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Grassland albedo as a nature-based climate prospect: the role of growth form and grazing

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Abstract

Nature-based solutions for mitigating climate change focus largely on land management to reduce carbon emissions and enhance carbon sequestration. Tree planting, commonly advocated for carbon offset, threatens grassland biodiversity and may induce positive radiative forcing (warming) by lowering albedo. Before making decisions about land-use changes in grasslands, an understanding of the fine-scale albedo of grassy versus woody vegetation is needed. Existing satellite-based albedo products offer global coverage with temporally fine, but spatially coarse, resolution, whereas fine-scale *in situ* grassland albedo data are sparse. We examined the hypotheses that albedo varies seasonally between grass type patches, between shrub and grass patches, and with grazing at the patch scale. Using a tripod-mounted albedometer, we quantified albedo of seven distinct grassland patches in South Africa's eastern Karoo during early and late dormancy and growing seasons. Patches included intensely-grazed grazing lawn (*Cynodon dactylon*), grazed and less-grazed red tussock grass (*Themeda triandra*), grazed and less-grazed white tussock grass (*Eragrostis lehmanniana*), shrub (*Pentzia incana*) encroached grass, and bare ground. Season influenced albedo in all patches and, additionally, we found strong differences for the same period between years due to varying rainfall and temperature patterns. For grass-dominated patches, albedo differences were most pronounced during early dormancy, likely due to an effect of grass inflorescences. Albedo of intensely-grazed grazing lawns was consistently higher than other patches, except during early dormancy when white tussock grass albedo was equally high. We found no albedo difference between grazed and less-grazed tussock patches of either red or white grass. Shrub-encroached patches exhibited consistently lower albedo than other patches. Our findings underscore the nuanced relationship between grassland patches and albedo, with shrub encroachment, proposed afforestation, and certain grasses possibly increasing warming potential through reduced albedo. As climate initiatives extend into grasslands, understanding these patterns is essential for climate change mitigation and grassland conservation.

1. Introduction

The pursuit of nature-based solutions (NbS) for mitigating climate change has gained widespread interest in the scientific community and international policy circles (Lafortezza *et al* 2018, Seddon *et al* 2020). These NbS, including so-called natural climate solutions, focus on the protection, restoration, or management of land to minimise carbon emissions and/or enhance ecosystem carbon sequestration, but without trade-offs for biodiversity and human well-being (Griscom *et al* 2017). At its core, NbS recognise that functional ecosystems provide services to society, ranging from erosion control, flood regulation, fuel and food provision, water and air purification, and carbon capture (Reid *et al* 2005). Common NbS approaches include 'greening the earth' (Zhu *et al* 2016, Chen *et al* 2019) through forest protection (Heinrich *et al* 2023) and large-scale tree planting (reforestation and afforestation) to avoid or offset anthropogenic carbon emissions, respectively (Freedman and Keith 1996, Osman *et al* 2023). The NbS pathways in grassy ecosystems (grassland and savanna), however, are largely restricted to the sustainable management of grazing livestock and fire (Griscom *et al* 2017).

Tree planting may be an effective and appropriate NbS for forested or historically forested areas. However, inappropriate tree-planting is widespread in non-forest, grassy biomes across Africa (Parr *et al* 2024) as a result of restoration pledges under initiatives like the Bonn Challenge (IUCN 2020) and AFR100 (AUDA 2020). Many African landscapes represent ancient grassy biomes that support unique biodiversity adapted to (semi-) open habitats (Bond 2019, Parr *et al* 2024). Extensive tree planting projects in these landscapes may undermine the biodiversity and ecosystem services they provide, while also threatening human livelihoods (Fischer and Hajdu 2018, Simba *et al* 2024). African grassy biomes are also threatened by encroachment of both native and alien invasive woody plants, driven by changes in climate but also changing land-use, including altered herbivory and fire regimes (Venter *et al* 2018). Grassy biomes may also suffer from undervaluation, which has been linked to 'arboreal chauvinism' and early misconceptions that forest cover is linked to civilization (Davis and Robbins 2018). Consequently, grassy landscapes are perceived as being anthropogenic and representing a secondary state, typically as degraded forest, a perspective that persists within the framework of contemporary climate change mitigation policies globally (Hajdu and Fischer 2017, Simba *et al* 2024).

Recent research has highlighted the potentially significant role of grassy ecosystems in mitigating climate change compared to forests under increased global warming scenarios, as they are better able to withstand increased temperatures, drought, and frequent fires (Dass *et al* 2018). The vast extent of the remaining intact grassy ecosystems (>20% of land on Earth and 50% in the southern hemisphere (Mishra and Young 2020, Stevens *et al* 2022)), combined with their moderate carbon stocks, means that they hold 20%–30% of terrestrial carbon (Scharlemann *et al* 2014), mostly belowground in soil and roots (Stevens *et al* 2022). Unlike forests, where significant aboveground carbon stocks may be released as CO_2 during fires or harvesting, the predominance of belowground carbon stocks in grassy ecosystems makes them more 'reliable' carbon stocks in significant parts of the world (Dass *et al* 2018, Zhou *et al* 2023). Moreover, recent work suggests that low-intensity fire may promote carbon sequestration and enhance carbon stocks in these grassy ecosystems (Findlay *et al* 2022). Herbivory and related processes, such as trampling through hoof action and nutrient deposition via excreta, are not only fundamental for the maintenance and biodiversity of grassy ecosystems (Koerner and Collins 2014), but may also significantly affect carbon dynamics. Carbon stocks in these grassy systems are both reliant on (Schmitz *et al* 2018), and resilient to (Vermeire *et al* 2021), fire and herbivory as natural disturbances.

In addition to carbon sequestration potential, surface albedo is another important climate driver that differs between woody and grassy ecosystems (Chen *et al* 2024, Lei *et al* 2024). Surface albedo is a hemispherical reflective quantity, representing the proportion of incoming shortwave solar radiation that is reflected back into space, affecting Earth's radiative budget by controlling how much solar radiation is absorbed or reflected by Earth's surface (Dickinson 1995). Albedo influences the microclimate and heat absorption of vegetation canopies, affecting physiological, physical and biogeochemical ecosystem processes including photosynthesis, respiration, evapotranspiration and radiative energy balances (Foley *et al* 2003, Wang and Davidson 2007, Chen 2021). Ecosystem and albedo dynamics are inherently linked, where changes in climate or ecosystem processes can trigger changes in surface cover and condition and hence albedo, and *vice versa* (Wang and Davidson 2007). Grassy biomes typically have higher albedo than woodlands and forests, thus reflecting more solar radiation back to outer space than tree-dominated systems. Afforestation (and woody encroachment) of grassy biomes may reduce surface albedo and induce a positive radiative forcing, i.e. warming (Barnes and Roy 2008, van Heerwaarden and Teuling 2014, Chen 2021). The literature on vegetation albedo, however, has focused largely on northern hemisphere and forested landscapes (see, for example, (Betts 2000, Beringer *et al* 2005, Barnes and Roy 2010, Lukeš *et al* 2013, te Beest *et al* 2016, Zhu *et al* 2024). As a result, we still poorly understand potential variation in albedo of grassy biomes and the drivers thereof.

Grassy biomes are spatially heterogeneous, with, for example, distinct grassy patches dominated by different species alternating at the scale of several metres to hectares (Grant and Scholes 2006). Such patches may differ widely in terms of structure (e.g. grass canopy height, density, growth form) but also darkness due to different leaf pigment concentrations or light versus darkly pigmented inflorescences. Moreover, grazing by large mammalian herbivores (livestock or wildlife) may also strongly affect grassland structure, leading to so-called grazing lawns (areas of very shortly cropped, prostrate grass) or even increased extent of bare soil in its most extreme form (Cromsigt and Olff 2008, Veldhuis *et al* 2014). Finally, in many grassy biomes worldwide, very low or very high levels of grazing may also lead to increased encroachment by woody vegetation (Stevens *et al* 2017, Venter *et al* 2018), further adding to heterogeneous patterns in vegetation structure and reduced reflectivity in grassy biomes. Here, we aim to increase our knowledge on how different drivers of heterogeneity in grassland structure and perceived reflectance may affect albedo in grassy ecosystems, which in turn may yield differences in radiative forcing on climate.

Existing remote sensing albedo data products have near global coverage and are temporally finely resolved but with coarse spatial resolution (Schaaf *et al* 2002, Chen *et al* 2024). Thus, for example, the NASA Moderate Resolution Imaging Spectroradiometer (MODIS) 500 m albedo product resolution is too coarse to capture spatial variations in albedo in heterogeneous grasslands. Other satellite sensors that have narrow fields of view and lower revisit cycles, like 30 m Landsat satellite observations, do not provide sufficient angular sampling of the surface to be able to characterize albedo reliably (Roy *et al* 2016, Tian *et al* 2018). More recently, fused MODIS and Landsat 30 m albedo products have been developed and advocated for global production (Radeloff *et al* 2024) but remain to be widely tested. In our study, we, therefore, measured albedo in distinct, homogeneous vegetation (and bare ground) patches with a tripod-mounted albedometer. We investigated seasonal variations in albedo among five distinct patch types within an Afromontane grassland landscape: patches of *Themeda triandra* (a darkly-pigmented tussock grass), *Eragrostis lehmanniana* (a visibly lighter-pigmented tussock grass), grazing lawn patches (intensely-grazed and dominated by short-statured, prostrate-growing *Cynodon dactylon*), shrub-encroached grass patches (encroached by dwarf shrub *Pentzia incana*), and also bare ground patches. We tested the hypothesis that albedo varies in response to seasonal phenology, across grass type patches (visibly dark versus light grass species, intensely-grazed lawns and grazed versus less-grazed tussock grass), and between shrub and grass patches, thus offering a novel contribution to understanding how grassy biome albedo varies at the patch scale. We hypothesized that grazing lawns would have a higher albedo than the tussock grass types and shrub-encroached grass, due to lower surface roughness of the prostrate-growing lawns (Fernandes 2018). Further, we hypothesized that grazed tussock grass patches would have lower albedo compared to less-grazed tussock grass. This is attributed to the compensatory growth of new, chlorophyll-rich primary tillers in response to cropping in grazed patches, as opposed to the moribund material found in less-grazed patches and due to more soil background being revealed due to grazing (McNaughton 1983, Knapp *et al* 1999). We, therefore, contrasted grazed versus less-grazed tussock grass patches of both *T. triandra* and *E. lehmanniana*. We finally hypothesized that shrub-encroached grass patches would have a lower albedo than the not encroached patches.

2. Materials and methods

2.1. Study site

All measurements were collected on the Kondoa Plateau within the Samara Karoo Reserve (SKR), South Africa (figure 1). The SKR is in the eastern Karoo, located 30 km southeast of Graaff-Reinet. Kondoa Plateau is a high altitude Karoo Escarpment Grassland (Mucina 2006) spanning ~1650 ha at 1200–1400 m elevation. The geology is comprised of mud- and sandstones from the Beaufort Group (Karoo Supergroup), with intrusions of dolerite (Mucina 2006). Soils are lithic (Fey *et al* 2010) and mostly reddish-brown in colour, appearing greyer in areas with higher clay content. The vegetation is characterised by grasses that remain palatable throughout the year, supporting a range of medium- to large-sized ungulates and an established guild of predators. The growing season for perennial grasses on the Kondoa Plateau is governed by rainfall and minimum temperatures. Grass dormancy begins after the first frost event, while the growing season coincides with the onset of spring rains and rising temperatures (Mucina 2006) (figure 2). Annual precipitation here ranges between 146 mm and 572 mm, with a mean of 337 mm (data: A. Feldon and R. Erasmus, SKR records, unpublished data). Austral winter months (June through August) are typically dry with frequent frost, although this can vary depending on broader climate patterns (Mucina 2006). Average daily temperature in the region ranges between 11.5 °C and 23.5 °C (Van Cauter *et al* 2005).

2.2. Field sampling

Albedo measurements were taken using a radiometrically-calibrated albedometer composed of upward and downward facing EKO MS-80 U pyranometers that sense spectral radiance from 285–3000 nm. The albedometer was mounted to an extendable 2–4.4 m aluminium pole via two Hitec HS-322HD servos, which were calibrated to keep the pitch and roll angles as close to 0° as possible. The pole was mounted on an extendable 0.6–1.5 m tripod. The albedometer took four readings per second, and the average albedo of typically one second of measurements was used (similar to Lei *et al* 2023). Light detection and ranging and GPS sensors were mounted adjacent to the downward pyranometer and used to record sensor height above the vegetation

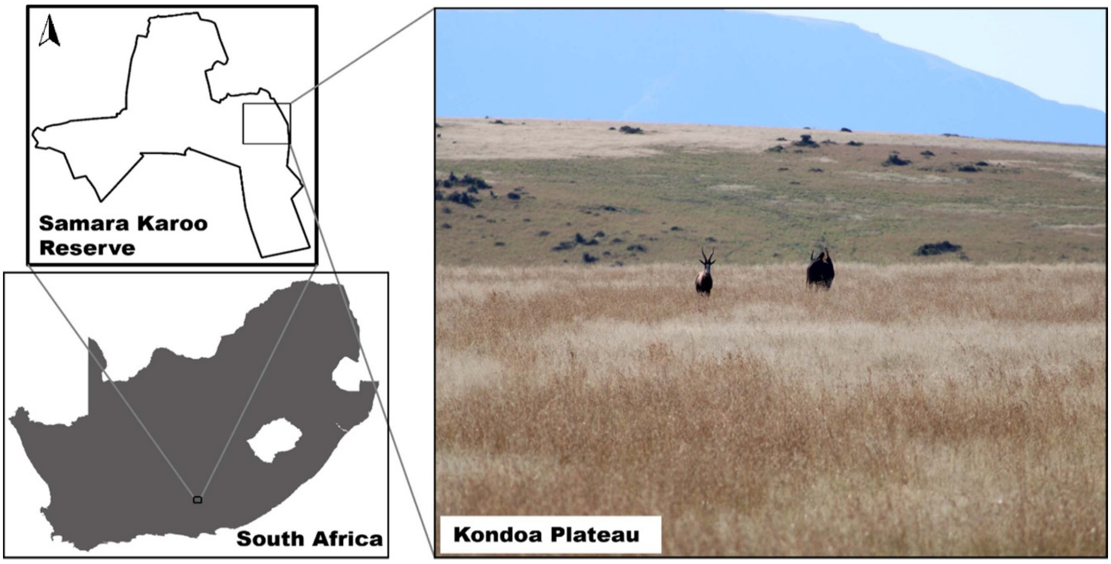

Figure 1. Geographical location of the Kondoa Plateau (32°23′S, 24°55′E) within the Samara Karoo Reserve (SKR), South Africa. Image of a portion of the plateau is included for context, showing a mosaic of red (*Themeda triandra*) and white tussock grass (*Eragrostis lehmanniana*) contrasts in the foreground, with green *Cynodon dactylon* grazing lawn patches visible in the background. Author photo credit : S McGregor.

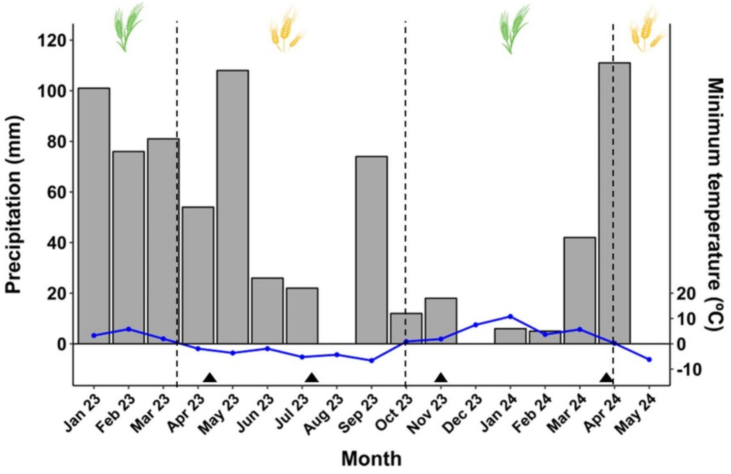

Figure 2. Monthly precipitation (grey bars) and minimum temperatures (blue line) for the study area between January 2023 and May 2024. Green and yellow inflorescences indicate the grass growing and dormancy periods, respectively; and black triangles represent albedo sampling dates. Precipitation data: A. Feldon and R. Erasmus, SKR records, unpublished data. Temperature data: The Weather Company (2024).

and location. In addition, the exact location of each of the tripod legs and directly below the pyranometers (centre of each patch) were marked using painted roofing nails to ensure the same fixed patches could be measured each time.

Sampling was conducted on four occasions aligned with the seasonal phenology of our study period, during early grass dormancy (austral autumn, April 2023), late dormancy (winter, July 2023), the early growing season (spring, November 2023), and late growing season (autumn, April 2024) (figure 2). Note that the seasonal phenology of our study period (figure 2) included a summer with average rainfall (December 2022–February 2023) and a dry summer (December 2023–February 2024) with very late growing season rainfall (March–April 2024). We only took albedo measurements on clear sky days because partial cloud cover may reduce albedo measurement reliability and so reduce our ability to compare the different albedo measurements (Stroeve *et al* 2005). The albedo of most surfaces is usually higher in the morning and evening when the sun is closer to the horizon (higher solar zenith) and so usually field based albedo measurements are made around solar noon (Liu *et al* 2009, Chen *et al* 2024). Therefore, all albedo measurements were taken within two hours of either side of midday for zenith angle consistency. This approach is critical to standardising data in our experimental design of comparing different patches and grazing treatments over different seasons.

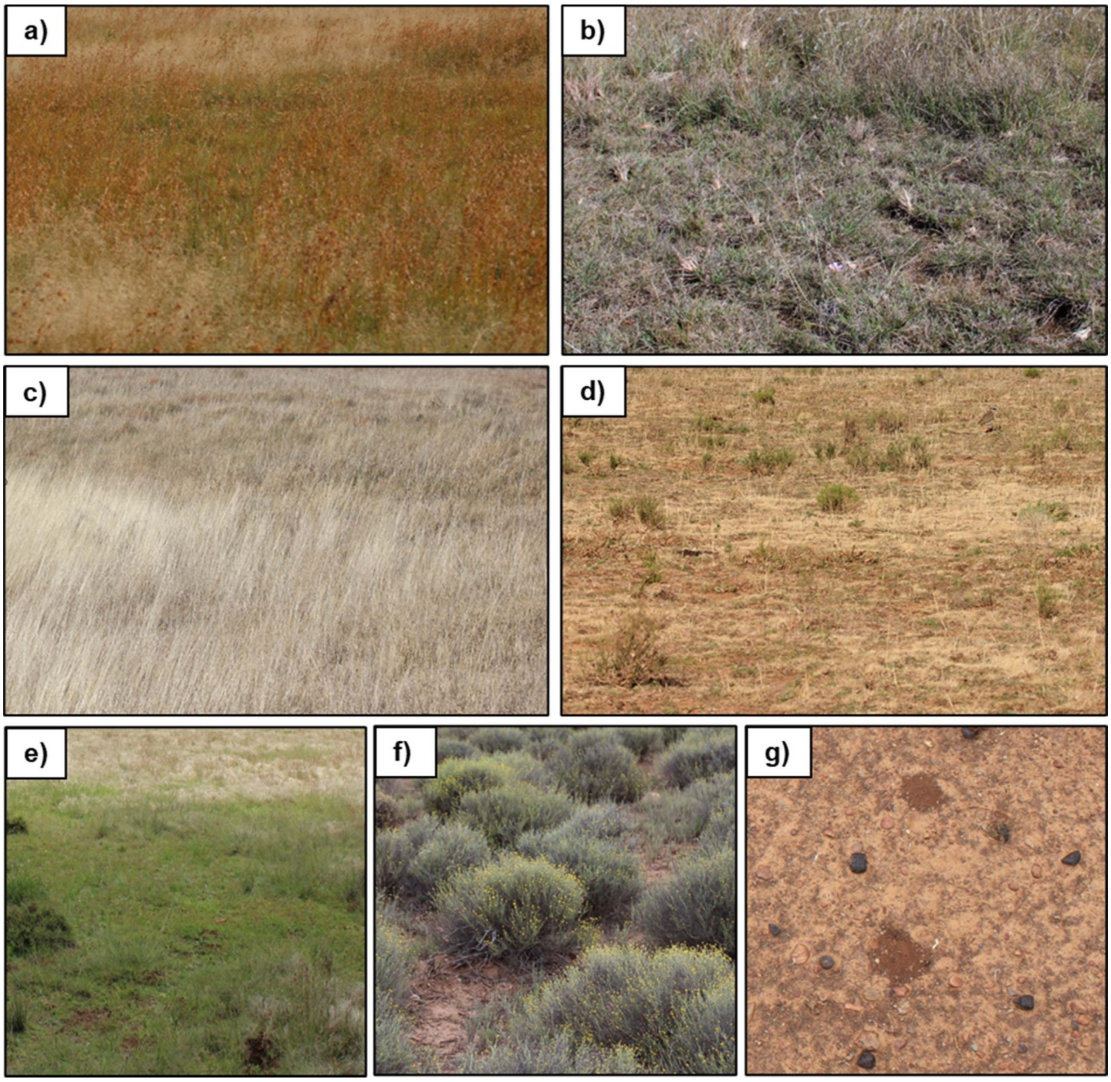

Figure 3. Images depicting contrasts amongst the seven distinct patch types on Kondoa Plateau, SKR, including: (a) less-grazed red tussock grass (*Themeda triandra*), (b) grazed red tussock grass, (c) less-grazed white tussock grass (*Eragrostis lehmanniana*), (d) grazed white tussock grass, (e) grazing lawn (dominated by *Cynodon dactylon*), (f) dwarf shrub (*Pentzia incana*), and (g) bare ground. Images (a), (b) and (e) were taken during the growing season, while images (c), (d), (f) and (g) were taken during the dormancy period. Author photo credit : S McGregor.

Albedo was measured in distinct patch types identified across the Kondoa Plateau, each with >90% homogeneous cover, these comprising of so-called 'red tussock grass' (*Themeda triandra*), Lehmann lovegrass or 'white tussock grass' (*Eragrostis lehmanniana*), intensely-grazed grazing lawns (dominated by *Cynodon dactylon*), shrub-encroached grass (by dwarf shrub *Pentzia incana*), and bare ground patches (figure 3). To explore effects of grazing, we firstly contrasted the albedo of the intensely-grazed grazing lawns with other vegetation patch types. Secondly, we contrasted albedo on grazed versus less-grazed patches of the two tussock grass types, red grass and white grass. This resulted in seven patch types: intensely-grazed *C. dactylon* grazing lawns, grazed red tussock grass, less-grazed red tussock grass, grazed white tussock grass, less-grazed white tussock grass, shrub-encroached grass patches, and bare ground patches. Grazing lawn and shrub-encroached patches did not include a grazed versus less-grazed contrast because these were either by definition always intensively grazed (grazing lawns) or less-grazed (shrub-encroached patches), respectively. Albedo measurements were taken from 35 patches in total, comprised of five replicate patches for each of the seven patch types, and recorded at a height of 1 m above the vegetation canopy following Williamson *et al* (2016). Measurements were recorded by positioning the tripod-mounted albedometer over the centre of each ~2 m^2 patch for a minimum of one minute (Sen and Roesler 2023), following which the average albedo for each patch was calculated. Measurements within replicate patches of the same type were always >25 m apart to provide independence of samples and decrease potential neighbourhood effects, exceeding the 15 m spacing of net radiometers at 3 m above the ground (Federer 1968). The furthest two patches were 3.1 km apart.

Grass height was recorded with a disc-pasture meter (DPM) based on the specifications of Bransby and Tainton (1977) at the centre of each patch, directly below where albedo measurements were taken, as well as adjacently in each of the four cardinal points, and averaged across all five measurements per patch. For shrub-encroached patches, a measuring tape was used to record the heights of tallest dwarf shrub stems in the same five positions (Kouamé *et al* 2022). The percentage vegetation cover in each patch was visually estimated within the sampling cylinder of the DPM (diameter = 46 cm) where each of the five height measurements were taken, and then averaged.

2.3. Statistical analyses

A two-way analysis of variance (ANOVA) was conducted to explore differences in albedo by patch type and season. The interaction between patch type and season was included. Subsequently, following a significant patch [type x season interaction], four independent one-way ANOVAs were undertaken to investigate potential differences in albedo across patch types. *Post-hoc* Tukey's honest significant difference (HSD) tests were applied to explore pairwise differences in albedo among the patch types for each season, where the one-way ANOVAs revealed significant results. All analyses were conducted in R (R Core Team 2024), using the packages 'tidyverse' (Wickham *et al* 2019), 'cowplot' (Wilke 2020) and 'multcompView' (Graves *et al* 2023). Statistical level of significance of $\alpha = 0.05$ was applied for all analyses.

3. Results

3.1. Characteristics of the patch types

Vegetation cover was consistently >90% for all patches (excluding bare ground patches) across the three sampling periods, except for grazed red tussock grass during late dormancy and late growing seasons where the average cover was 89.2% and 85.8%, respectively (figure 4). The average vegetation height of the less-grazed red and white tussock grass patches was 10.5 cm, except during the late growing season where the average less-grazed white tussock grass patch height was 9.3 cm. Grazed red tussock grass patches were slightly shorter (mean = 2.0, range = 1.8–2.2 cm) than grazed white tussock grass patches (mean = 2.9 cm, range = 1.8–3.8 cm), while grazing lawn patches averaged 2.0 cm throughout the seasons (range = 1.5–2.5 cm), confirming that mammalian herbivory removed biomass on 'grazed' sites.

3.2. Variations in albedo across patch types

Albedo varied significantly among the seven patch types ($F_{6,112} = 33.54$, $p < 0.001$). We also observed an effect of season on albedo ($F_{3,112} = 131.33$, $p < 0.001$) and an interaction between patch type and season ($F_{18,112} = 3.83$, $p < 0.001$), indicating that differences in albedo across patch types varied between seasons. Bare ground patches exhibited the greatest variability within each of the four sampling periods (mean albedo = 0.18, range = 0.15–0.20), while shrub-encroached patches had the most consistent albedo (mean = 0.13, range = 0.11–0.15) (figure 5). We also recorded significantly lower surface albedo of shrub-encroached patches compared to the grass patches, with albedo differences ranging between −0.12 (shrub-encroached versus both grazing lawn and grazed white tussock grass patches) and −0.06 (shrub-encroached versus both grazed and less-grazed red tussock grass patches) in early dormancy. In late dormancy, the differences were slightly less pronounced, ranging between −0.09 (shrub-encroached versus grazing lawn patches) and −0.06 (shrub-encroached versus grazed and less-grazed red tussock grass patches). During the early growing season, there were no significant differences in albedo between shrub-encroached patches and the four types of tussock grass patches (Tukey's HSD test, $p > 0.05$). However, in the late growing season, albedo of shrub-encroached patches was significantly lower than that of all other patch types (Tukey's HSD test, $p < 0.05$).

Both grazed and less-grazed red tussock grass patches had lower albedo than intensely-grazed grazing lawn patches and both grazed and less-grazed white tussock grass patches, but only during early dormancy (Tukey's HSD test, $p < 0.05$). During the early growing season, less-grazed red tussock grass had a lower albedo than grazing lawn patches (Tukey's HSD test, $p < 0.05$). There were no significant differences observed between grazed and less-grazed tussock grass patches of the same species (Tukey's HSD test, $p > 0.05$).

Although not statistically significant in all cases, grazing lawns on average exhibited higher albedo than other vegetation patches, except during early dormancy when the average albedo of grazed white tussock grass matched that of grazing lawn patches (mean = 0.27 for both; range = 0.20–0.30 and 0.25–0.28 for grazed white tussock grass and grazing lawn patches, respectively). The white tussock grass patches had a pronounced albedo decrease from early dormancy to late dormancy, whereas red tussock grass and grazing lawn patches exhibited lower albedo later in the year during the early growing season.

4. Discussion

Due to the coarse resolution of satellite albedo products, remote sensing is not well suited to study albedo at fine spatial scale (Li *et al* 2018, Chen *et al* 2024). We examined fine-scale ground-based albedo data across seasons and over patches in a wild

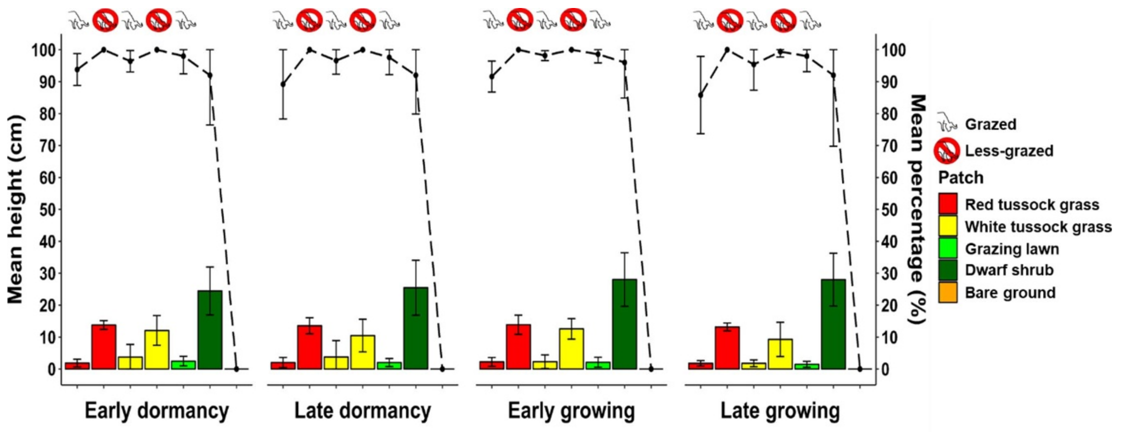

Figure 4. Mean vegetation height and percentage cover recorded across the seven patch types by season on the Kondoa Plateau, SKR. Bars = mean vegetation height (cm), lines = percentage vegetation cover. Error bars = 95% confidence intervals.

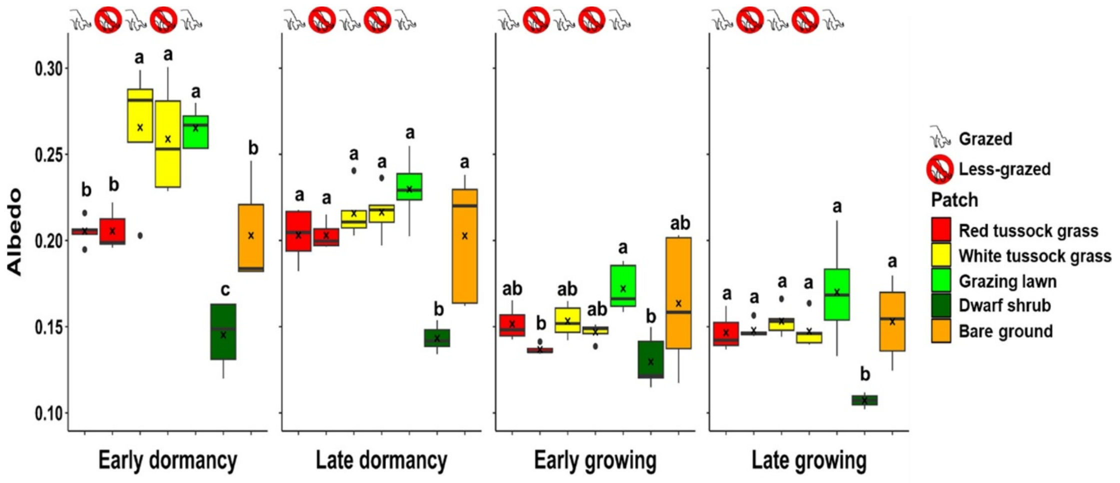

Figure 5. Average albedo of the seven patch types across seasons on the Kondoa Plateau, SKR. The means of each patch type are denoted by 'X'. Boxes sharing a letter are not significantly different (Tukey's HSD test, $p < 0.05$) within a sampling period.

herbivore-dominated grassland, and included shrub-encroached and bare ground patch types. The inclusion of shrub-encroached patches is notable because woody encroachment is a threat in grassy biomes globally, driven by factors including changing herbivory regimes (overgrazing practices, replacement of browsing wild ungulates with livestock, fire suppression), changing climate, and tree planting for carbon credits (Freedman and Keith 1996, Macias *et al* 2014, Venter *et al* 2018). Thus, our findings are relevant in a global context where similar grassy mosaics occur.

4.1. Bare ground albedo

We found considerable variance in albedo measurements among bare ground patches, likely driven by differences in soil type, texture, and moisture content. Soils on the Kondoa Plateau may exhibit fine-scale variations in particle size and mineral composition due to their derivation from different parent rocks, including the underlying sand- and mudstones, and doleritic intrusions (Mucina 2006, Fey *et al* 2010). These variations can significantly affect soil albedo. For example, lighter-coloured soils derived from sandstone may have higher albedo than darker soils of doleritic origin or with higher organic matter content (Post *et al* 2000, Molaro and McKay 2010). Soil particles of varying sizes also exhibit different spectral reflectance properties (Sadeghi *et al* 2018). Additionally, it is well established that increasing soil moisture reduces reflectance from the visible to the shortwave infrared spectra (Lobell and Asner 2002), and so reduces albedo (Liu *et al* 2014, Zheng *et al* 2021). Unfortunately, our small sample size prevented us from statistically analysing the complex, interrelated, effects of variation in soil moisture, soil texture, and soil colour on the albedo of our bare ground patches.

4.2. Effects of season

As expected, seasonal phenology influenced surface albedo of all patch types. Surface albedo showed high variability across patches during early dormancy, but became more uniform towards the late growing season. This supports the hypothesis that albedo varies with season, among grass patch types, and between shrub and grass patches, as also observed in satellite studies (Schaaf *et al* 2002, Rechid *et al* 2009, Wang *et al* 2017) and in comparable patch-scale research in Arctic tundra (te Beest *et al* 2016, Williamson *et al* 2016). Perennial grasses emerging from dormancy increase chlorophyll concentrations going into the growing season (Ustin and Jacquemoud 2020), lowering albedo compared to dormancy periods (Wang *et al* 2014). As seen in figure 5, in our study all grass patch types indeed had lower albedo during growing seasons than during dormancy periods. The lower albedo of red tussock grass patches during early dormancy is likely due to increased anthocyanin (red pigment) concentrations, which are higher during dormancy (van Oudtshoorn 1999) and result in lower albedo compared to greener canopies (Carvalho *et al* 2022). The high albedo for white tussock grass in the early dormancy season, compared to the other three seasons, is likely due to this grass producing strikingly white inflorescences during this time, which can have distinct reflective properties compared to leaves (Kuester and Spengler 2018). The high variation in albedo among less-grazed white tussock grass patches during this time of the year may stem from variation in the abundance and stage of inflorescences among replicate patches.

The observed albedo patterns varied significantly between the two different autumns (April 2023 and 2024). This variation stems from the timing of the growing season, which is dictated by minimum temperatures and precipitation—factors influenced by broader climate patterns (Mucina 2006, Currier and Sala 2022). In March 2023, an early frost prematurely ended the growing season, leading us to classify late April as early dormancy. Conversely, delayed summer rainfall in 2024, coupled with later frost, extended the growing season into late April, just before the onset of frost signalled the beginning of the next dormancy period. These findings show that albedo, and its variation among vegetation types, not only fluctuates seasonally within a year but may also vary across the same period in different years, driven by strong inter-annual variation in summer rainfall and the onset of cold winter temperatures. Consequently, shifts in seasonal phenology driven by climate change (Chmura *et al* 2019) could have broader implications for albedo patterns.

4.3. Effects of grazing

Our most intensively grazed patches, the *Cynodon dactylon* grazing lawns, had a consistently higher albedo than grazed and less-grazed tussock grass patches, although in most cases not statistically significant at the 0.05 level (figure 5). Here, statistical power, with only five replicates per patch type, may have been an issue. Previous work in a South African savanna similarly showed higher albedo for grazing lawn patches compared to other grassland types (Fernandes 2018). Interestingly, in this case of grazing lawns, intense grazing increases albedo in contrast to our hypothesized reduction of albedo for grazed tussock grass. We suggest that the higher albedo observed in grazing lawn patches is unlikely caused by a more exposed soil understory, since vegetation cover in our lawn patches remained consistently above 90%. Instead, greater trichome density associated with high altitude *C. dactylon* ecotypes (Ahmad *et al* 2016) may be influential as a positive relationship between increased trichome density and albedo has been observed (Hamwey 2007). Moreover, the stoloniferous, prostrate-growing growth form of the grazing lawn grasses may also explain the higher albedo of lawns due to resulting low surface roughness and the reflective properties of exposed stems (Shendye and Gurav 2014). Grazing lawn patches are established and maintained by herbivore pressure (Cromsigt and Olff 2008). In southern and eastern Africa the size of grazing lawns varies from a few m^2 (Grant and Scholes 2006) to km^2 (McNaughton 1984), which could have implications for shaping grassland albedo and contributions to regional warming—particularly in large grazing systems like the Serengeti where grazing lawns form key components of the vegetation heterogeneity (McNaughton 1984, Frank *et al* 1998).

We hypothesized that grazed tussock grass patches would have a lower albedo than less-grazed tussock grass patches. The assumption was that higher densities of green, chlorophyll-rich primary tillers and more soil background being revealed in grazed patches (McNaughton 1983, Knapp *et al* 1999) would lower albedo relative to less-grazed patches. Contrary to this, we found no influence of grazing on the surface albedo of red and white tussock grasses. This, we speculate, could be due to insufficient differences in canopy structure and roughness between grazed and less-grazed tussock patches, with only 8–12 cm height variation between the two. Due to our small sample size, we could unfortunately not statistically test for a relation between grass height variation and albedo. Previous studies have shown that intense grazing can reduce perennial grass cover while increasing that of bare ground, annuals, and woody vegetation, which may reduce albedo (Aguiar *et al* 1996, Li *et al* 2000, Wang and Davidson 2007), while others have shown intense grazing to increase short grass and reduce woody plant cover resulting in higher albedo (te Beest *et al* 2016). Although our study directly compared grazed and less-grazed tussock patches, it was limited in that data were collected in an open grazing system, without fenced-off grazing exclusion plots. Grazing pressures on the Kondoa Plateau vary between low and high (McGregor *et al* 2024) relative to the grazing capacity of the region (12 ha^{-1} per Large Stock Unit (LSU), or 0.08 LSU per ha^{-1} (DAFF 2018)) but we could not determine grazing pressure at the fine patch scale of our albedo measurements. Mowing treatments to alter grass height across a greater number of patches may provide a more comprehensive analysis.

4.4. Potential warming associated with woody encroachment

Increased woody encroachment and changing land-use in grassy ecosystems can induce significant warming effects brought on by decreased albedo (Zhao *et al* 2021). The relationship between a change in albedo at the surface and net radiative forcing on the climate is complex as it depends on the exchange of sensible and latent energy through the atmosphere (Chen 2021). Despite this, many straightforward (not processed-based) modelling studies have observed quite small changes in albedo, due to land-use and land cover, to translate into significant radiative forcings (e.g. Myhre and Myhre 2003, Davin *et al* 2007, Barnes and Roy 2010, Zhai *et al* 2014). We observed significantly lower surface albedo of shrub-encroached patches compared to grass patches, with albedo differences ranging between −0.12 and −0.06 over the study period. The consistently lower albedo of shrub-encroached patches is likely attributed to higher chlorophyll concentrations and greater surface roughness associated with woody canopies compared to grasses (Aguiar *et al* 1996, van Heerwaarden and Teuling 2014, Genesio *et al* 2021). These significant albedo differences underscore the importance of conserving grassy biomes and limiting the extent of woody encroachment or tree planting in grassy biomes, to maintain the NbS contributions of grasslands.

4.5. Climate goals and grassland management

Grassland protection and restoration offers an important NbS for the global effort to maintain climate change within 1.5 °C above pre-industrial temperatures, as proposed by the IPCC (2018), not only via a 'reliable' carbon stock (Dass *et al* 2018), but potentially also via albedo-related cooling. However, there is currently no penalty for converting intact old-growth grasslands into another land-use, and few incentives to conserve them (Slooten *et al* 2023). This is a major conservation issue, because secondary grasslands can take centuries to millennia to recover former old-growth species richness after extensive disturbance from ploughing or other land-use change (Buisson *et al* 2022).

Our findings suggest that management approaches that influence shifts in grass types will influence the NbS potential of grassy ecosystems. For example, overgrazing can increase the abundance of certain grasses known as increasers, while decreasing others known as decreasers (Tainton *et al* 1980). Among the grasses sampled in our study, red tussock grass is a highly palatable decreaser, showing decreased abundance when over- or underutilised (Foran *et al* 1978). In contrast, the less palatable white tussock grass is deemed an increaser, proliferating under light grazing (Van Rooyen *et al* 1991). Additionally, *C. dactylon* (grazing lawn) is also an increaser, with its abundance increasing with overutilisation (Foran *et al* 1978). While grazing lawns are an important component of wild grazer-dominated systems (McNaughton 1984, Frank *et al* 1998, Knapp *et al* 1999), their importance diminishes for domesticated livestock where taller swards are preferred (Hempson *et al* 2015). Management of rangelands or native grassy ecosystems is thus a key determinant of grass sward structure and composition, which may have implications for the albedo of these grassy systems, as suggested by our findings. Based on this, we suggest that we need to increase our understanding of how variation in albedo associated with variation in grassland vegetation patches affects surface albedo at larger landscape scales (Hamwey 2007, Genesio *et al* 2021, Carvalho *et al* 2022). Our findings also raise questions for managing rangelands in African grassy ecosystems, particularly in terms of managing potential trade-offs between climate change mitigation and livestock production goals. We show how highly palatable red tussock grass with high forage availability for livestock has lower albedo, whereas less palatable white tussock grass and/or grazing lawns have low aboveground biomass but higher albedo.

5. Conclusion

We show that specific grass patches, such as white tussock grass and grazing lawns, can increase albedo compared to red tussock grass and shrub-encroached patches and so changes from these patches can impose negative radiative forcing (i.e. cooling), particularly outside the growing season. If these patches cover large extents, this may have implications for regional climate dynamics and the overall radiative forcing in grassland systems dominated by these perennial grasses. Our results also suggest that woody encroachment into grasslands may lower albedo, leading to further warming. The spatial scaling and composition/structure of patches within grassy biomes becomes pivotal in understanding their contribution to climate processes through albedo. Future studies should calibrate patch-scale albedo measurements with remotely sensed data, expanded across dominant patch types and land-uses over multiple growing seasons. Such studies should also explore the radiative forcing effects from potential shifts in dominant patch types to enhance our understanding of the role of grassland patches in mitigating climate change. This approach may provide a more comprehensive understanding of albedo patterns, facilitating more informed and effective rangeland management strategies in the quest for nature-based climate prospects.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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