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Ecological Solutions and Evidence

RESEARCH ARTICLE

Nature-based approaches to invasive plant management: Insights from East African rangelands for sub-Saharan landscape restoration

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Abstract

1. Worldwide, there is increasing recognition in the application of nature-based solutions (NbS) that can be generated among others from nature-based approaches (NbA) to restore degraded natural habitats.
2. This paper reports systematic evidence established from performing a series of laboratory, screen house (ex situ) and field (in situ) experiments for over a decade to collate and communicate the effectiveness of NbA for managing ecosystems degraded by invasive plants. We first tested ex situ (2015–2017); the effect of *Desmodium uncinatum* leaf extracts and re-seeding of a native grass *Cynodon dactylon* on the growth and development of selected species of the family *Asteracea* following a completely randomized design (CRD). We then tested in situ (2018–2020) by targeting invasive plants of the same family in the Ngorongoro Conservation Area (NCA) by setting 12 pilot blocks of 28 × 28 m, following a Randomized Complete Block Design (RCBD). The in situ trials were conducted to assess the effectiveness of *C. dactylon* re-seeding, spraying of *D. uncinatum* leaf extract and *D. uncinatum* seeding on invasive plant species ground cover, native plant species diversity and invasive and native plants' seedling density. The in situ trials were then followed by a validation workshop (2020–2021) and later on (2022 onwards) the approach was up-scaled.
3. Compared to control plots, in situ we found that our NbA were able to reduce invasion by over 60%. The highest level of invasive plant suppression was observed when 6.65 g/m^2 of Bermuda grass (*Cynodon dactylon* (L.) Pers) and 100% Silver leaf Desmodium (*Desmodium uncinatum* (Jacq.) DC.) leaf extract were re-seeded and sprayed, respectively. This improved forage species diversity by four species and reduced the number of germinated invasive plant seeds by over 85%. These two treatments further improved the soil seedbank of forage species by over 55%.
4. Practical implication: Taken together with the ex situ evidence, the in situ evidence suggests that invasive plants, often dominated by the family *Asteraceae*,

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can be effectively controlled in sub-Saharan Africa landscapes by our novel NbA while simultaneously restoring them. Our results inform wider landscape level restoration actions to prevent and mitigate further invasive plants' encroachment and associated negative effects.

KEYWORDS
allelopathic effects, competition, ecological invasion, land degradation, plant community

1 | INTRODUCTION

Habitat degradation due to invasive alien plants has been increasingly reported worldwide (IPBES, 2023). Invasive alien species have been declared as one of the five major threats to biodiversity (Gichua, 2014; IPBES, 2023) that not only cause species extinction (Clavero Pineda & García-Berthou, 2005; Gurevitch & Padilla, 2004) but also alter ecological processes (Fei et al., 2014; IPBES, 2023). Fuelled by climate change and increased spatial movement of the human population, land degradation as a result of invasive alien plants will likely affect ecosystems more rapidly than previously predicted (Poesen, 2018; Vicente et al., 2013). Currently, invasive alien plants colonization worldwide is increasing tremendously (IPBES, 2023). While management of invasive alien plants in agricultural lands has succeeded, it is still challenging in rangelands, that is, areas occupied by native vegetation that are grazed by both wild and domestic animals and managed as natural ecosystems (Zerga, 2015). Thus, management authorities overseeing rangelands lack information on the most effective integrative management tools against invasive alien plants.

Rangelands are estimated to cover 25% of the global land surface (Zerga, 2015), harbour high biodiversity and support over 2 billion people. However, rangelands and the livelihoods of the people who depend on them are threatened by the compounding effects of land degradation by invasive alien plants (Vasquez et al., 2010), which among others, causes biodiversity loss and decreased pasture land. Restoring degraded rangelands is critical to addressing these interlinked crises and enhancing human wellbeing. However, significant gaps in knowledge, skills and best practices continue to limit effective rangeland restoration and adaptation efforts.

Managing invasive alien plants in rangelands is challenging due to the impacts of chemical or biological applications, which are conventionally used in farmlands (Mitra et al., 2011). Chemical, biological and mechanical control have potentially large-scale negative impacts on native flora and fauna and are often costly and labour-intensive to carry out over large spatial areas (Shackleton et al., 2017). One alternative for managing invasive alien plants in invaded rangelands is to use nature-based approaches (NbA) (Ngondya & Munishi, 2022). The NbA is a broader framework that can generate varieties of nature-based solutions (NbS), which—as per the International Union for Conservation of Nature (IUCN)—aims at protecting, sustainably managing and restoring natural and modified ecosystems (Le Gouvello et al., 2023). It is an ecosystem-based management and/or restoration procedure that relies on the direct utilization of native flora and fauna in addressing challenges arising from ecosystem degradation drivers (Ngondya & Munishi, 2022). The approach promotes among others, the establishment of native plant species with a suite of characteristics, such as higher growth rates, that can out-compete and suppress the target invasive alien plants, while improving ground cover and reducing surface run-off (Ngondya et al., 2019). Likewise, plants with allelopathic potential (Kaiira et al., 2021) can also be used as components of NbA to suppress invasive alien plants.

Management approaches that are used to control invasive alien plants in rangelands need to be authenticated and supported by evidence in terms of their efficacy, relevance and scalability. While ecological restoration efforts promote NbA for sustainability, efforts should not only focus on controlling the target invasive alien plants but also ensure minimal or no negative impact to biodiversity, the ecosystem components and their functioning (Ngondya & Munishi, 2022). This paper reports systematic evidence established from performing a series of laboratory, screen house (ex situ) and field experiments (in situ) over about 10 years to collate and communicate the effectiveness of the NbA for restoring rangelands degraded by invasive alien plants and its utilization potential to develop management/mitigation actions at landscape level.

The current study complements two parallel ex-situ (screenhouse and pot) experiments that were conducted in the years 2014–2019 (Ngondya et al., 2016a, 2016b; figure 1) in Arusha, Tanzania. The results of these studies were published in 2016 and 2019 (Ngondya et al., 2016a, 2016b, 2019, respectively). In these experiments, we assessed the effects of a naturalized allelopathic plant, *Desmodium uncinatum* (Jacq.) DC., leaf and root crude extracts on the seed germination, seedling height, leaf chlorophyll content and fresh weight (biomass) of the two encroaching herbaceous species *G. cordifolia* and Wild marigold (*Tagetes minuta* L). We further investigated the suppressive effects of the highly competitive native grass species, *Cynodon dactylon* (L) Pers, reseeding on invasive plants *T. minuta* and *G. cordifolia* (Ngondya et al., 2019).

2 | MATERIALS AND METHODS

2.1 | Study permission

This study was conducted under permit number TWR/RS-331/2013/56 that was issued to the authors by Tanzania Wildlife Research Institute (TAWIRI) on 27/5/2015.

2.2 | Theoretical basis of the methods applied

Stability of plant communities is driven by natural forces that shape ecological communities, such as plant–animal mutualism and plant–plant interactions in form of allelopathy and density-dependent competition (Dayan & Simberloff, 2005). If thoroughly studied, such natural forces are likely to be useful in devising mechanisms to overcome land degradation resulting from ecological invasion (Figure 1). In croplands, the use of competitive native palatable plant species for reducing cover of invasive alien plants has been recently recommended (Csákvári et al., 2023; Ngondya & Munishi, 2022). In rangelands, some native species can likely also play such a role while leaving the ecosystem uncompromised (Ngondya et al., 2019). Similarly, the use of natural extracts (allelo-chemicals) from native plants is an emerging opportunity to suppress invasive alien plants (Munishi & Ngondya, 2022). We claim that when the two NbAs are combined, they have the potential to sustainably manage invasive alien plants in degraded landscapes. This paper complements ex situ findings that were previously reported (Ngondya et al., 2016a, 2016b, 2019) on the effectiveness of using the NbA in managing invasive alien plants in sub-Saharan African rangelands and elsewhere by highlighting its effectiveness in situ.

In this study, the NbA was further tested in-situ in the Ngorongoro Conservation Area, northern Tanzania, an area that had been invaded by plants of the family *Asteraceae* (*Gutenbergia cordifolia* Benth. Ex. Oliv. and *Bidens schimperi* Sch.Bip. ex Walp; Figure 2). The Ngorongoro Conservation Area proved to be a suitable system to assess our NbA's effectiveness in an upscaling process of the previously reported results (Ngondya et al., 2016a, 2016b, 2019).

2.3 | Study design

2.3.1 | In situ experiment

We conducted in situ field trials over the years 2017–2020 to assess the effectiveness of density-dependent competition (using *C. dactylon*) and allelopathy (using *D. uncinatum*) at a larger spatial scale, within the landscapes of Ngorongoro Conservation Area (NCA). Ngorongoro Conservation Area is a World Heritage site and Man and Biosphere Reserve in northern Tanzania (https://www.ncaa.go.tz/) located at 2°30′–3°30′ S, 34°50′–35°55′ E. The area is a multiple land use area, allowing for both conservation of biodiversity and a limited inhabitation of indigenous Maasai people. Several

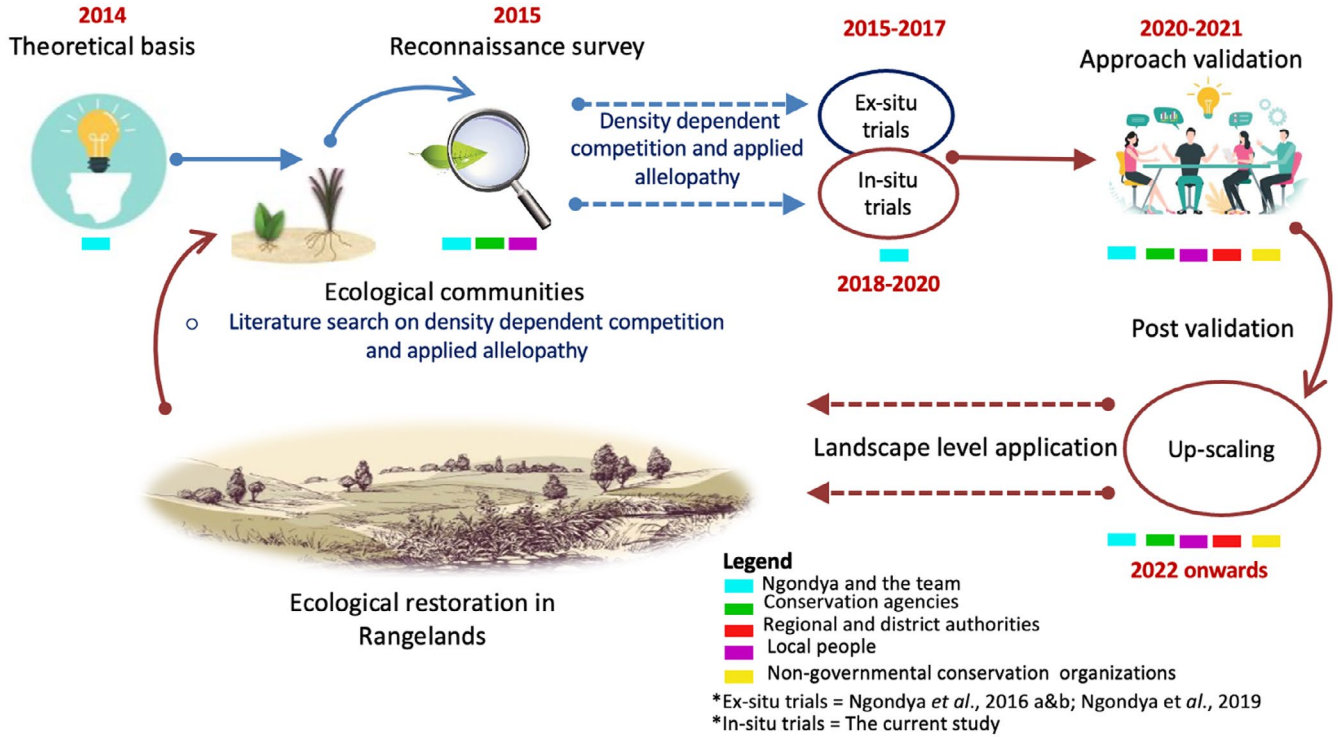

FIGURE 1 A methodological framework detailing how a NbA for managing invasive alien plants was generated through our studies in an interdisciplinary and trans-sectoral manner over the years, including different stakeholders from environmental and conservation organizations at local and national level. The development of this methodological framework started by examining an existing natural ecosystem, especially its plant species composition, and screening suitable native plants that can be manipulated during ecological restoration. Both suitable native species, their traits and functions were then subjected to ex situ experiments to test their effectiveness in addressing the degradation followed by in situ experimentation. Our in situ studies ensured the involvement of relevant stakeholders through workshops, during which results were communicated, commented and validated by these stakeholders. Lastly, an approach was scaled-up for use over larger rangeland areas that have been degraded by invasive alien plants.

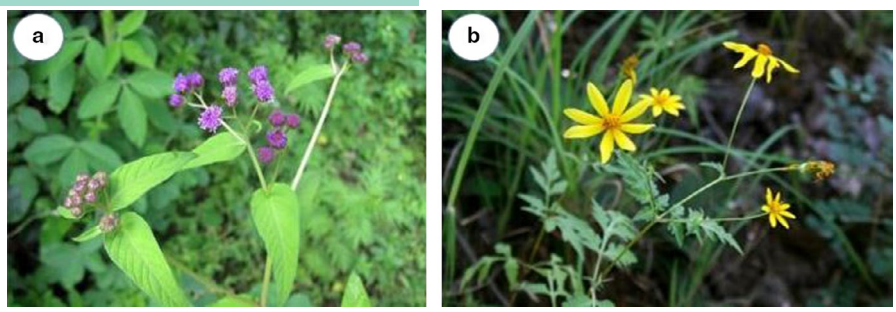

FIGURE 2 The two species of flowering plants of the family *Asteraceae* (a) *Gutenbergia cordifolia* and (b) *Bidens schimperi* that acted as invasive species in our study sites and were tested for the effect of NbA for invasive alien plant management (Image sources: https://eol.org/pages/5114579 and https://www.botswanaflora.com/speciesdata/species.php?species_id=160660, respectively).

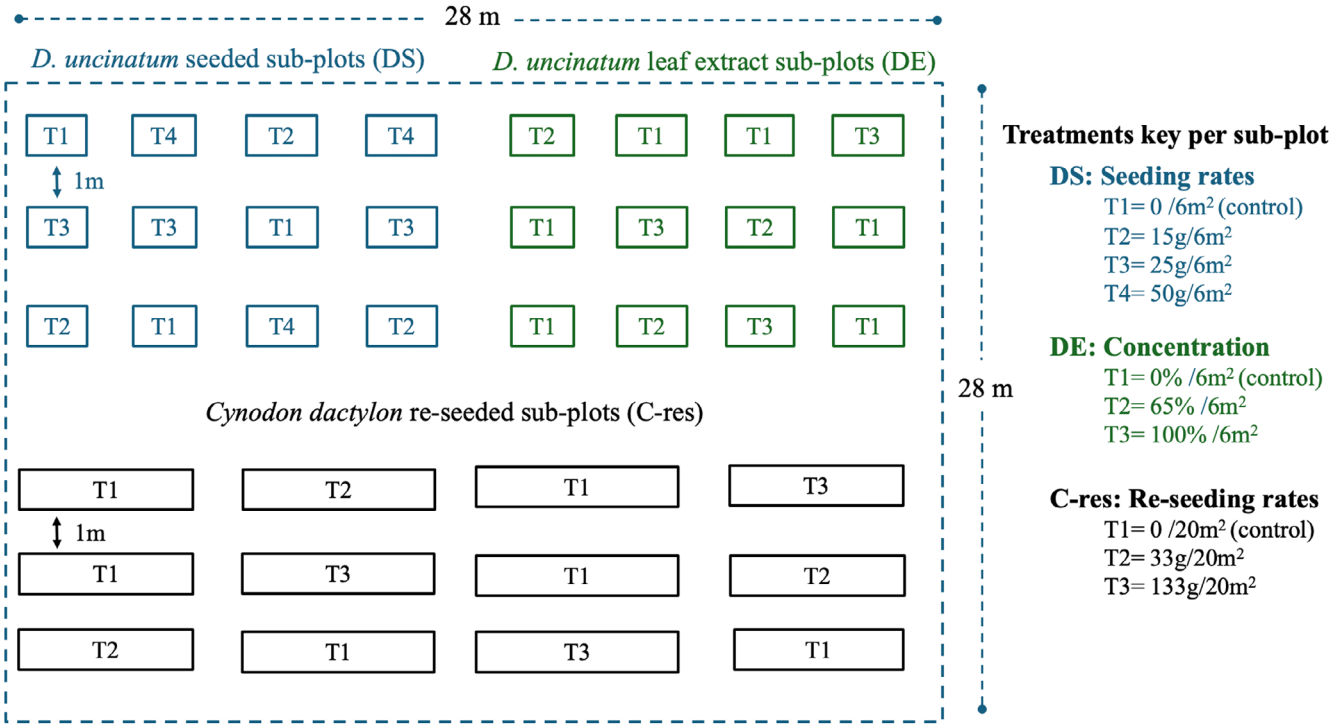

FIGURE 3 Pilot blocks layout and sub-plots treatments following a Randomized Complete Block Design (RCBD) established in the Ngorongoro Conservation Area in the years 2018–2020.

non-consuptive activities including extensive pastoralism and tourism are allowed in the area while consuptive utilization such as hunting and cultivation are not allowed. *Desmodium uncinatum* was selected due to its richness in phyto-chemicals as reported by Ma et al. (2011). The trials were then followed by a validation workshop in which relevant stakeholders (i.e. 20 local people from Karatu and Ngorongoro districts, four people from the two district authorities, four Government conservation agencies including Tanzania Wildlife Research Institute (TAWIRI) and two non-governmental organization involving on wildlife conservation) confirmed usability of NbA (Figure 1). The approach was then adopted by different Non-Governmental Conservation Organizations (NGOs) and local pastoralists in northern Tanzania. Our trials were conducted in 12 pilot blocks of 28 ×28 m, that were established in the NCA following a Randomized Complete Block Design (RCBD) (Figure 3).

Blocks were purposefully chosen in areas that were highly invaded by *G. cordifolia* and *B. schimperi*. Due to excessive above-ground vegetation overgrowth and to ensure that treatment seeds reached the ground during the reseeding treatment, all blocks were mowed once before the treatment application (Williams et al., 2007) (Figure 4a). The blocks were then divided into six fenced and six un-fenced plots of 28 × 28 m each (Figures 3 and 4) that were distributed at Ndutu (3° 01′ 44″ S, 34° 59′ 31″ E), Ziwani (3° 13′ 32″ S, 37° 33′ 21″ E), Munge (3° 09′ 21″ S, 37° 36′ 42″ E), Mawe meusi (3° 09′ 06″ S, 37° 34′ 56″ E), Round table one (3° 08′ 04″ S, 37° 33′ 24″ E) and Round table two (3° 08′ 11″ S, 37° 32′ 40″ E) areas with NCA. The fenced plots were set to limit grazers' interference and to allow recovery without grazers interruption. Each plot was further subdivided based on three treatment applications, namely *C. dactylon* reseeding, *D. uncinatum* reseeding and



FIGURE 4 (a) Experimental plot preparation (mowing) and (b) fenced experimental plot after treatment application within the Ngorongoro Conservation Area, northern Tanzania (Image source: Field survey in the NCA in 2018).

D. uncinatum leaf extract spraying. We used 144 *C. dactylon* reseeded sub-plots of 4 × 5 m ($N = 144$), 144 *D. uncinatum* reseeded sub-plots of 2 × 3 m ($N = 144$) and 144 *D. uncinatum* leaf extract sub-plots of 2 × 3 m ($N = 144$) (Figure 3). To avoid treatment interference at sub-plot levels, buffer zones of 1 m were set between subplots (Koutra et al., 2023).

2.3.2 | Treatments application

Cynodon dactylon and *D. uncinatum* were seeded at rates of 0 g/20 m^2, 33 g/20 m^2, 133 g/20 m^2 and 0 g/6 m^2, 15 g/6 m^2, 25 g/6 m^2, 50 g/6 m^2, respectively, while *D. uncinatum* extracts of 0%, 65% and 100% concentrations were sprayed at the rate of 3 L/6 m^2 (Ngondya et al., 2016a, 2016b, 2019). Reseeding of 0 g/20 m^2, 0 g/6 m^2 and spraying of 0% *Cynodon dactylon*, *D. uncinatum* and *D. uncinatum* extracts, respectively, were used as controls. Each treatment was replicated three times over 2 years. In assessing performance of the treatments, the dependent variable, that is, the relative percentage ground cover of the invasive alien plants and the native plants diversity were quantified.

2.3.3 | Soil sampling

One composite soil sample per each treatment and sub-plot was collected in each block making up a total of 24 samples per block ($N = 144$). The samples were collected at 20 cm depth for soil seedbank assessment at the beginning of the rainy season in February 2018 (before application of treatments) and again in July 2019 (after application of treatments). For the soil seedbank load, the invasive alien and native plants soil seedbank density (see below) was calculated before and after treatment application.

2.3.4 | *Desmodium uncinatum* leaf extract preparation

D. uncinatum leaf extract was prepared as per Ngondya et al. (2016a, 2016b) with some modification as follows. Three (3) kg of *D. uncinatum* leaves were soaked in 120 L of water for 48 h, followed by filtering the *D. uncinatum* crude leaf extract and diluting it into 65% (78 L crude extract: 42 L water) and 100% (120 L crude extract: 0 L water). The three extract concentrations of 0% (=pure water), 65% and 100% were then used as treatments in established plots. The extract was stored at 4°C prior to experiment.

2.3.5 | Soil seedbank density determination experimental set-up

From an initial 1 kg soil sample, we placed 0.5 kg in plastic bags of 25 cm diameter × 8 cm depth (Korres et al., 2018) in an open area, where the ground was covered by sand and stones to avoid seed predation by ants and termites. Plastic bags were irrigated twice daily at a rate of 300 mL/0.5 kg mimicking the Ngorongoro's Conservation Areas mean daily rainfall (Moehlman et al., 2020) in order to induce germination and monitored for a 6-month period (Alvarez-Aquino et al., 2014).

2.4 | Assessment of in-situ treatment performance

The relative percentage ground cover of the respective invasive alien plant was assessed as per California Native Plant Society Relevé Field form (CNPS, 2007) from three observers, averaged to one cover value. All plant species within experimental plots were identified to species level and counted with the help of a field guide

book and a botanist and counted. For the soil seedbank assessment, the numbers of emerging seedlings were recorded on a weekly basis and identified during the 30th, 60th, 90th, 120th 150th and 180th day of the experiment to species or genus level. For most grasses, identification was carried out after inflorescence. Identified seedlings were removed to reduce the competitive effect (Anderson et al., 2012) to allow for further seedlings to germinate. The soil samples in plastic bags were tended regularly to reduce compactness after the rate of seedling emergence had slowed.

2.5 | Data analysis

We performed a Shapiro–Wilk test for normality on the in situ generated data. For non-normally distributed data, that is, the % ground cover of invasive plants and the species diversity of forage plants, the Kruskal–Wallis test was used. Wilcoxon tests with Bonferroni correction were used to test for significant differences in mean values for non-normally distributed data. Chi-square goodness-of-fit test was performed on comparing the invasive alien and forage plant soil seedbank count data. Shannon-Wiener diversity index for forage plants was calculated as per Spellerberg (2003) and converted into the effective number of species (ENS) as per Jost (2006) (Equation 1). In assessing the seedbank, we calculated the seedling density of invasive alien and native (forage) plants as per Kuuluvainen and Pukkala (1989) (Equation 2) as the number of each species per unit volume of the plastic bag.

$$\text{Effective number of species} = \text{Exp}\,(H), H = -\Sigma p_i \times \ln(p_i) \quad (1)$$

where Exp = exponential, H = Shannon-Wiener diversity index, ln = natural logarithm and p_i = the proportion of the entire community made up of species i.

$$\text{Seedling density} = \text{No. of seedlings / pot size (area)} \quad (2)$$

The statistical software used was JAMOVI version 2.3.28 and the level of significance was set at $p < 0.05$.

3 | RESULTS

3.1 | Pre-treatment plant biodiversity status

Before the beginning of the treatment, herbs, particularly of the family *Asteraceae*, dominated in all study plots at NCA (Table 1).

TABLE 1 Mean percentage ground cover of the major plant families that were observed before the application of treatments in our study plots in the Ngorongoro Conservation Area, northern Tanzania.

Family	Growth form	Mean percentage ground cover (%)
Asteraceae[a]	Herb	38
Poaceae	Graminoid	13
Acanthaceae	Herb	12
Fabaceae	Herb	12
Euphorbiaceae	Herb	9
Cyperaceae	Graminoid	7
Malvaceae	Herb	7
Sterculiaceae	Herb	3

[a]*Asteraceae* = *G. cordifolia*, *T. minuta* and *B. schimperi*.

3.2 | Invasive alien plant percentage ground cover after treatment application in the NCA

Generally, we observed a significant reduction of over 50% invasive alien plant cover under *C. dactylon* reseeding, *D. uncinatum* extract and *D. uncinatum* seeding ($H_{(3)} = 22.8$, $p < 0.001$; $H_{(3)} = 16.4$, $p = 0.002$ and $H_{(4)} = 10.30$, $p = 0.041$, respectively) compared to control treatments after 2 years under all three treatment categories in both fenced and unfenced plots (i.e. *C. dactylon* reseeding of 133 g/20 m^2 resulted in a reduction of over 67%, *D. uncinatum* extract application of 100% resulted in a reduction of over 80% and *D. uncinatum* seeding of 50 g/6 m^2 resulted in a reduction of over 50%; Figure 5 in both fenced and unfenced plots).

3.3 | Forage species diversity after treatment application

Although we observed no significant differences in forage species diversity under all three treatments categories, that is, under *C. dactylon* reseeding, *D. uncinatum* extract and *D. uncinatum* seeding ($H_{(2)} = 5.27$, $p = 0.26$; $H_{(2)} = 2.77$, $p = 0.21$ and $H_{(2)} = 3.14$, $p = 0.4$, respectively), we found a slight trend of higher forage species diversity by over six, three and two species (ENS) under higher reseeding of *C. dactylon* (133 g/20 m^2), high *D. uncinatum* extract (100%) and *D. uncinatum* seeding (50 g/6 m^2), respectively, in both fenced and unfenced plots during both short and long rainy seasons (Figure 6).

3.4 | Invasive alien and forage plant species soil seedbank after treatment application

We recorded a significant reduction in germinated invasive alien plant seeds in the soil of over 85% ($\chi^2_{(3)} = 47.4$, $p < 0.001$ and $\chi^2_{(3)} = 16.5$, $p < 0.001$) under *C. dactylon* seeding and *D. uncinatum* leaf extract, respectively (Figure 7a,b), while *D. uncinatum* seeding treatment only slightly (by 25%) reduced the invasive alien plant seedbank ($\chi^2_{(3)} = 4.09$, $p = 0.394$) (Figure 7c). Generally, the higher the seeding density and the plant extract concentrations, the more strongly the invasive alien plants seedbank was reduced as reflected by fewer number of germinated invasive alien plants.

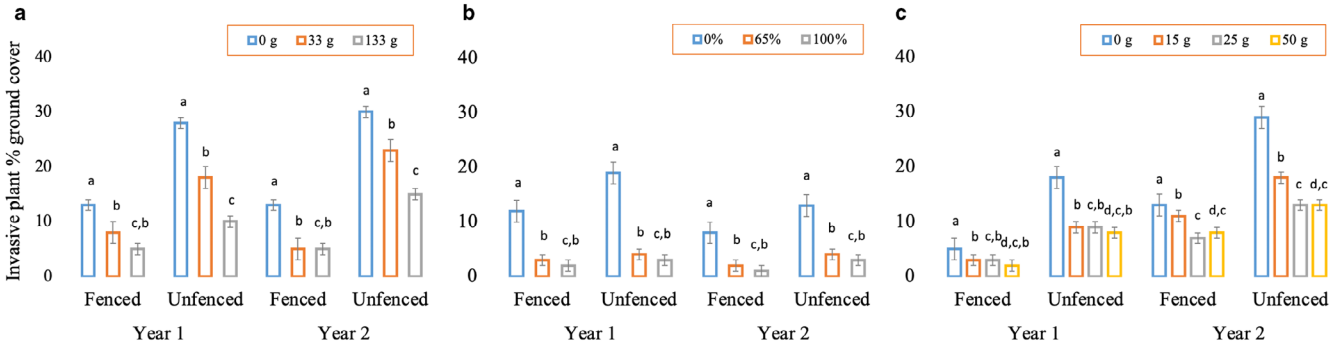

FIGURE 5 Invasive alien plant percentage ground cover in plots where three different treatments were applied in different concentrations in the Ngorongoro Conservation Area under: (a) *C. dactylon* reseeding ($N=36$), (b) *D. uncinatum* leaf extract spraying ($N=36$) and (c) *D. uncinatum* seeding ($N=48$).

We observed significantly higher forage plants seed germination of over 55% ($\chi^2_{(3)}=20.8$, $p<0.001$; $\chi^2_{(3)}=14.4$, $p=0.002$ and $\chi^2_{(4)}=9.40$, $p=0.052$) under *C. dactylon* seeding, *D. uncinatum* extract and *D. uncinatum* seeding treatments, respectively (Figure 8). Generally, both higher treatments of *C. dactylon* reseeding, *D. uncinatum* extract and *D. uncinatum* seeding showed higher forage plant seed germination as reflected by higher forage seedlings density.

4 | DISCUSSION

As previously reported by Li et al. (2015); Chen et al. (2017) and Ngondya et al. (2016a, 2016b, 2019), reseeding of competitive native forage plants and allelopathic plants such as *C. dactylon* and *D. uncinatum*, respectively, presents an opportunity to successfully manage invasive alien plants, especially those of the family *Asteraceae*. It was found that both reseeding of competitive forage (*C. dactylon*) and spraying of *D. uncinatum* leaf extract negatively affected the growth of invasive alien plants *T. minuta* and *G. cordifolia* through suppression of leaf total chlorophyll and biomass, which was manifested by increased levels of leaf anthocyanins. In this paper, we have continuously proven the effectiveness of *C. dactylon* and *D. uncinatum* in reducing invasive alien plants cover, improving forage plant diversity and reducing invasive alien plants soil seedbank while improving that of the native forage plants. This complements not only our previous findings across various spatial–temporal scales (Ngondya et al. 2016a, 2016b, 2019; Ojija et al., 2019, 2021) but also other findings elsewhere (Cueva-Chamba et al., 2023; Guchu, 2007; Singh et al., 2013). Reducing invasive alien plants soil seedbank and improvement of the forage plants seedbank and standing biomass during restoration of degraded areas has been the target of most restoration projects (Torok et al., 2012). While reduction of standing biomass of invasive alien plants is important to promote growth of natives immediately after management action, reducing invasive alien plant seed bank density is a long-term goal that will be crucial for the effectiveness of the invasive alien plants management regime (Torok et al., 2012).

The observed high cover of non-grass species, particularly of the family *Asteraceae*, is an indication of the degradation of the NCA (Wang et al., 2020) as the majority of these species have been reported to be invasive (Fridley, 2013) elsewhere. Herbs can be a great source of fodder for both wild animals and livestock but have also been associated with some negative effects on rangeland health (Arnalds & Archer, 2000; Burkinshaw & Bork, 2009). A mixture of plant species with different life forms often represents a healthy rangeland (Pyke et al., 2002) and therefore should be the aim for any rangeland protection management efforts. The high shrub cover in NCA can be associated with increasing disturbance, mainly from an increasing number of livestock that had been allowed to graze in the NCA over the decades, coupled with negative effects from climate change (Leweri et al., 2021). As the livestock sector is among the leading sectors in sub-Saharan African where pressure on land due to this is severe, there is a need to further incorporate plant species monitoring for early detection and rapid response (EDRR) on invasive plants to address their imminent danger.

Our findings have laid a roadmap on how to effectively formulate nature-based solutions (NbS) that are likely to have positive feedback in addressing land degradation. As it has been reported that invasive alien species are likely to increase globally (IPBES, 2023) in the near future, the vast area of rangelands will face a great challenge in managing invasive plants using conventional methods (Lake & Minteer, 2018). The complex interactions of current and future landscapes and the interdependence between their components (fauna and flora) will likely call for the screening of native individuals that coexist well with invasive alien plants (Li et al., 2015; Ngondya & Munishi, 2021) while managing them. Therefore, we advocate the re-seeding of native highly competitive and allelopathic plants as an environmentally friendly and sustainable approach to address ecological invasion. While reseeding of non-native and/or naturalized plants is not recommended due to invasion risk, we claim that an opportunity exists via the utilization of extracts from parts of such plants with allelopathic properties as components of NbAs (Chen et al., 2017). Climate change is increasingly affecting the majority of pastoral societies, especially in sub-Saharan Africa, where approximately 70% of rural poor people

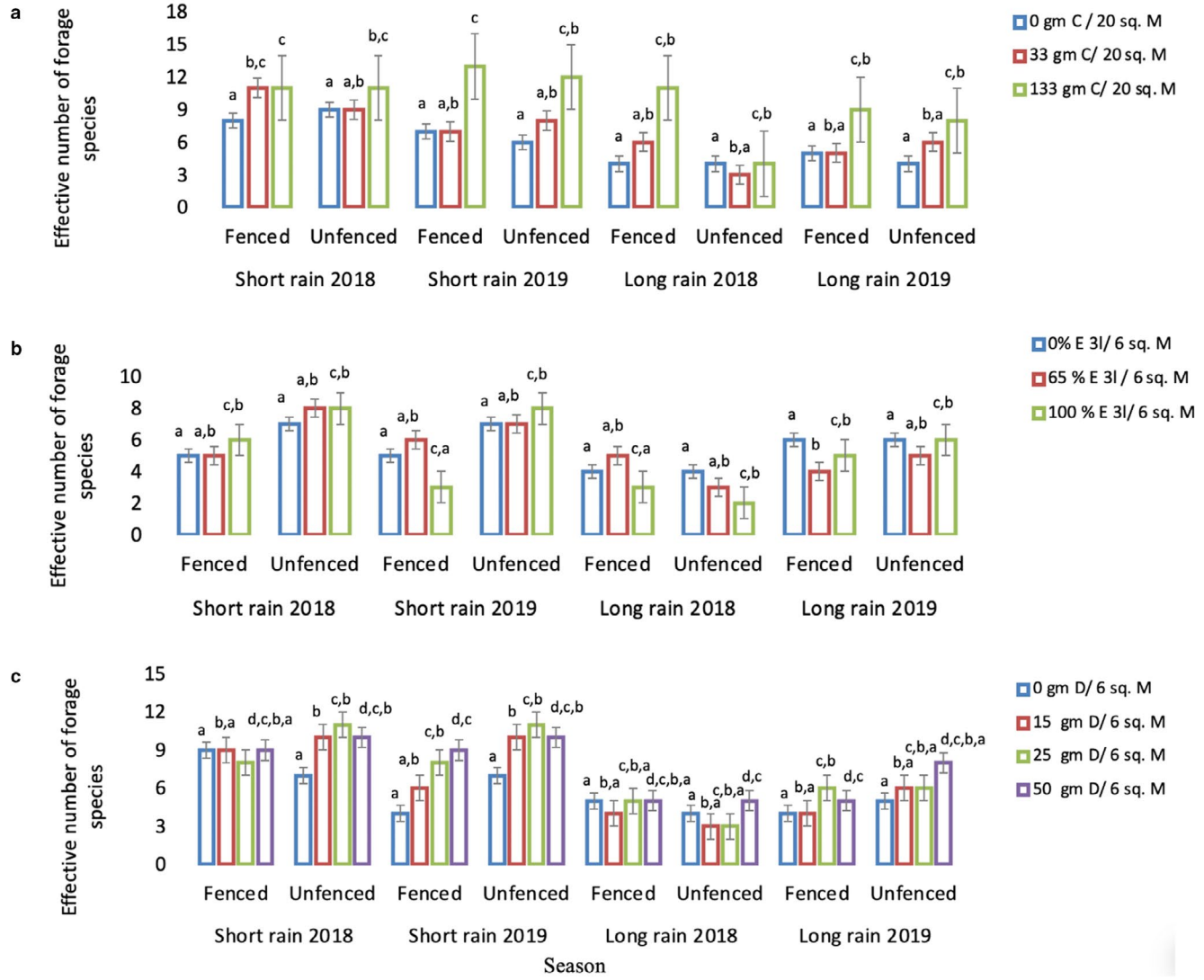

FIGURE 6 Effective number of forage species in plots where three different treatments were applied in the Ngorongoro Conservation Area under: (A) *C. dactylon* reseeding ($N=36$), (B) *D. uncinatum* leaf extract (N = 36) and (C) *D. uncinatum* seeding ($N=48$). Bars with dissimilar letters indicate significant differences in the means by Fisher LSD at $P=0.05$.

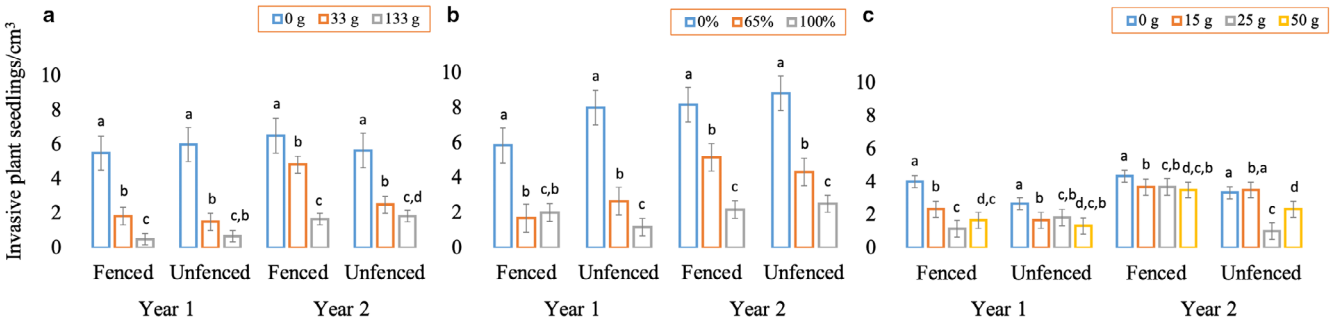

FIGURE 7 Mean (±SE) invasive alien plant seedlings density per plot under (a) *C. dactylon* reseeding ($N=36$), (b) *D. uncinatum* leaf extract (N = 36) and (c) *D. uncinatum* seeding ($N=48$) in the field trial at the Ngorongoro Conservation Area in the year 2018–2020. Bars with dissimilar letters indicate significant differences in the means by Fisher LSD at $P=0.05$.

depend on livestock and related activities (Erdaw, 2023). These areas are insufficient in size to support a continuously increasing livestock population, leading to over-grazing and, consequently, an increasing invasion of unpalatable plants. Hence, we state that immediate environmentally friendly invasive alien plant species management approaches are of paramount importance.

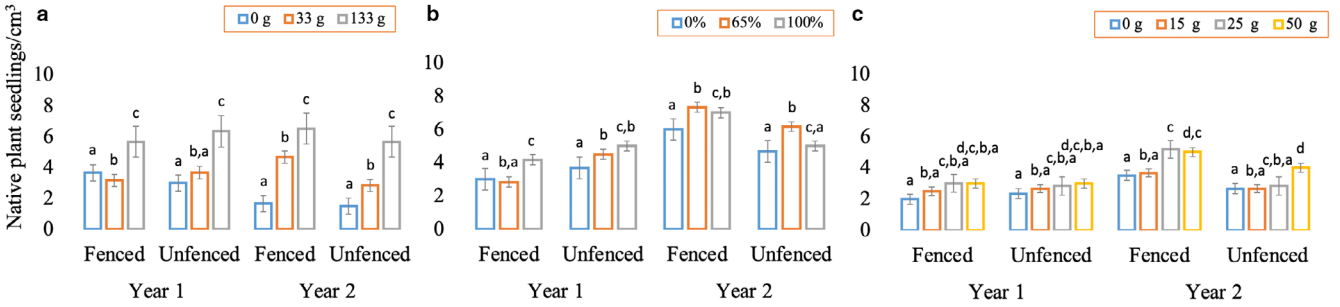

FIGURE 8 Mean (±SE) plots forage plants soil seedlings density under; (a) *C. dactylon* reseeding ($N = 36$), (b) *D. uncinatum* leaf extract ($N = 36$) and (c) *D. uncinatum* seeding ($N = 48$) in the field trial at NCA in the year 2019. Bars with dissimilar letters indicate significant differences in the means by Fisher LSD at $P = 0.05$.

We observed that the re-seeding of native forage plants such as *C. dactylon*, which is high in nutrients (e.g. Treydte et al., 2006), not only improved soil cover and, therefore, reduced plant invasion but also facilitated the growth of other native forage plants. As *C. dactylon* represents also a good candidate plant for soil binding, especially in eroded landscapes (Zhong et al., 2015), screening of such plant species with multiple beneficial traits and functions within sub-Saharan Africa and elsewhere is important in formulating effective nature-based approaches (NbA) for restoration of invaded rangelands (Davy et al., 2017). Although our study was limited by covering only 2 years we expect that native forage plants enrichment will become even more based on the trends we have observed, so we recommend long-term monitoring.

Based on evaluation of our long-term studies on NbA in the laboratory and field trials, we conclude that the application of native and/or naturalized herbaceous species in suppressing invasive alien plants can reduce them and help restore invaded rangelands. Our NbA uses resources that are readily available within the landscape, promoting positive feedback loops within savanna ecosystems, which benefits both Sub-Saharan pastoralists and conservation organizations. While we point out that the NbA is a promising approach in restoring invaded land, it also requires continuous research and monitoring of available suitable native plants to be used. Our results inform wider landscape level actions to prevent further spread and negative effects of invasive alien plants in Sub Sahara African rangelands and elsewhere while building resilience to future climate challenges.

AUTHOR CONTRIBUTIONS

Issakwisa B. Ngondya and Linus K. Munishi conceived the ideas; All authors designed the methodology; Issakwisa B. Ngondya collected the data; Issakwisa B. Ngondya, Linus K. Munishi and Anna C. Treydte analysed the data; Issakwisa B. Ngondya and Linus K. Munishi led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

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CONFLICT OF INTEREST STATEMENT

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.

PEER REVIEW

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DATA AVAILABILITY STATEMENT

The authors confirm that data underlying the findings are fully available without restriction. The data generated during and/or analysed during the current study are available via Zenodo at https://doi.org/10.5281/zenodo.18887459 (Ngondya, 2026).

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