasslands provide non-monetary benefits, including cultural and regulating services (regulation of climate, floods, erosion). However, it is difficult to estimate the magnitude of expected or realized non-monetary benefits, especially since some of these benefits need to be considered in the context of increased carbon and methane emissions as a result of charcoal production and increased cattle numbers. Our calculations do not allow inclusion of potential effects of carbon or methane emissions. Moreover, the effects of such emissions as a result of activities in Baringo would be difficult to distinguish from the effects of changes in emissions outside the study area. Yet, it is clear that benefits of grassland restoration for the local communities in Baringo would be significant.

The likelihood of grasses establishing depends on suitable climatic conditions and grazing management. With climate change and the associated higher variability of the beginning and duration of the various seasons, grass is considered a more secure crop compared to local staple crops like maize or beans; particularly perennial grass species require less rain for completion of a cropping cycle. Growing grass for seed production is widespread in some of the sublocations, and farmers can also sell the hay (Lugusa et al., 2016). Pressure on grazing land is generally very high in Baringo and other pastoralist regions in Eastern Africa, with overgrazing having contributed considerably to land degradation and an increase in bare areas (Kiage et al., 2007). Accordingly, restored grasslands must be protected from grazers to enable the sown seeds to establish and to reduce the risk of *Prosopis* re-establishment as a result of introduction of seeds with cattle dung. When cattle are allowed to graze, a prior quarantine period should be imposed to ensure no seeds are left in the gut when they enter the grassland. Although grazing management on communal and open-access grazing land is challenging, past experiences show that traditional, community-administered rotational grazing systems can effectively achieve sustainable use of grasslands and SOC restoration (Oduor et al., 2018; Verdoodt et al., 2010). A potential limitation on large-scale grassland restoration on the cleared land could be the cost and the required amount of grass seed (Lugusa et al., 2016), especially of *Cenchrus ciliaris*, *Enteropogon macrostachyus*, *Eragrostis superba*, *Cymbopogon pospischilii* and *Sehima nervosum*. A significant increase in seed production may be required, which would create jobs during the transition period.

We found a trade-off between gains in SOC and financial benefits: While the largest increase in SOC is expected to result from treating sparsely invaded areas, treatment of densely invaded areas would enable a larger increase in cattle numbers and a larger immediate financial benefit from charcoal production. Our estimates of financial benefits from the increase in SOC following *Prosopis* removal and grassland restoration are comparatively rough, and they make up less than one-tenth of all estimated financial benefits. Hence, carbon credits are unlikely to be an important argument for managing *Prosopis*, as they would generate much less income than the additional cattle that could be kept, but it might provide an additional income stream resulting from conservation and sustainable land management efforts (Native Energy, n.d.).

4.3 | Prioritization of *Prosopis* management in a spatial context

Our study illustrates how the costs and benefits of *Prosopis* management depend on *Prosopis* density. At high densities, the costs are higher, but so are the calculated financial rewards. In areas with lower densities, which include the invasion front and recently invaded areas, the calculated financial return is much lower. However, other benefits are higher, particularly the increase in SOC and, in areas where *Prosopis* is sparse, conservation of remaining biodiversity and prevention of environmental degradation from *Prosopis*. Areas with lower *Prosopis* densities are more rapidly cleared—enabling clearing of larger areas—and were likely invaded more recently, thus having a more intact seed bank than areas that were invaded longer ago. Accordingly, they may be easier to revert to grassland than densely invaded areas. This suggests that prioritizing sparsely invaded areas offers significant benefits.

It is plausible that the motivation for *Prosopis* management depends on its contribution to conserving cattle-based livelihoods and on the associated financial benefits—also because this is part of the local cultural heritage. Yet, opinions about *Prosopis* and the willingness to manage the species vary among stakeholders (Bekele, Haji, Legesse, & Schaffner, 2018). *Prosopis* management plans should therefore be developed in a participatory process and should take account of the priorities and preferences of all involved stakeholders. While the protection or restoration of grasslands would benefit pastoralists and agro-pastoralists, management decisions should also involve stakeholders who depend on charcoal burning. Therefore, a management plan should consider and reflect on the need for alternative sources of wood and energy. The location and extent of valuable assets must be identified and delineated, and stakeholders must agree on the suitability, efficacy and feasibility of the selected management methods. Consideration of these principles will result in an optimized *Prosopis* management plan that not only helps to protect the jointly identified assets but also results in the highest possible benefits for local communities following grassland restoration (Adams & Setterfield, 2015; Epanchin-Niell & Wilen, 2012). The optimal management strategy depends on the rate of invasion, *Prosopis* abundance and density, and the invasion's location in the landscape and may vary for each sublocation.

5 | CONCLUSIONS

Addressing climate change and land degradation are major issues that affect livelihoods of many people and that require targeted use of scarce financial resources. This study describes IAS management scenarios using a novel spatial and integrated approach using various detailed data about IAS distribution and density, management costs, financial benefits and land use history. Integrating and linking such data may be particularly useful to develop accurate and realistic IAS management scenarios that can be used to illustrate costs and benefits of management interventions, where they are most needed and most cost-effective, and thus help stakeholders select the most appropriate and feasible approach that suits their needs.

This study of *Prosopis* in Baringo shows that relatively small investment in IAS clearing and restoration of degraded grassland in Eastern Africa may result in significant benefits for local communities managing the land that will support traditional livelihoods and increase SOC in the long term. Such investments could be made as part of novel or existing payment for ecosystem services schemes like those paying carbon credits (Native Energy, n.d.). This approach can be applied to other rangelands in the world affected by *Prosopis* or other IAS invasions, in which case different costs–benefit outcomes will arise as a result of local conditions, livelihood strategies or IAS characteristics. Spatial and integrative management scenarios should be used more extensively to support land management decisions, especially where natural as well as financial resources are scarce and costs and benefits unequally distributed.

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AUTHORS' CONTRIBUTIONS

All authors co-designed the study; K.B. and P.R.M. led the data collection and all authors contributed to the data analysis; R.E. and S.E. led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

DATA AVAILABILITY STATEMENT

Data available via the Dryad Digital Repository https://doi.org/10.5061/dryad.4xgxd258c (Eschen et al., 2021).

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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