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Do we need post-tree thinning management? Prescribed fire and goat browsing to control woody encroacher species in an Ethiopian savanna

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Worldwide, bush encroachment threatens rangeland ecosystem services, including plant biodiversity and forage for livestock. Various control methods for encroaching woody species and restoring herbaceous vegetation exist but have rarely been explored experimentally. We assessed the impact of post-tree thinning management on tree mortality, the herbaceous community, and overall rangeland condition in Borana, an Ethiopian savanna ecosystem. At two 1.4 ha areas of encroached mono-specific *Vachellia drepanolobium* (whistling thorn) stands, we set up twenty-four 20 × 10 m experimental plots with four post-tree-thinning treatments (goat browsing only (1), prescribed fire (2), fire and goat browsing (3), and control (4) (i.e., no management after tree cutting), with three replications in a complete block design. Over two growing periods, we monitored resulting tree mortality, coppicing, seedling mortality and recruitment, as well as herbaceous layer attributes (diversity, biomass) and overall rangeland condition. All three post-tree thinning management scenarios significantly enhanced tree mortalities, reduced seedling recruitment and increased the abundance of the dominant desirable grass species. Prescribed fire and fire and goat-browsing treatments resulted in significantly greater grass and forb species richness, forb diversity, and biomass, as well as the overall rangeland condition compared to goat browsing only and the control treatment. However, grass species diversity did not respond to treatments. Post-tree management significantly increased tree mortality, reduced seedling recruitment, and increased the abundance of desirable grass species. Our findings strongly suggest that post-thinning management, particularly prescribed fire or a combination of fire and browsing, is highly effective in suppressing woody encroachment and improving biomass and overall rangeland condition.

KEYWORDS

bush encroachment, herbivores, rangeland condition, *Vachella drepanolobium*, Ethiopia

Introduction

Woody plant encroachment is described as an increase in the density, cover, and biomass of native woody plants at the expense of herbaceous species, particularly grasses (Stevens et al., 2016; Briske et al., 2020). This phenomenon has become a global challenge, leading to a decline in biodiversity, herbaceous plant cover, and productivity (Hare et al., 2021b). It can also suppress palatable herbaceous species, resulting in changes in species compostion and reducation in species diversity (Stephen et al., 2023). Consequently, there is a decrease in rangeland condition (Guido et al., 2017), increased bare ground cover and soil erosion (Kimaro et al., 2019) and rangeland degradation (Bedunah and Angerer, 2012). Low rangeland quality reduces livestock productivity, thereby threatening the livelihoods and food security of pastoral societies. (Liao et al., 2018). Worldwide, woody plant encroachment poses a threat to rangelands (Wieczorkowski and Lehmann, 2022), particularly in the arid and semi-arid regions of East African savannas (Hare et al., 2020; Utaile et al., 2021).

Woody encroachment is driven by multiple interacting environmental and social factors across the arid and semi-arid East African savannas. This includes climate variability, particularly fluctuations in annual rainfall, which increase the competitiveness and colonisation of drought-tolerant woody species over herbaceous species that cannot withstand water shortage stress (Komac et al., 2013). The increasing levels of atmospheric CO2 concentrations enhance the efficiency of photosynthesis and plant water use, promoting the growth of woody species (Bond and Midgley, 2012). Edaphic factors such as soil moisture and nutrient availability (Tiawoun et al., 2022) and herbivory pressure, particularly heavy livestock grazing alter plant species composition and replace highly palatable perinnal grasses with unpalatable species (Shezi et al., 2021), which reducing herbaceous species diversity, grass biomass, and basal cover (Mureithi et al., 2016). Overgrazing leads to change in soil cover, exposing it to runoff, compacting soils, causing soil erosion, and increasing bare ground cover (Ravhuhali, 2018). These condition indirectly promotes tree growth and seedling establishment by enhancing soil moisture availability (Levick et al., 2009). Herbivores can facilitate the establishment of woody plants through increased seed dispersal (Tjelele et al., 2015). Grazing can also reduces the fuel load, which decreases the frequency and intensity of fire (van Langevelde et al., 2003), favouring the establishment of tree seedlings and saplings. Fire suppression often assocatted with increased bush encroachment and loss of herbaceous plant (Angassa and Oba, 2010), but the role of fire in maintaining grass-woody plant balance in Africa savannas - protected area has long been recognized (Johansson et al., 2021; Croker et al., 2023).

Controlling encroaching woody plants has been suggested as an effective management strategy to restore and improve savanna rangeland productivity (Hare et al., 2020; Eldridge and Ding, 2021). Globally, many woody plant control methods, such as prescribed fire, browsing animals, mechanical tree removal, herbicides, or various combinations of these, have been used (Archer and Predick, 2014). These management options have variable success rates (Marquart et al., 2023) and impose differential impacts on woody and herbaceous plant diversity, cover, and productivity (Nkosi et al., 2018). However, our knowledge regarding the long-term outcomes of control methods, particularly on both woody and herbaceous layers, is limited.

Selective tree thinning, has been suggested to control bush encroachment in savanna rangelands (Ward et al., 2022). This management practice reduces woody plant density to a predetermined level (Ward et al., 2022). This approach is often followed by post-thinning management interventions to control the respruting of woody plant and to restore the desired balance between grasses and trees (Smit, 2005).

Tree thinning can improve grass productivity (Hare et al., 2021a; Mndela et al., 2022a), herbaceous species diversity, ground cover of the vegeataion (reducing the % bare ground) (Stephens et al., 2016; Mndela et al., 2022b; Lerotholi et al., 2023), and range condition (Monegi et al., 2022). However, tree thinning is often not effective, and the outcomes of tree removal are short-lived, likely due to a lack of post-tree thinning management (Ding and Eldridge, 2019). The effectiveness of tree thinning often varies across ecosystems, with thinning more effective in high rainfall mesic areas than arid-enviroment (Ding and Eldridge, 2019), the trait of the encroaching plant (e.g., resprouting capability) (Monegi et al., 2023b; Utaile et al., 2023) and environmental conditions such as soil texture and fertility (Ding and Eldridge, 2019; Eldridge and Ding, 2021; Ding and Eldridge, 2022; Monegi et al., 2023b). While studies have suggested that the use of follow-up management (e.g., fire, herbivory, and a combination) after tree thinining can control bush encroachment, restore and improve herbaceous vegetation productivity (Mndela et al., 2022a; Ward et al., 2022; Monegi et al., 2023a), few studies exist that have quantified post-treatment outcomes.

Prescribed fire and herbivory are key disturbances and adaptive management intervention in savanna ecosystems (Hamilton et al., 2022). Fire and herbivory can keep trees in the 'fire' and 'browse traps' and preventing them from growing into adult trees (Sankaran et al., 2013; Staver and Bond, 2014; LaMalfa et al., 2019). Prescribed fire can control woody seedling recruitment and suppress the transition of tree seedlings and saplings to mature trees (LaMalfa et al., 2019). On the other hand, fire can facilitate regeneration by breaking seed dormancy in some species (Pausas and Lamont, 2022). Fire can further influence ground cover, species diversity, and the productivity of herbaceous vegetation (Bassestt et al., 2020), enhancing forage quality (Sensenig et al., 2010; Kimuyu et al., 2014) and improving the over rangeland condition (Trollope et al., 2014). Range condition is described as the 'state of health' of the range in terms of ecological status, resistance to soil erosion, and potential for producing forage for sustain animal production (Barac, 2003). Thus, assessing range condition is crucial for estimating the grazing capacity and making grazing management decisions (Jordaan et al., 1997).

The effect of fire on vegetation can vary depending on the fire regime, e.g., frequency and intensity (Case and Staver, 2017). Fire intensity depends on timing of fires and fuel loads; for example, late dry season fires are more likely to kill seedlings and are more effective in controlling bush encroachment than early dry season fires (Croker et al., 2023). In many cases, a high intensity fre can control bush seedlings, coppice, or maintain woody plants at a specifc height for the use of browsers. The influence of fire vary with the interaction with herbivory browsing, and rainfall, it pronounced in areas that receive higher rainfall (Archibald et al., 2005; Govender et al., 2006).

Browsers can strongly control the recruitment of trees (LaMalfa et al., 2019; Hare et al., 2021a) by preventing seedling establishment, survival, and growth (Morrison et al., 2019; Donaldson et al., 2022) as well as controlling tree and shrub cover (Amsten et al., 2021). This effect is further intensified following the fire (LaMalfa et al., 2019). Fire create favorable conditions for browsing by promoting nutritional feed and attracting browsers to burned areas, as regrowth and nutrients in plants are often higher (Archibald et al., 2005; Sensenig et al., 2010; Nieman et al., 2022). Browers feed on the newly grown herbaceous palatable species and regrowth (Kimuyu et al., 2014). This regrowth, combined with reduced competition from fire, weakens trees further, suppressing tree height, and biomass and potentially delay demographic transitions from sapling to mature trees (Okello et al., 2001). Grazing can indirectly facilitate woody seedling and sapling growth by reducing grass competition (Riginos and Young, 2007) and fuel loads, thereby reducing fire intensity and frequency (Kimuyu et al., 2014; Johansson et al., 2021). This effect suggests that the use of livestock, especially goats, can be effective tool to alleviate wildfire risk (Beebe et al., 2021a; Beebe, 2021b).

Goats (*Capra hircus*) are recognized as effective biological agents for controlling woody plant encroachment, particularly following fire or mechanical tree clearing (Zimmermann et al., 2003). In African savannas, goats play a valuable role in consuming many woody species and tolerate anti-nutritional factors often found in woody plants (Elias and Tischew, 2016; Nolden, 2020). Studies have shown that goats can succeed in controlling woody plants and suppressing tree coppicing (Doi et al., 2020; Hare et al., 2020). However, the specific role of goats in controlling encroaching woody trees in East African savannas following tree removal still remains unclear (Hare et al., 2021a). Only a few replicated experiments exist that evaluated the effects of fire and goat browsing on the dynamics of woody and herbaceous vegetation after tree removal (Hare et al., 2021a), and yet more information is required on how herbivores in combination with fire can control woody species (Sankaran et al., 2013).

Studies have shown that using a combination of bush control methods can be more effective insuppressing the recovery of woody plants than the use of single method alone (Angassa and Oba, 2009; Hare et al., 2020; Hare et al., 2021a). Tree cutting in combination with prescribed fire reduced woody plant cover (Case and Staver, 2017), increased the herbaceous plant biomass (Bates and Davies, 2018), and diversity (Bates, 2005). However, little is known about how post-thinning management after tree removal influences herbaceous communities (e.g., diversity, and rangeland condition) in East African savannas.

The Borana rangelands of southern Ethiopia support a large population of diversified livestock species (Liao et al., 2018). The rangeland is encroached by many native encroaching woody plant species (Hare et al., 2020). Of these, *V. drepanolobium* is the most prominent encroacher species in Ethiopia and other East African countries (Riginos et al., 2009; Kimaro et al., 2019; Hare et al., 2020). The expansion of this woody plant species is most likely due to a combination of factors, including overgrazing, exclusion of browsers, fire suppression, drought, and climatic factors (Angassa, 2012). While various attempts to control encroaching woody plants and improve the productivity of the rangelands through tree clearing exist, successful results have not been attained, especially over the long term (e.g., Angassa and Oba, 2009).

Several encroaching woody plants can regenerate using coppicing and seedling establishment after thinning (LaMalfa et al., 2019; Monegi et al., 2023b). These regeneration strategies make it difficult to manage woody tree encroachment in the long run. Thus, understanding how woody plants regenerate through seedling recruitment or coppicing can be valuable (Mokgosi, 2018). Hence, our objectives were to: (i) assess the impact of different post-tree thinning management on mortality of the native woody plant encroacher *V. drepanolobium* in the Borana rangelands, southern Ethiopia; and (ii) investigate how different post-tree thinning treatments affect the herbaceous vegetation (plant species diversity, biomass, and overall rangeland condition). We hypothesized that a combination of fire and browsing management is most successful in controlling bush encroachment and improving the herbaceous diversity, biomass, and rangeland conditions in this savanna habitat of southern Ethiopia.

We set up experimental field sites of different post-tree thinning follow-up treatments in the Borana rangelands, Ethiopia, and examined the responses of both woody and grassy vegetation over 1 year. Our results will help the decision-making process in designing effective woody control strategies in the long run (Nghikembua et al., 2023). The results provide valuable insights into how browsing herbivores and fire control encroacher woody plants and improve the overall rangeland condition. They offer suggestions for the management and restoration of encroaching rangelands in savannas.

Materials and methods

Study area

The study was conducted in the Borana rangelands of southern Ethiopia (Figure 1), covering a total area of 95,000 km^2, bordering Somalia and Kenya (Megersa et al., 2014; Tuffa and Treydte, 2017). The Borana rangelands are situated within the altitudinal range of 750–2000 m above sea level (m.a.s.l) (Dalle et al., 2006b) and experience an arid and semi-arid climate with pockets of sub-humid zones (Megersa et al., 2014). The inter-annual rainfall varies, with an average annual rainfall of 527 mm (Dalle et al., 2006a) and a high coefficient of variability (18%–69%) (Angassa and Oba, 2008). The rainfall in Borana is bimodal, with a long rainy season between March and May and a short rainy season between September and November. The average annual temperature of the area varies from 19°C to 26 °C. Drought is common in the area, with isolated dry years (<400 mm) happening once every 5 years but becoming more frequent (Tuffa and Treydte, 2017). The region is characterised by limited availability of surface water; the major sources of water for humans and livestock are deep wells and ponds (Homann, 2004). The soils of the study area are derived from ancient alluvial and volcanic materials (FAO, 1986), with shallow red sandy loam in the uplands and vertisols in the bottomlands (Dalle et al., 2006b). Vertisols are characterised by their black colour, relatively high in soil nutrients compared to other locally abundant soil types such as the friable sandy loam 'red soils' (Augustine and Mcnaughton, 2004), with high clay content, reduces the infiltration of water and expands and contracts with changes in moisture content disrupts root systems (Pringle et al., 2016). While the high nutrient content and moisture availability can favour the establishment of certain encroching woody plants, like *Vachellia drepanolobium* (Kenfack et al., 2021), poor drainage can limit others species prefer well-drained soils. Tthe impacts of vertisols on encroaching plants depends on the specific plant species and its adaptations.

The livelihood of the Borana pastoralists mainly depends on livestock production in this tropical savanna with varying proportions of open grassland and perennial herbaceous and woody vegetation, composed of Vachellia-Commiphora small-leaved deciduous woodlands (Coppock et al., 2007). Encroachment of woody plants has become a major challenge, causing a decline in herbaceous species, rangeland productivity, range condition, and livestock production (Tefera et al., 2007; Yusuf et al., 2011). Borana pastoralists have historically used controlled fire to manage rangelands for suppressing undesirable woody plants, promoting grass growth, and reducing tick population (Angassa and Oba, 2008). However, in the early 1970s local burning practices were prohibited (Angassa and Oba, 2008; Feyisa et al., 2023), which largely contributed to the prolifirication of certain woody species including Vachellia brevispica, V. bussei, V. drepanolobium, V. etbaica, V. mellifera, V. nilotica, V. seyal, and Commiphora africana (Yusuf et al., 2015; Feyisa et al., 2017). Fire can have a considerable impact on seedlings, growth, survival and adult recruitment of woody plants (O'Connor et al., 2014). The expansion of woody plant species due to the ban on fire use is likely attributed to combination of factors, including overgrazing, rainfall and soil fertility influences (Liao et al., 2018). Vachella drepanolobium is a perennial, leguminous, thorny plant that reaches up to 7 m in height

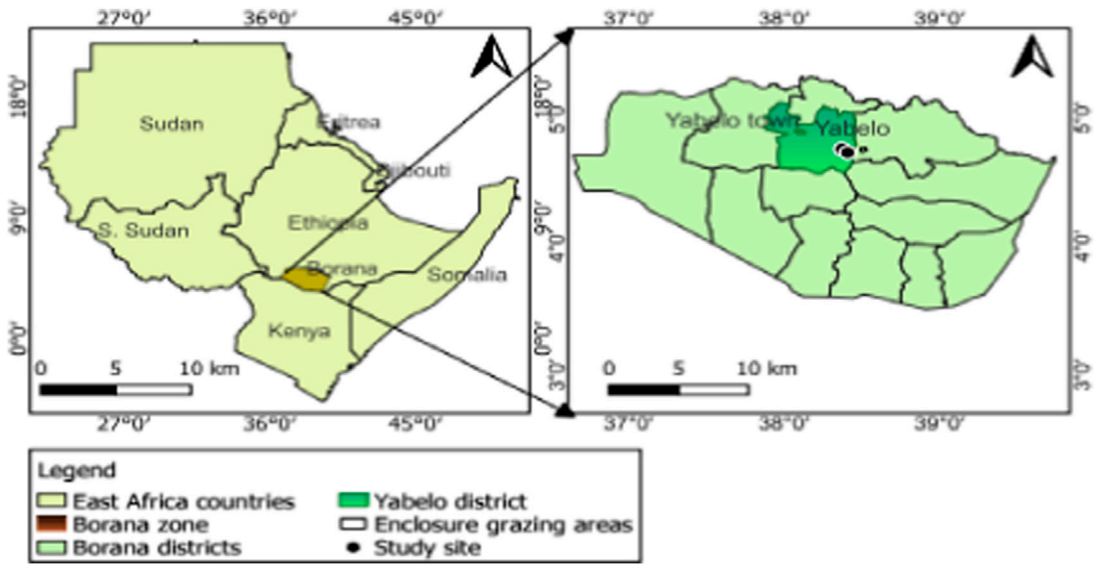

FIGURE 1
Map of the study area, the Borana rangelands of southern Ethiopia.

and is mostly found on black cotton soils, where it grows in mono-dominant stands and makes up 98% of the individual tree species (Hare et al., 2020). This species is highly adapted to fire, with relatively thick bark (Midgley et al., 2016) and strong post-fire resprouting (Okello, 2007). It is the most widespread myrmecophyte tree in East Africa, producing domatia (swollen thorns) and extrafloral nectaries that provide shelter and food rewards to ants (Palmer et al., 2008). Vachellia. drepanolobium trees host four symbiotic ant species; these include *Crematogaster sjostedti, Crematogaster mimosae, Crematogaster nigriceps,* and *Tetraponera penzigi*, which provide varying levels of protection against browsing insects and mammalian herbivores including elephants (Palmer et al., 2008). These ants can increase the survival of trees and stabilise tree cover across the landscape (Goheen and Palmer, 2010). *Vachellia drepanolobium* is aggressively encroaching into rangelands, suppressing grass production and affecting the productivity of the rangelands (Tefera and Mlambo, 2010). This is most likely due to a combination of factors, including grass-tree competition (Riginos et al., 2009), being protected from browsing herbvior by ants and spines (Okello, 2007; Kenfack et al., 2021), the lack of fire, the exclusion of browers, and soil properties (black vertisol soil, Okello, 2007). As Riginos et al. (2009) reported that a stronger suppressive effect of grass competition on tree growth. The elimination of grass competition resulted in a doubling of the tree growth rate across all tree age classes. Vachellia drepanolobium has a low forage value because it is heavily protected against herbivores by spines and ants (Okello, 2007). but it provides the main sources of feed for black rhinos (*Diceros bicornis*) and giraffes (*Giraffa camelopardalis*) (Birkett, 2002). Thus, all woody plants should not be removed from savanna landscapes, woody plants play important ecological roles (Smit, 2005). Complete removal rather than selective thinning of trees could negatively affect rangeland productivity, biodiversity, and ecosystem services, particularly in the long term (Smit, 2014). Maintaining ceratin trees species on the rangelands can have multiple benefits to pastoralists, ranchers, and wildlife (Monegi et al., 2023a).

Site selection and field layout

The study was conducted in the year 2020 over two growing seasons in the Borana rangelands of the Yabello district, Dida Hara Kebele Administration (KA), which has a total area of 985 km^2 and is located between 1,200 and 1,600 m. a.s.l. (Angassa and Oba, 2010; Figure 1). The experimental sites were selected within the community enclosure named Kelo Olla Doyo Dube. The enclosure, established before 25 years ago, and cover over 4.3 square kilometers, which was fenced and grazed only during the dry season, providing some fuel load for fire (Angassa and Oba, 2010). We selected two representative grazing areas through participatory mapping together with local elders, who knew the history and nature of the rangeland as experimental sites. The sites had similar soil types (vertisol), topography, and no history of earlier disturbances such as bush clearing and burning of the grazing areas. The vegetation consisted mainly of savanna, dominated by V. drepanolobium trees and herbaceous species. The human population settlements in the Dida-Hara area are semi-permanent settlements with an average livestock holding per household of 13 cattle, 11 small ruminants (goats and sheep), and 2 camels (Tefera et al., 2007). The majority of the open communal rangelands have deteriorated as a result of the high stocking rate, which was estimated to be 0.235 Tropical Livestock Units ha^{-1} (1 TLU 250 kg; Homann et al., 2008). Despite the unregulated stocking rate outside on the communal grazing land, overgrazing was not a threat within the enclosure, and grazing effects after thinning could be excluded as a factor in our analyses (Angassa and Oba, 2010). Overgrazing outside the study plot may have spatially compressing effects on soil condition (e.g., soil moisture) and vegetation composition within the plot, potentially affecting tree-grass competition. This external grazing could be limiting factor on the observed results.

We selected two 1.42 ha experimental sites that had mono-specific stands of “whistling thorn” stands (V. drepanolobium). At each site, we established 12 plots of 10 m × 20 m (200 m^2), with 3 m-wide firebreaks between the plots and a 5 m-wide distance between replication treatments. Similar to a study conducted in Ethiopia (Hare et al., 2021a) and in Burkina Faso (Savadogo et al. (2008), we thinned each experimental plot by 67% of the initial tree density (2,808 ± 161 tree per ha^{-1}) found in the control plot (Abate et al., in review). We applied four different post-thinning management treatments to each plot: 1) Browsing, i.e., allowing goats to browse freshly growing stump buds after tree cutting within the entire plot. 2) Fire = burning of the entire plot once following tree cutting. 3) Fire and browsing = the entire plot was burned with prescribed fire, and goats were allowed to browse the entire plot afterwards, and 4) Control = 33% tree cover remaining, and tree stumps in the plot were left untreated. The treatments were replicated three times and assigned randomly to the plots. Before the post-tree thinning operation, the density of trees and the number of seedlings within each plot were counted and measured. During thinning, we marked and tagged each cut tree with aluminium tags at the base of the trunk, below the cutting point. Using a local axe, trees had been cut at the base (0.5 m above ground), and the stumps had been debarked to facilitae death of the tree at the end of the dry season in February 2021. While cutting, we did not favour any particular tree sizes and made sure the remaining trees were scattered to reduce competition (Hare et al., 2020; Abate et al., in review). The cut woody materials were chopped up into finer pieces and then piled on tree stumps as fuel load for burning (Angassa and Oba, 2009). The burning was conducted late in February, the peak of the long dry season. Before burning, we assessed the herbaceous biomass to determine the amount of fuel load for a plot. In average the fuel load in fire alone treatment (2) was 2,623 ± 118 kg ha^{-1} with moisture content of 14%, while the amount of fuel load in fire and browsing plot (3) was

2,803 ± .290 kg ha^{-1} with moisture content of 19%. A fuel load of more than 2000 kg DM ha^{-1} has been reported sufficient to ignite fire and killing tree (Angassa and Oba, 2009; Kahumba, 2010; Hare et al., 2021b). We conducted the burning between 15:00 and 17:00 local time, considering the local weather conditions (e.g., air temperature, relative humidity, wind direction and speed, fuel load availability, and fire risk control). We did not record the temperature at the time of burning due to the absence of infrastructure and technology.

For the browsing treatment plots, 10 mature male Borana goat individuals were allowed to browse each plot (50 heads of goats ha^{-1}) (Bonanno et al., 2007). We started browsing following the main rains, when tree stump buds emerged after coppicing in the control plots. The browsing on each plot was conducted biweekly for 1 hour (equivalent to one goat utilising a plot for 10 h) in each of the two growing periods in 2020.

The experimental plots were fenced off and protected to prevent disturbance from humans and livestock grazing and browsing. During the post-thinning management periods, the number of V. drepanolobium trees, saplings, and seedlings were counted and measured at the end of each growing period. We monitored the V. drepanolobium tree and shrub stump mortality (CutMort) of all trees per plot that had been cut in the previous bush-clearing treatment. We further measured tree and shrub mortality (TreeMort) of trees that had not been cut at the previous treatment, coppicing (TreeCopp) (referring to regrowth in response to treatment effects), seedling mortality (SeedMort), and new seedling recruitment (SeedRec), i.e., V. drepanolobium plants of <0.5 m in height (Angassa and Oba, 2010).

Rangeland condition assessment

We evaluated rangeland condition in each plot based on grass and soil factors used for range condition scores adopted by Baars et al. (1997) and other studies (Dalle et al., 2006b; Angassa, 2012; Melak et al., 2019). The criteria include botanical composition of grass species, basal cover, litter cover, number of grass seedlings, age distribution, and soil factors (soil erosion and compaction) (Baars et al., 1997; Supplementary Table S1). The maximum possible score for a plot was 50 points, indicating excellent (41–50 points), good (31–40 points), fair (21–30 points), poor (11–20 points), or very poor rangeland condition (<10 points) (Baars et al., 1997; Supplementary Table S1). The methodologies have described below and presented in Supplementary Table S1.

Grass species composition

The grass species composition was assessed in three 1 × 1 m quadrants within each plot. Individual grass species were counted and identified during both the main (May) and short rainy season (November), i.e., growing period 1 and 2, respectively. The identified grass species were classified according to life forms (annual and perennial) and ecological status into (i) decreasers (desirable species likely to decrease with heavy grazing pressure), (ii) increasers (intermediately desired species likely to increase under heavy grazing intensity), and (iii) invaders (undesirable species likely to increase under heavy grazing intensity) based on the histories of particular grass species (Jenkins et al., 1974; Tainton, 1981) and the opinions of local communities. For grass species composition rating, a one-to-ten-point scale was given (see Supplementary Table S1).

Grass basal cover and plant litter cover

Basal cover and litter cover of grass species were evaluated on a scale of 0–10 points (Supplementary Table S1). Basal cover refers to a ground cover by the base of the grasses. Grass litter was defined as dead plant material that had fallen to the ground (Mengistu, 2005). In each experimental plot, a representative sample area of three 1 m^2 quadrants were established for the detailed assessment of both basal and litter cover (Baars et al., 1997), which was visually estimated and then harvested. The rating for litter cover within the same square meter was given the maximum score (10 points) when grass litter cover exceeded 40%, and the minimum score was given when the litter cover was less than 3% (Supplementary Table S1).

Number of seedlings and age of grasses

For both the number of grass seedlings and the age distribution of grasses, a score of 1–5 points was used (Supplementary Table S1). The number of grass seedlings was counted in three areas of each experimental plot following Baars et al. (1997). An A4 sheet of paper (30 × 21 cm) was dropped at random from a distance of 2 m height. A maximum score of five points was given when all age categories of grasses (i.e., young, medium, and old) were present (see Supplementary Table S1).

Soil condition assessment

For the soil condition, a score of 0–5 points was used, estimated by the status of soil erosion considering pedestals and pavements Baars et al. (1997). Soil compaction (0–5 points) was assessed based on the amount of capping (crust formation), following the methods described by (Baars et al., 1997; Supplementary Table S1).

TABLE 1 Summery of woody plant, range condition, biomass and diversity variables measured with description and units.

Variable	Description	Unit
Woody plant variables		
CutMort	Mortality of tree/shrub stump out of all cut trees per plot (200m^2)	Average (±SE) percent (% of trees died out of cut ha^{-1}
TreeMort	Mortality of non-cut tree/shrub per plot (200m^2)	Average (±SE) percent (% of trees died from non-cut ha^{-1})
TreeCopp	Regrowth of tree/shrub out of cut tree in respone to treatment effects per plot (200m^2)	Average (±SE) percent (% of trees copping out of cut tree ha^{-1})
SeedMort	Mortality of seedling (plant less than 0.5 m height) per plot (200m^2)	Average (±SE) percent (% of seedling died ha^{-1})
SeedRec	New seedling recruitment per plot (200m^2)	Average (±SE) percent (% of seedling recriment ha^{-1})
Range condition assessement		Rating (according to Baars et al., 1997; Supplementary Table S1)
Grass composition (GC)	Grass composition	10 points per plot m^2
Grass Basal cover (BC)	Grass basal cover	10 points per plot m^2
Grass Litter cover, (LC)	Litter cover	10 points per plot m^2
Number of grass seedlings (NS)	Number of grass seedlings	5 points, A4 paper
Grass age distribution (AD)	Grass age distribution	5 points, A4 paper
Soil erosion (SE)	Soil erosion	5 points per plot m^2
Soil compaction (SC)	Soil compaction	5 points per plot m^2
Total Range condition (TRC)	Total Range condition	Total score
Above ground biomass		
Biomass of grasses (Highly desirable, Intermediate desirable, Less desirable)	DM biomass of grass in terms of desirability (highly desirable, Intermediate desirable, Less desirable)	kg ha^{-1}
Forb biomass	DM biomass of forb	kg ha^{-1}
Diversity index variables		
Abundanc	Abundance of the individual herbaceous species recorded per plot (m^2)	Average (±SE), number of individuals per species perplot
Diversity of grass and forb species	Grass and forb species diversity per plot (m^2)	Average (±SE) Shannon-Wiener indices of grass and forb per plot (m^2)
Species richness of gass and forb	Average (±SE) number of grass and forb species richness per plot (m^2)	Average (±SE) number of grass and forb species richness per plot (m^2)

Herbaceous dry matter yield

Dry matter (DM) biomass of the herbaceous species was determined in each treatment plot by harvesting biomass from three 1 m^2 quadrants at ground level. The harvested fresh material was weighed and hand-separated into grasses and forbs. The grasses were further separated into different species, and the proportional contribution of each species was determined. The samples of collected grasses and forbs were oven-dried at Hawassa University, College of Agriculture, in the Animal Nutrition Laboratory at 65°C for 24 h and weighed. Identification and nomenclature of plant species followed the guidelines of Hedberg (1996). Additional references such as the Guide to the Grasses of Ethiopia (Froman and Persson, 1974) and Grasses Common to Arero Area (Jenkins et al., 1974) were used for plant identification. A summery of collected variables is presented in Table 1.

Data analysis

A total of 24 sample units (4 treatments x 3 replicates x 2 sites) were considered for the data analysis on the response of woody trees to post-thinning management, while for the herbaceous layer, we included growing period as an additional factor (4 post thinning management treatments x three replications x two sites x two growing periods). Data were checked for normality, homogeneity of variance, and assumptions of linearity. For data that did not fulfill the normality assumption, we used square root transformation for tree mortality, log transformation for DM biomass and range condition parameters (Osborne, 2002). The woody plant parameters, herbaceous species composition (abundance of grass and forb species), diversity, range condition, bare ground cover, and DM biomass parameters were analyzed using the general linear model procedure of the Statistical Analysis System (SAS, 9.4) and SPSS, 26. To investigate the impact of post tree thinning treatment, we used the tree species attributes (e.g., TreeSBMort, TreeCopp, TreeMort, SeedMort, and SeedRec) as dependent variables and post-thinning managements as independent variables. The range condition assessment parameters, including grass composition, basal cover, litter cover, the age distribution of grasses, number of grass seedlings, soil condition, DM biomass parameters, and bare ground cover, were considered as dependent variables and analyzed using one way ANOVA to examine the effect of post-thinning management and two-way ANOVA to assess effect of post tree-thinning management and growing period.

Herbaceous species that were recorded in each of the treatment plots at the end of the second growing period were ordinated using Correspondence Analysis (CA) (Greenacre, and Blasius, 2006) in PAST 4.13 software (Hammer et al., 2001). Total herbaceous species, grass, and forb species alpha diversity, richness, and evenness were analyzed using the Shannon-Wiener index (Kent, 1992) using PAST 3 software. Tukey-HSD *post hoc* test was used to test for differences in averages of woody and herbaceous (grass and forb) layer responses, biomass and rangeland condition parameters at $p < 0.05$.

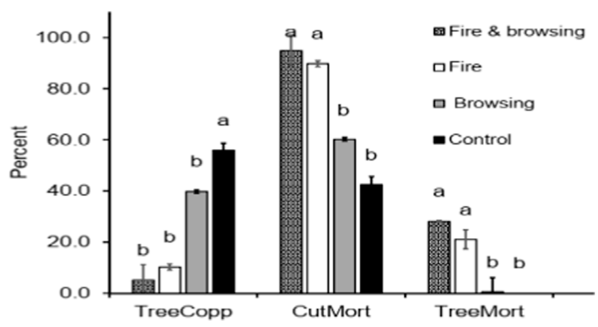

FIGURE 2
Average (±SE) percent (% of trees that were cut and uncut ha^{-1}) of woody vegetation response: cut tree and shrub mortality (CutMort), tree coppicing (TreeCopp), non-cut tree and shrub mortality (TreeMort) compared across different post-tree thinning management (Fire and browsing, Fire, Browsing, and Control (67% thinning). Different letters represent significant differences among post-thinning follow-up treatments at $p <$ 0.05 based on Tukey-HSD *post hoc* test. N = 24.

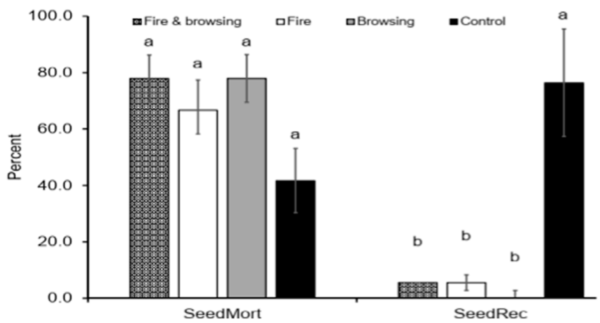

FIGURE 3
Average percent (±SE, of the initial seedlings ha^{-1}) response of seedling parameters (seedling mortality (SeedMort), and new seedling recruitment (SeedRec), to post tree thinning management (Fire and browsing, Fire, browsing, and control). Different letters represent significant differences among post-thinning management treatments at $p < 0.05$ based on Tukey-HSD *post hoc* test. N = 24.

Results

Post-thinning management on woody species parameters

All the three post-tree thinning management scenarios significantly enhanced tree mortalities, reduced seedling recruitment, Prescribed fire (2) and fire and goat-browsing (3) treatments resulted in significantly greater (compared to goat browsing (1) and control treatment (4). We found that post-thinning management significantly affected tree mortality (Wilks' λ = 04; F = 4.24; $p < 0.001$).

Relative to the control plot, tree mortality approximately doubled under the fire and browsing treatment and fire only plots and increased by about 20% under goat browsing only (Figure 2). For trees that had not received thinning management (i.e., not-cut), mortalities increased by >20% in the fire and browsing and fire only (F = 17.8; $p < 0.001$) plots and did not change in the goat browsing only plot (Figure 2). Tree coppicing was five times lower in the fire and browsing and 11-fold lower in the fire only plots relative to the control plot (F = 54.3; $p < 0.001$; Figure 2). Seedling recruitment was significantly reduced under post-thinning treatments, with control plots showing more than 14-times higher than other treatments (F = 4.6; p = 0.013; Figure 3). Surprisingly, seedling mortality did not show a significant difference among treatments (F = 2.0; p = 0.140; Figure 3) and was generally high with 62% ha^{-1} across all treatments. Almost 78% of seedlings died in the fire and browsing plots; about 67% died in fire only plots while 75% died in the browsing only treatment and only 42% died in the control plots (Figure 3).

TABLE 2 The average (±SE) abundance of the individual herbaceous species recorded per plot (number of individuals per species per m^2) in response to the different post-tree thinning management (Fire and browsing, Fire, Browsing, and Control).

Grass species	Treatment							Statistics		
	LF	Des	Fire and browsing	Fire	Browsing	Control	Mean	Df	F	P
Cenchrus ciliaris	P	HD	26.7 ± 4[ab]	29.5 ± 3[a]	15.2 ± 3[c]	14.3 ± 2[c]	21.4 ± 2	3	5.62	0.002
Chrysopogon aucheri	P	HD	32.3 ± 3[ab]	37.2 ± 4[a]	21.8 ± 2[c]	25.3 ± 2[bc]	29.1 ± 2	3	4.87	0.005
Cynodon dactylon	P	HD	2.1 ± 1[b]	6.8 ± 1[a]	0.0 ± 0[b]	1.7 ± 1[b]	2.6 ± 1	3	14.09	0.001
Digitaria milanjiana	P	HD	1.8 ± 0[c]	1.0 ± 0[c]	3.5 ± 1[b]	8.6 ± 1[a]	3.7 ± 1	3	30.76	0.001
Eragrostis papposa	A	LD	2.5 ± 1[b]	3.2 ± 2[b]	7 ± 1[a]	7.5 ± 1[a]	3.9 ± 1	3	1.50	0.229
Pennisetum mezianum	P	LD	34.0 ± 6[a]	29.3 ± 5[ab]	12.7 ± 1[c]	16.1 ± 3[bc]	23.0 ± 2	3	6.00	0.002
Pennisetum stramineum	A	LD	21.3 ± 5[a]	24.4 ± 6[a]	7.8 ± 2[b]	10.1 ± 2[b]	15.9 ± 3	3	3.05	0.039
Sporobolus pyramidalis	P	LD	10.3 ± 1[a]	8.8 ± 1[a]	2.4 ± 1[b]	5.1 ± 1[ab]	6.6 ± 1	3	13.69	0.001

LF = life form (annual = A or perennial = P), Des = Desirability (highly desirable = HD, ID, Less desirable = LD), Different letters represent significant differences among post-thinning treatments at $p < 0.05$ based on Tukey-HSD *post hoc* test (n = 48 plots).

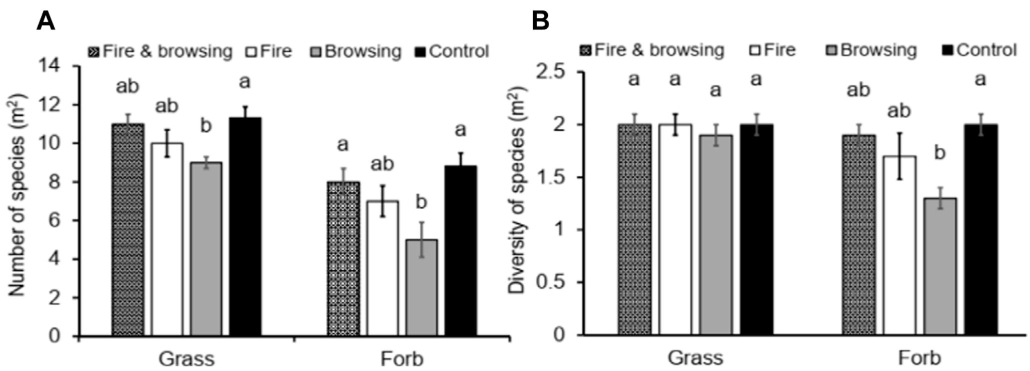

FIGURE 4
Average (±SE) grass and forb species **(A)** richness and **(B)** diversity per plot (m^2) as response to the different post-thinning management (Fire and browsing, Fire, browsing, and control). Different letters represent significant differences among post-thinning treatments at $p < 0.05$ based on Tukey-HSD *post hoc* test. N = 48.

Post-thinning management on herbaceous species composition and diversity

Post-thinning management significantly increased the abundance of the dominant desirable grass species. Grass and forb species richness, forb diversity. Prescribed fire (2) and fire and goat-browsing (3) treatments resulted in significantly higher as compared to goat browsing (1) and control treatment (4).

We identified a total of 42 herbaceous species, 21 grasses, and 21 forb species across treatments. (Table 2; Supplementary Figure S1). The grass species comprised 67% perennials and 33% annuals, and they were composed of 29% highly desirable, 12% intermediately desirable, and 48% less desirable grass species. The dominant grass species in our study were Chrysopogon aucheri, Pennisetum mezianum, Cenchrus ciliaris, Pennisetum stramineum, Sporobolus pyramidalis, Eragrostis papposa, Digitaria milanjiana, and Cynodon dactylon. The correspondence analysis (CA) results did not clearly associate the herbaceous species with different treatments, as about 93.1% of the total variance in species abundance was explained by the model (Supplementary Figure S1). We found that the abundance of C. ciliaris, C. aucheri, P. mezianum, and P. stramineum was more than twice as high in the fire and browsing treatments compared to the control and browsing only treatments (Table 2). Moreover, S. pramidalis and D. milanjiana were more than double that in the control compared to the browsing only treatment (Table 2). In the fire only plot, the abundance of C. dactylon was more than four times higher than in the browsing and in the control treatments (Table 2).

We further found that post-thinning management significantly influenced grass species richness (F = 3.5; $p < 0.022$), forb species richness ($F = 5.2$; $p = 0.004$), with grass and forb species richness

TABLE 3 Our ANOVA model on comparing parameters for rangeland conditions under the post-thinning management (Management: fire and browsing, fire, browsing, control) across two growing periods and their interaction.

Dependent Variable	Sources of variation								
	Management			Growing period			Management & growing period		
	df	*F*	*P*	*df*	*F*	*P*	*df*	*F*	*P*
Grass composition	3	24.45	0.001	1	7.63	0.009	3	0.189	0.903
Basal cover	3	5.82	0.002	1	6.27	0.016	3	0.119	0.948
Litter cover	3	6.32	0.001	1	2.08	0.157	3	0.582	0.630
Age distribution	3	3.49	0.024	1	0.00	0.968	3	0.236	0.871
Number of grass seedlings	3	9.49	0.001	1	0.08	0.785	3	0.729	0.541
Soil compaction	3	1.53	0.221	1	0.01	0.921	3	1.543	0.218
Soil erosion	3	1.21	0.318	1	0.56	0.459	3	0.681	0.569
Bare ground cover (%)	3	1.39	0.261	1	0.08	0.775	3	2.213	0.102
Forb biomass	3	11.58	0.001	1	0.91	0.346	3	0.072	0.974
Grass biomass	3	54.49	0.001	1	18.98	0.001	3	0.147	0.931
Total biomass	3	19.69	0.001	1	8.31	0.006	3	0.202	0.894
Highly desirable grass biomass	3	64.68	0.001	1	27.08	0.001	3	0.885	0.457
Intermediate desirable biomass	3	29.66	0.001	1	0.27	0.607	3	1.014	0.397
Less desirable biomass	3	10.32	0.001	1	28.78	0.001	3	5.745	0.002
Total range condition	3	11.79	0.001	1	3.37	0.074	3	0.128	0.943

Data were collected during (First growing period = March to May, Second growing period = September to November) in 48 plots at the Borana rangelands, Ethiopia.

TABLE 4 Different post-tree thinning management treatments and their effect on rangeland condition (Mean ± SE) in the Borana rangelands of southern Ethiopia in the year 2021.

	Treatment						
Parameters	Fire and browsing	Fire	Browsing	Control	F	df	P
Grass composition	7.5 ± 0.3[b]	8.4 ± 0.1[a]	6.7 ± 0.2[c]	6.3 ± 0.1[c]	40.7	3	0.001
Basal cover	7.2 ± 0.3[a]	7.6 ± 0.2[a]	6.0 ± 0.4[b]	6.9 ± 0.3[ab]	9.2	3	0.001
Litter cover	5.9 ± 0.3[ab]	6.7 ± 0.3[a]	5.0 ± 0.3[a]	6.1 ± 0.3[a]	20.1	3	0.001
Age distribution	3.8 ± 0.2[ab]	4.5 ± 0.1[a]	3.7 ± 0.2[b]	3.8 ± 0.1[ab]	12.9	3	0.001
Number of seedlings	4.1 ± 0.2[ab]	4.6 ± 0.1[a]	3.5 ± 0.2[c]	3.7 ± 0.1[bc]	13.7	3	0.001
Soil compaction	4.8 ± 0.1[a]	4.9 ± 0.1[a]	4.6 ± 0.2[a]	4.7 ± 0.1[a]	1.7	3	0.532
Soil erosion	5.0 ± 0.0[a]	5.0 ± 0.0[a]	4.9 ± 0.1[a]	4.9 ± 0.1[a]	0.6	3	0.959
Bare ground cover (%)	18.2 ± 4[a]	18.6 ± 4[a]	29.2 ± 6[a]	22.9 ± 4[a]	6.0	3	0.001
Total range condition	38.4 ± 1.1[ab]	41.7 ± 0.6[a]	34.3 ± 1[c]	36.4 ± 0.8[bc]	28.3	3	0.001

Rangeland condition was classified according to Baars et al. (1997). Different letters represent significant differences among post-thinning treatments (fire and browsing, fire, browsing, control), at $p < 0.05$ based on Tukey-HSD *post hoc* test. N = 48.

increased by 18% and 40% in the control plot than in the browsing only treatment, respectively (Figure 4A), but no significant difference with fire only and fire and browsing treatments. Similarly, the diversity of forb species differed (F = 7.1; $p < 0.001$), being higher in the control plots (F = 9.4; $p < 0.001$) compared to the browsing only plots but similar to fire only and fire and browsing treatments

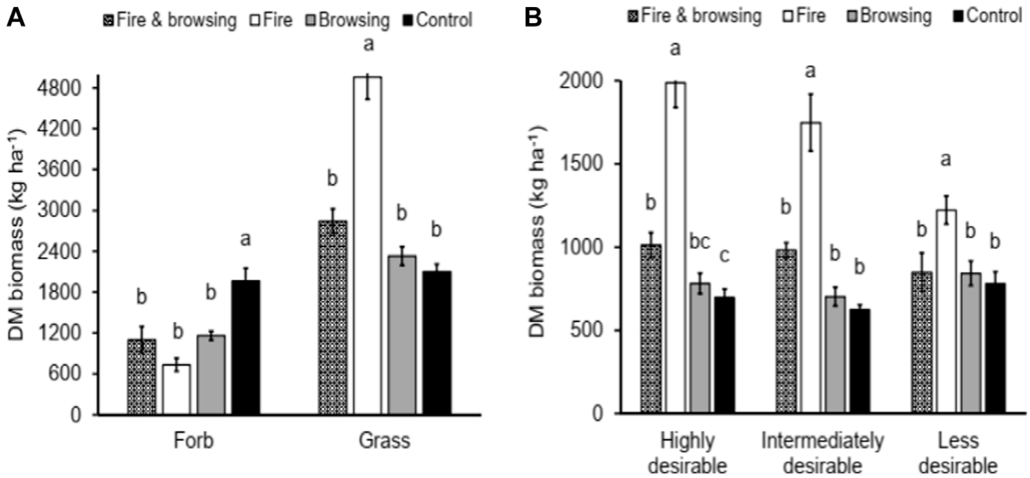

FIGURE 5
The effect of post-tree thinning management on **(A)** average (±SE) forb and grass DM biomass yield (kg ha^{-1}) and **(B)** DM biomass of grass species of different desirability according to pastoralists. Different letters represent significant differences among the post-tree thinning management (fire and browsing, fire, browsing, control) at $p < 0.05$ based on Tukey-HSD *post hoc* test. N = 48.

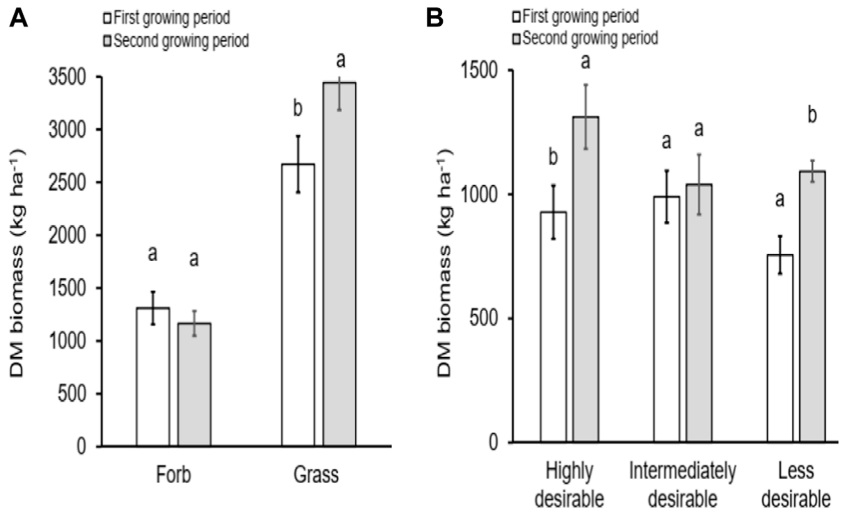

FIGURE 6
The effect of growing period (First growing period = March - May, Second growing period = September - November) on **(A)** average (±SE) biomass of forbs and grasses (kg ha^{-1}) and **(B)** on grass biomass in terms of desirability. Desirable (highly desirable, Intermediate desirable, Less desirable). Different letters represent significant differences in means between growing period at $p < 0.05$ based on Tukey-HSD *post hoc* test. N = 48.

(Figure 4B). The diversity of grass species did not show significant differences among treatments (F = 0.8; $p = 0.551$).

Post-thinning management on rangeland condition and biomass yield

Post-thinning treatments significantly influenced parameters of range condition (Table 3), except soil condition (erosion and compaction), and interactions with the growing period were insignificant. Relative to the control plot, the grass species composition rating increased by 25% in the fire only treatment (Table 4). The total range condition scores were highest in the fire and browsing and fire, treatments (Table 4). The total range condition was 10% better under the fire treatment than in control, and the fire plot was rated as excellent condition while the other treatments showed good condition. Bare ground cover was more than 1.5 times as high

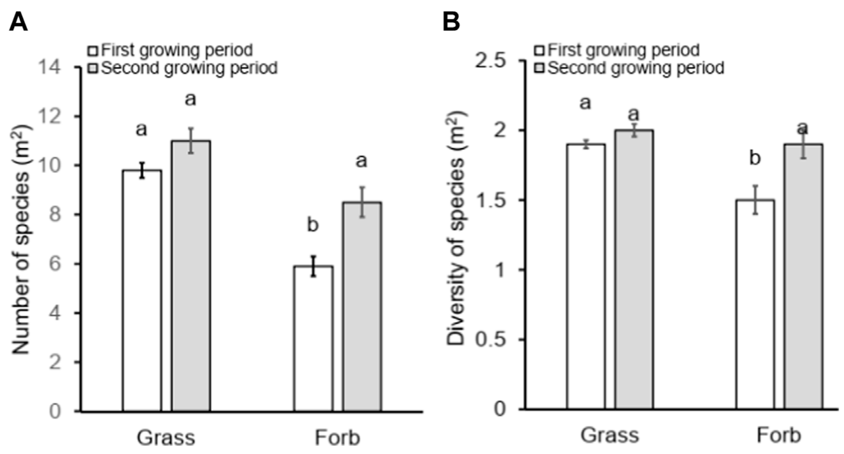

FIGURE 7
Average (±SE) number of grass and forb species **(A)** richness and **(B)** diversity per plot (m^2) as response to growing period (First growing period = March - May, Second growing period = September - November). Different letters represent significant differences among post-thinning treatments at $p < 0.05$ based on Tukey-HSD *post hoc* test. N = 48.

in the browsing treatment than in the fire and browsing and fire only treatments (Table 4).

Grass DM biomass was more than double that in the fire treatment compared to browsing only and in the control treatments ($F = 54.5$; $p < 0.001$; Figure 5A), while forb DM biomass ($F = 111.6$; $p < 0.001$; Figure 5A) showed more than 1.6 times higher values in the control plot than the other treatments. The DM biomass of highly desirable ($F = 64.7$; $p < 0.001$) grasses was more than double under the fire only treatment compared to the other treatments (Figure 5B).

Growing period significantly affected overall grass biomass ($F = 19.0$; $p = 0.001$), biomass of highly desirable ($F = 27.1$; $p = 0.001$), and less desirable grass species ($F = 28.8$; $p = 0.001$) (Figure 6), grass species richness ($F = 5.6$; $p = 0.014$), and forb richness and diversity ($F = 15.6$; $p = 0.001$ and $F = 4.3$; $p = 0.001$, respectively) (Figure 7), with all those trends being higher in the second growing season than in the first (Figure 7). With the exception of low desirable grass biomass ($F = 5.7$; $p = 0.002$). The diversity of grass did not show significant differences between growing periods ($F = 0.8$; $p = 0.393$). There was no interaction between thinning intensity and growing period on biomass, range condition metrics, and diversity indices.

Discussion

Response of woody species to post-thinning management

Our study showed that prescribed fire, combined fire and browsing and goat browsing treatments could effectively complement the benefits of tree thinning by increasing the encroacher species' tree mortality, resulting in reduced tree cover. Tree mortality was particularly strong in treatments that involved prescribed fire. Our observed results are similar to earlier studies made on tree thinning, herbivory and fire disturbance in southern Ethiopia and Namibia (de Klerk, 2004; Hare et al., 2020; Hare et al., 2021a), Burkina Faso (Savadogo et al., 2008) and in Missouri, United States (Beebe et al., 2021a). The higher mortalities of mature trees and saplings under fire, and fire and browsing after thinning can impose separate or combined disturbances and weaken trees and seedling' resilience to environmental conditions (e.g., drought, insects; Kane et al., 2017; Hood et al., 2018), amplifying mortalities. Although goat browsing did not show a significant difference from the control treatment, we showed that browsing alone could increase tree mortality by 20% but is likely insufficient on its own in completely controlling regrowth (Hester et al., 2006). We found that prescribed fire and combined fire and goat browsing significantly increased non-cut sapling mortalities and reduced tree coppicing compared to the control plots, which suggests that resprouting abilities are hampered when fire is included (LaMalfa et al., 2019; Monegi et al., 2023a).

As expected, all our treatments reduced seedling recruitment, which is consistent with other studies, that claim that browsing herbivores (Staver and Bond, 2014; Augustine et al., 2019) and a combination of fire and browsing (Staver et al., 2009) negatively affect seedling survival. Moreover, the higher herbaceous biomass we found after tree thinning (Abate et al., in review) can further be attributed to seedling mortality through strong grass competition (Riginos et al., 2009; Pillay and Ward, 2021;

Boys, 2022; Donaldson et al., 2022; Monegi et al., 2022), As reported by Riginos et al. (2009) grass competition has strong suppressive effect on seedling and tree growth. when grass competition was removed, it resulted in a doubling of the growth rate across all demographic stage of the tree classes, suggesting that fire and herbivory as well as grass competition may create demographic bottlenecks that influence tree populations (Donaldson et al., 2022) and may in the future contribute to a reduction in woody cover and help keep savanna systems open up (Barton and Hanley, 2013). We claim that in Ethiopia, the re-introduction of fire as a management tool can likely maintain the savanna ecosystems of Borana.

Response of herbaceous species post-thinning management

Our result showed that the use of prescribed fire, goat browsing, and combinations thereof significantly enhanced the benefit of tree thinning by increasing the abundance of certain grass species, similar to research in South Ethiopia (Hare et al., 2021b). The increased abundance of certain grass species under the conditions of a fire-only plot and fire and browsing after thinning can lead to separate or combined disturbances. These disruptions can decrease the canopy gap, reduce competition for resources, and increase irradiation, nutrients, and soil moisture. This creates a favourable condition for the establishment and growth of herbaceous plants (grasses and forbs), resulting in an increase in the abundance and diversity of plants (Hare et al., 2021b; Monegi et al., 2022). Other studies indicated that herbaceous plant abundance increased with fire treatments (Bielski et al., 2021; Gold et al., 2023) and fire-goat browsing treatments (Beebe, 2021b). The high abundance of *C. ciliaris, C. aucheri, P. mezianum, P. stramineum, S. pramidalis, C. dactylon,* and *T. triandra* in fire and fire and browsing plots suggests that these species are fire-tolerant, which was found for some of those species already in South Africa (Ratsele, 2013). In contrast goat browsing and control plots favoured the abundance of *Aristida adoensis, Bothriochloa insculpta, Chloris roxburghiana, Digitaria milanjiana, Eragrostis papposa, Heteropogon contortus, Panicum maximum* and *Setaria verticillata* grasses, complementing findings that *P maximum* (Fynn et al., 2005; Smith et al., 2013; Monegi et al., 2023a) and *B. insculpta* (Monegi et al., 2023b) increased in abundance in unburned plots.

We also found that the abundance of certain forb species such as *Abutilon hirtum, Commelina africana, Pavonia erlangeri,* and *Tagetes minuta* was substantially reduced under post-thinning treatments, which might be important for managers as forbs are often less preferred by grazer livestock (Oba et al., 2000). We found that the goat browsing treatment significantly reduced grass and forb richness. Selective and high browsing pressure in the goat-browsing treatment could explain the reduced herbaceous species richness (Salgado-Luarte et al., 2019; Nolden, 2020). Grass diversity was not affected by our post-thinning treatments, which agrees with Monegi et al. (2023a), but it might also indicate that a longer experimental period could have shown more pronounced shifts in the diversity of grass species.

Response of biomass and range condition to post-thinning management

As we expected our treatments increased the rangeland condition and biomass of the herbaceous layer, similar to Hare et al. (2021b). The improved rangeland condition and biomass of the herbaceous layer under fire only and fire and browsing after thinning can demonstrate the combined impacts of disturbances with the reduction of competition due to competitive release from existing trees (shading, competition for moisture, and nutrients). This creates a conducive environment for the growth of herbaceous plants. This led to an increase in basal cover of grasses, which in turn reduced bare ground cover, thereby enhancing biomass and range conditions (Monegi et al., 2022), which supporting livestock grazing and contributing to biodiversity conservation (LaMalfa et al., 2019; Monegi et al., 2022), Similar to Hare et al. (2021b), we found a stronger response in rangeland biomass, diversity and species compostion to variation in climatic conditions (rainfall and seasonality) and soil moisture contents.

Conclusion

We conclude that post-tree thinning management can successfully reduce woody plant density and increase the abundance of many desirable grass species, enhance grass and forb species richness, and herbaceous biomass. The best results, i.e., highest richness, rangeland health, lowest encroacher tree recruitment was achieved prescribed fire, and combined fire and browsing treatment. Our study suggests that a fire, and combination of fire and browsing can control encroaching trees by increasing mortality and suppressing seedling recruitment, resulting in enhanced restoration of herbaceous species in terms of biomass production, rangeland condition, and maintenance of biodiversity. We demonstrated that our treatments can suppress *V. drepanolobium* seedling recruitment and goat browsing alone can prevent the recovery of regrowth but might not be sufficient for controlling woody plants overall. The fire suppression on Borana rangeland promotes bush encroachment. We suggested the revision of the ban on the use of fire and the implementation of prescribed fires with proper precautions in combined with other methods could be an alternative option. However, implementing prescribed fires on communal rangelands under the present condition is uncertain because there is insufficient fuel load for effective burning. This suggesting that more restoration effort on communal rangeland was necessary to accumulate a sufficient fuel load. Prescribed fire can be effective on controlled settings like community enclosures and ranch. Finally, we highlight the need for repeated management actions and long-term studies. Overall, our results support recommendations for controlling bush encroachment, restoring biodiversity, and improving rangeland productivity in Ethiopia and similar regions.

Data availability statement

The original data presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

TAba Designed the experiment, conducted the fieldwork, analyzed the data, interpreted the results, and wrote the manuscript. TAbe Administered the project, served as the main supervisor, reviewed and edited the manuscript. TAn contributed as a co-supervisor and reviewed and edited the manuscript. All authors contributed to the article and approved the submitted version.

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Conflict of interest

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

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontierspartnerships.org/articles/10.3389/past.2024.13039/full#supplementary-material

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Nomenclature

ANOVA	Analysis of variance
FAO	Food and Agricultural Organization
SAS	Statistical Analysis System
SPSS	Statistical Package for the Social Sciences
TLU	Tropical Livestock Units