Extensive woody encroachment altering Angolan miombo woodlands despite cropland expansion and frequent fires

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Extensive woody encroachment altering Angolan miombo woodlands despite cropland expansion and frequent fires

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Abstract

Woody encroachment (WE) and agricultural expansion are widespread in tropical savannas, where they threaten biodiversity and ecosystem function. In Africa's largest savanna, the miombo woodlands, cropland expansion is expected to cause extensive habitat loss over the next 30 years. Meanwhile, widespread WE is altering the remaining untransformed vegetation. Quantifying the extent of both processes in the Angolan miombo woodlands (~570,000 km^2) has been challenging due to limited infrastructure, a history of conflict, and widespread landmines. Here, we analyze spectral satellite imagery to investigate the extent of WE and cropland expansion in the Angolan miombo woodlands since 1990. We asses WE using two complementary metrics: multi-decade canopy greenness trends and conversion from grassland to woodland. We also examine whether WE trends are driven by landscape fragmentation and decreasing fire frequency. We found that from 1990 to 2020, 34.1% of the Angolan miombo woodlands experienced significant WE or was converted to cropland, while open grassy vegetation declined by 62%. WE advanced rapidly even in areas experiencing extraordinarily high burn frequencies and was not adequately explained by changing temperature or precipitation. WE was concentrated far from the agricultural frontier, in remote areas with low population densities. These results challenge the hypothesis that human-altered fire regimes are the primary driver of WE in mesic savannas. The results will help decision-makers conserve the miombo woodlands' biodiversity and ecosystem services, by highlighting that strategies to slow habitat loss must address WE and cropland expansion together.

KEYWORDS
Angola, fire frequency, grassy ecosystem, land-use change, remote sensing, savanna, woody encroachment

1 | INTRODUCTION

Tropical savannas cover 20% of the world's land and supply ecosystem services to hundreds of millions of people (Bond, 2019). They provide habitat for thousands of endemic species composing a rich, ancient, and disturbance-dependent biodiversity (Bond & Parr, 2010; Veldman et al., 2015). These benefits are threatened by two global change processes: woody encroachment (WE) and land conversion for agriculture (Potapov et al., 2022; Stevens et al., 2022). Savannas include grassy ecosystems that span a tree cover gradient from nearly treeless grasslands to dense woodlands (Staver et al., 2011). In virtually all savannas, interactions between fire, herbivory, and climate maintain a balance between C4 grasses and open-canopy trees (Lehmann et al., 2011; Scholes & Archer, 1997). Interpreting how savannas are changing therefore requires understanding how disturbance regimes such as fire interact with anthropogenic changes (Strömberg & Staver, 2022). Although long acknowledged, the interactions between WE, cropland expansion, and fire are seldom viewed together and remain poorly understood in mesic savannas (Archibald et al., 2009; Schulte to Bühne et al., 2023). Clarifying these interactions can guide efforts to conserve biodiverse, resilient savannas under changing conditions (SEOSAW, 2020).

Tropical savannas are experiencing the world's highest rates of agricultural conversion and have experienced greater historical conversion than tropical rainforests (Ellis, 2021; Potapov et al., 2022). In Africa, 430 million hectares of natural vegetation are expected to be cleared for agriculture by 2060 (Tilman et al., 2017). Cropland expansion poses the leading threat to global biodiversity (Maxwell et al., 2016). It also degrades ecosystem services such as soil maintenance and water provision, which sustain long-term food production (Brondizio et al., 2019). In savannas, agriculture irrevocably destroys belowground root structures, permanently decreasing the capacity of savannas to conserve biodiversity and store soil carbon (Buisson et al., 2019; Nerlekar & Veldman, 2020).

Unconverted savannas, meanwhile, are experiencing long-term increases in woody cover (Rosan et al., 2019; Stevens et al., 2017; Venter et al., 2018). This phenomenon, termed WE, is driven by varying combinations of global and local factors. Global factors include rising atmospheric CO_2, increasing temperatures, and changing precipitation regimes (Bond & Midgley, 2012; Buitenwerf et al., 2012; Franco et al., 2014; Moncrieff et al., 2014). Local factors include altered fire, herbivory, and land use regimes (Devine et al., 2017; Rosan et al., 2019; Stevens et al., 2016). WE threatens livelihoods by inhibiting livestock grazing and reducing available water for crops (Luvuno et al., 2018; White et al., 2022). WE also threatens biodiversity, particularly specialist species, including birds, mammals, and plants, that are adapted to open, grassy ecosystems (Abreu et al., 2017; Sirami & Monadjem, 2012; Smit & Prins, 2015).

While land use change can interact with WE and fire in multiple ways, one prominent hypothesis suggests that cropland expansion drives WE by suppressing fire (Andela et al., 2017). Cropland expansion prevents fires from spreading, as it fragments flammable natural vegetation (Andela et al., 2017). As burned area decreases across African savannas, woody plants are released from disturbance, and woody cover increases (Sagang et al., 2022; Venter et al., 2018). Following this hypothesis, we would expect to see increasing woody cover concentrated around areas with expanding cropland and declining fire frequencies. Contrasting models of fire behavior, however, suggests that cropland expansion has little impact on fire spread in mesic savannas. In ecosystems such as the miombo woodlands, high fuel accumulations would combine with long dry seasons to make fire inevitable (Archibald et al., 2009). Such models are supported by empirical evidence that suggests WE is advancing rapidly in some frequently burning landscapes (see e.g., Stevens et al., 2016; Veenendaal et al., 2018).

To test these hypotheses, we conducted a spatially explicit analysis of cropland expansion, WE, and fire regimes in the Angolan miombo woodlands. The miombo woodlands are Africa's largest savanna, covering 1,969,000 km^2 (Huntley & Walker, 2012). They are defined by the floristic uniformity of their dominant tree genera—*Brachystegia*, *Julbernardia*, *and Isoberlinia*—and occur over areas characterized by infertile soil, mesic rainfall conditions (650–1400 mm) and a long dry season (Campbell et al., 1996). Despite their size, the miombo woodlands are chronically understudied (SEOSAW, 2020). Their Angolan portion ranks among the world's least-studied ecosystems due to war (1961–2002), landmines, and travel restrictions (Huntley & Ferrand, 2019). Yet, a lack of research understates the miombo woodlands' importance: In addition to containing Africa's richest savanna plant biodiversity, the miombo woodlands store globally significant carbon stocks and supply ecosystem services to 75 million people (Dewees et al., 2010; Kier et al., 2005; Ryan et al., 2016).

The miombo woodlands are an ideal ecosystem in which to investigate interactions between global change and disturbance, because they feature both rapid ecosystem change and frequent fires. Angola is currently experiencing the world's highest annual rate of cropland expansion and constitutes part of a broader agricultural frontier spanning the miombo woodlands (Estes et al., 2016; Potapov et al., 2022). In addition, continent-scale remote sensing analyses have found that the miombo woodlands are experiencing exceptionally high rates of WE among African savannas (McNicol et al., 2018; Mitchard & Flintrop, 2013; Venter et al., 2018). These changes are occurring within a fire-dependent landscape: though miombo covers just 17% of Southern Africa's area, it accounts for 37% of the region's fires (Archibald et al., 2009). Frequent burning maintains the ecosystem's vegetation structure, biodiversity, and ecosystem function (Campbell, 1996; Ryan et al., 2016; Saito et al., 2014; Staver et al., 2011).

This paper contributes novel evidence to the literature on global change in mesic African savannas by investigating WE, cropland expansion, and fire jointly; at the ecoregion scale; and using updated remote sensing methods. WE, cropland expansion, and fire have rarely been considered together in mesic savannas, despite projections that their combined impacts pose a widespread threat to savanna biodiversity and function (Newbold, 2018; Stevens et al., 2022). Adopting the scale of the ecoregion instead of the continent capitalizes on the ecoregion's floristic and structural uniformity, to ensure ecological differences among savannas will not confound results (Olson et al., 2001). Ecoregion-scale remote sensing studies also complement plot-based studies by examining fewer metrics of ecosystem change across a greater area (Nagendra et al., 2013). Finally, we employ two complementary but unrelated remote sensing metrics to report WE in order to increase confidence in the results. The first metric, a landcover classification, showcases areas where tree cover has crossed the 10% threshold used by UNESCO to differentiate grassland from savanna woodland. This approach highlights threats to Angola's vanishing and ecologically unique grasslands. But, it fails to capture shifts in woody cover that do not cross the 10% tree cover threshold. The second metric, a vegetation index analysis of canopy greenness trends, uses a single tailored measure of WE: median May enhanced vegetation index (EVI). This metric accurately captures minor changes in canopy greenness that accrue over decades. But, it has higher sensitivity than landcover classifications to annual phenological variation.

The aim of this study was to examine how two of the principal threats to African savannas—cropland expansion and WE—are progressing and interacting with fire in the Angolan miombo woodlands. Our first objective was to determine the rate and extent of cropland expansion and WE in the Angolan miombo woodlands since 2000. Our second objective was to clarify the relationships between WE, cropland expansion, and fire frequency. To do so, we assessed WE trends within land use classes and burn frequency classes. We also related WE to precipitation and temperature. The results provide novel evidence that the miombo woodland's grasslands are giving way to woodlands and croplands despite the ecoregion's frequent fires. This evidence can help decision-makers attune conservation and fire management plans to the changes transforming Africa's largest savanna.

2 | METHODS AND MATERIALS

2.1 | Study area

The study analyzed the Angolan miombo woodlands (Figure 1), a mesic savanna ecosystem defined by the floristic uniformity of its tree genera, and featuring a May–September dry season and a unimodal October–April wet season (650–1400 mm rainfall) (Huntley, 2023). The Angolan miombo woodlands cover 570,000 km^2. Boundaries were defined using, using the Resolve Ecoregion dataset (Dinerstein et al., 2017). The study area included all portions of the Angolan miombo woodlands ecoregion (>90% of the ecoregion) falling within Angola's borders (Figure 1).

2.2 | Landcover classification

All analyses were carried out within Google Earth Engine (Gorelick et al., 2017). We built a land use classification to classify Landsat surface reflectance imagery into four landcover classes: grassland, savanna woodland, cropland, and urban. Landsat provides a near-complete set of 30 m satellite imagery for the Angolan miombo woodlands from 1986 until 2022 (Woodcock et al., 2008). First, we processed four epochs of Landsat imagery to create multitemporal composite, multi-band images of the Angolan miombo woodlands for the Years 1990, 2000, 2014, and 2020. Landsat 5 Thematic

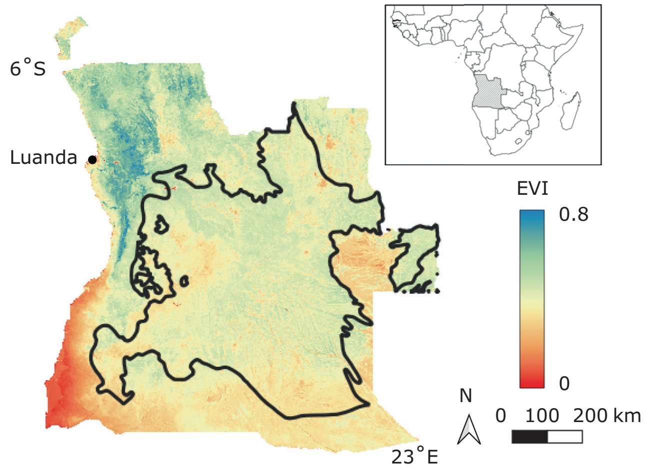

FIGURE 1 Location of the Angolan miombo woodlands ecoregion (black outline), the study area, within the country of Angola. Colors designate average values of the median May enhanced vegetation index (EVI), a proxy for canopy greenness, over the 2000–2020 period. The value of EVI for healthy vegetation ranges from 0.2 to 0.8. Inset shows Angola's location within Africa. Map lines delineate study areas and do not necessarily depict accepted national boundaries.

Mapper (LS5 TM) imagery was used for the 1990 composite, Landsat 7 Enhance Thematic Mapper Plus (LS7 ETM+) was used in combination with LS5 TM imagery for the 2000 composite, and Landsat 8 Operational Land Imager (LS8 OLI) was used for the 2014 and 2020 images. We used published cross-calibration coefficients to harmonize spectral values across the Landsat datasets (Roy et al., 2016). We analyzed imagery from 2014 rather than 2010 due to the Landsat 7 satellite's scan line corrector failure, which left systemic gaps in 2004–2013 Landsat imagery.

For each year of analysis, we extracted a time series of Landsat images spanning Angola's May–September dry season to prevent wet season cloud cover from distorting the imagery, and applied a cloud mask to create cloud-free image collections. Reflectance data for each image in the series was derived from visible, near-infrared, and short-wave infrared bands, as well as from four vegetation indices: the normalized difference vegetation index or NDVI (Tucker, 1979), the EVI (Liu & Huete, 1995), the normalized difference built-up index (Zha et al., 2003), and the bare soil index (Li & Chen, 2014). While cropland and natural vegetation can sometimes appear spectrally similar in the late dry season, in the early dry season (i.e., May) unharvested crops provide a distinctive phenological signal (Domptail et al., 2013). Because crops and miombo vegetation display different phenological patterns (Frost, 1996), we created multitemporal composite images for each year of analysis by extracting multi-band, median-value images for three seasons: early dry season (April 29–May 30), mid-dry season (June 1–July 31), and late dry season (August 1–September 15). These periods align with different phenological stages of deciduous miombo trees, respectively leaf flush, leaf fall, and pre wet-season green-up (Frost, 1996). To avoid temporal inconsistency, these seasonal images were retained as separate bands within the composite images. Because the 1990 and 2000 Landsat collections feature data gaps for Angola, we mosaicked multitemporal composite images spanning the surrounding years (1989–1991 and 1999–2001) where necessary.

We mapped landcover change between 1990 and 2020 by performing supervised classification using a 100-tree random forest classifier. We trained the classifier on the 2020 LS8 multitemporal composite image, consisting of separate bands for each wavelength and vegetation index in each of the three seasons. We then applied the classifier to the 2014, 2000, and 1990 composite images. To create training data, we manually classified 5000 30 × 30 m pixels of Landsat 8 imagery. These pixels were selected using a stratified random sampling approach and were evenly divided between each of four classes: urban areas, cropland, savanna woodland, and grassland, with the cutoff for closed savanna placed at 10% tree cover, following the UNESCO vegetation structure classification (UNESCO, 1973). A drawback of this approach is that fallow cropland may be misclassified as grassland or woodland. Since 2000, however, Angolan smallholders have switched to a system of semi-permanent farming with scarce fallow periods, mitigating the problem (Schneibel et al., 2017). Pixel class was determined by comparing Landsat 8 imagery to very high spatial resolution images derived from Google Earth, following Venter et al. (2018). Where Google Earth imagery was not available for 2020, we compared 2019 Google Earth imagery to lower resolution 2020 PlanetLabs imagery to determine whether land use had changed. In addition, training pixels within each class were distributed evenly into 10 sampling quadrats encompassing the Angolan miombo woodlands. This ensured that training data for each class was distributed across the entire gradient of the ecoregion, so that urban pixels, for example, were not dominated by a few major cities. We trained the classifier using 70% of the training data, reserving 30% of pixels for out-of-bag validation, following standard practice (Breiman, 1999).

The classifier was highly accurate when tested on the validation dataset, with an overall accuracy of 86.6% when assessed following Olofsson et al. (2014). User's accuracies ranged from 79% to 90% (Table S2). Across all years classified, producer's accuracies range from 90% to 97% for woodland, 70% to 91% for grassland, 61% to 88% (75%–88% from 2000) for cropland, and 24% to 52% for urban and bare ground. The low value for bare urban and bare ground does not undermine the analysis, as bare ground and urban areas made up <2% of the study area and are not hypothesized to be experiencing WE. To reconstruct land cover in 1990, 2000, 2014, and 2020, we applied the classifier to each of the four multitemporal composite Landsat images. We calculated the areas of each landcover class in the 1990, 2000, 2014, and 2020 classified images. We analyzed shifts from grassland to woodland as a proxy for WE, alongside the results of our EVI trend analysis. Although in some years, some areas of bare ground were unintentionally classified as urban areas, these represented 0%–2% of the study area.

2.3 | Burn frequency classes

To create burn frequency classes, we used the monthly MODIS Burned Area pixel product (FireCCI51 v 5.1) at 250 m resolution (Giglio et al., 2009) We composited burned area into annual images of the study area. We then counted the number of years each pixel burned from 2002 to 2021 (inclusive) and divided the ecoregion into five classes based on burn frequency: areas that burned 0, 1–5, 6–10, 11–15, and 16–20 years of the 20-year study period.

2.4 | EVI from MODIS

We used median May values of the EVI (May EVI_{med}) as a proxy for WE. Spectral vegetation indices are designed to measure canopy "greenness," a metric that captures chlorophyll and photosynthetic activity as well as canopy and leaf structure. Vegetation indices isolate this greenness signal from spatiotemporal variability (Huete et al., 2002). The EVI was developed to optimize vegetation signals in high-biomass tropical regions. It reduces interference from atmospheric aerosols and from background soil signals (Huete et al., 2006). These features are advantageous in the miombo woodlands, where frequent fires raise aerosol concentrations, and an open canopy reveals soil (Frost, 1996). Prior studies show that MODIS EVI accurately captures seasonal cycles of canopy phenology and leaf area in miombo (Ryan et al., 2014). In more arid savannas, however, the contribution of grass greenness to EVI can overwhelm that of tree greenness, so results should be interpreted with caution (Archibald & Scholes, 2007).

The miombo woodland's climate and phenology make May EVI_{med}, a better measure of WE than annual EVI_{max}, the metric employed by Rosan et al. (2019). May is the optimal month for measuring EVI to ensure (i) cloud cover does not create unmanageable imagery gaps; (ii) trees retain full, green leaf cover; and (iii) the grass signal is minimized. In the April to October wet season, cloud cover can mask the period of annual maximum greenness (Frost, 1996). Between June and October, deciduous miombo trees lose their leaves, confounding canopy greenness metrics (Chidumayo & Frost, 1996). In September and October, some species flush with red foliage (Chidumayo & Frost, 1996). While grass phenology varies within the Angolan miombo woodlands, many areas feature green-up after dry season fires in June, making the winter a poor time to measure canopy greenness (Estes, 1974). We used median rather than maximum May EVI to reduce covariation between greenness and cloudiness, which are both highest in early May.

To measure the change in May EVI_{med}, we extracted 250 m resolution, 16-day composite images, from the MODIS Terra Vegetation Indices product (MOD13Q1 V6) and masked clouds. These images spanned 2000 to 2022. We used a pixel-by-pixel reducer to create 23 annual images of pixelwise May EVI_{med}. To locate areas where WE is occurring, we ran a pixel-wise linear regression of May EVI_{med} against time following Rosan et al. (2019). We considered pixels significant when they presented a best-fit line using an F test with a 90% confidence level. Following Rosan et al. (2019) and Mitchard and Flintrop (2013), we only designated pixels as encroached when their EVI increased by at least .03 EVI units over the 20-year study period ($p<.1$).

2.5 | EVI trends in land use and burn frequency classes

To compare EVI trends across landcover classes, we first upscaled 30 m Landsat pixels into 250 m MODIS pixels. We classified 250 m pixels as either mixed or pure, with pure pixels comprising over 90% of either 30 m cropland pixels or 30 m natural vegetation pixels (Figure S6). Pure pixels were treated separately from mixed pixels. Pure pixels were upscaled using nearest-neighbor resampling.

We calculated average EVI trends for mixed pixels as well as for each class of pure pixels: urban, cropland, grassland, and woodland. Pixel class was assigned according to the 2020 land use classification. We also calculated average EVI trends for pixels that had transitioned between and remained within land use classes from 2000 to 2020. Assessing trends based on class changes allowed us to avoid conflating natural vegetation with fallows, as well as to assess EVI trends in pixels that had transitioned from grassland to cropland. Finally, we calculated average EVI trends within each burn frequency class. As we sought to assess whether fire hinders WE in natural vegetation, we masked urban, cropland, and mixed pixels. To compare EVI trends, we calculated the spatial means of May EVI_{med} for each class across each year of the study. We extracted the annual spatial means and variances of pixel values for the EVI of each class in each year. We then analyzed EVI trends using weighted least squares regressions, a common technique for analyzing vegetation change across large landscapes (Zhang et al., 2020).

2.6 | EVI trends and climatic variables

Finally, we assessed the relationship between EVI trends and two climatic variables previously found to be associated with WE: mean annual precipitation and mean annual temperature. We extracted temperature and precipitation data from the Era 5 Monthly climate dataset (ECMWF/ERA5_LAND/MONTHLY_AGGR) and calculated each variable's average annual values across natural vegetation pixels within the study area. We used linear regressions to relate temperature and precipitation to EVI trends within natural vegetation pixels.

3 | RESULTS

3.1 | Savanna woodland and cropland expanded at the expense of grassland

The study area experienced widespread conversion of grassland to woodland. The area of savanna woodland (>10% tree cover) increased by 54% between 1990 and 2020, expanding from 38.2% ± 3.87 to 58.8% ± 10.73 (335,309 km^2) of the study area (Figure 2). Grassland contracted by nearly two-thirds over the same period, from 50.6% ± 7.6% to 19.2% ± 2.9% of the study area (Figure 2e). Grassland area decreased by 13% between 2014 and 2020, declining proportionally faster than woodland or cropland expanded. Landcover change was distributed unevenly across the ecoregion (Figure 2). Shifts from grassland to woodland were concentrated in the ecoregion's northeast and southeast, areas with low human population densities, few roads, and high landmine densities (Mendelsohn, 2019). Closed woodland persisted in the ecoregion's center. Urban areas and bare ground made up <2% of the ecoregion over the study period.

To test whether woodland was expanding more quickly in areas experiencing canopy greening, we analyzed landcover change within pixels showing positive May EVI_{med} trends, a proxy for increasing canopy greenness. As expected, closed savanna expanded more quickly in areas showing positive greening trends than in the study area at large (89% versus 54% increase; Figure 2). Woodland expanded within greening pixels more rapidly after 2000, suggesting that WE accelerated.

Cropland area increased by 155% between 1990 and 2020, expanding from 8.3% ± 1.0% to 21.2% ± 2.7% of the ecoregion, with 94.7% of that increase occurring before 2014 (Figure 2c). Agricultural areas expanded only 3% between 2014 and 2020. Cropland expanded disproportionately outside of greening pixels, and expansion within greening pixels largely occurred before 2000 (Figure 2c). Most cropland expansion took place in the ecoregion's west, a densely populated highland region (Mendelsohn, 2019).

3.2 | Woody encroachment as measured through canopy greenness was widespread in natural vegetation

To test for WE trends, we analyzed May EVI_{med} trends, a proxy metric for canopy greenness. Nearly 10 times more land exhibited positive greenness trends than negative trends (Figure 3). EVI increased significantly in 25.9% of the study area (147,788 km^2) over the study period ($p<.1$; increase in at least 0.03 EVI units). By contrast, just 2.8% (15,923 km^2) of the study area showed decreasing EVI trends ($p<.1$; decrease in at least 0.03 EVI units; Figure 3).

Canopy greenness increased by 8.3% when averaged across pixels of pure natural vegetation in 2020, an annual increase of 0.36% ($p<.01$; Figure 4a). The average increase was 7.8% in woodland ($p<.01$) and 10.1% in grassland ($p<.01$). In contrast, average canopy greenness did not increase significantly in pixels designated as cropland or urban areas in 2020 ($p>.05$). Greenness also did not significantly increase in mixed pixels, defined as having 10%–90% cover of both natural vegetation and cropland ($p>.05$). The increasing trend through time explained 47.6% of the variation in mean EVI values within natural vegetation, with greater explanatory power in woodland (49.5%) than in grassland (40.4%; Table 1).

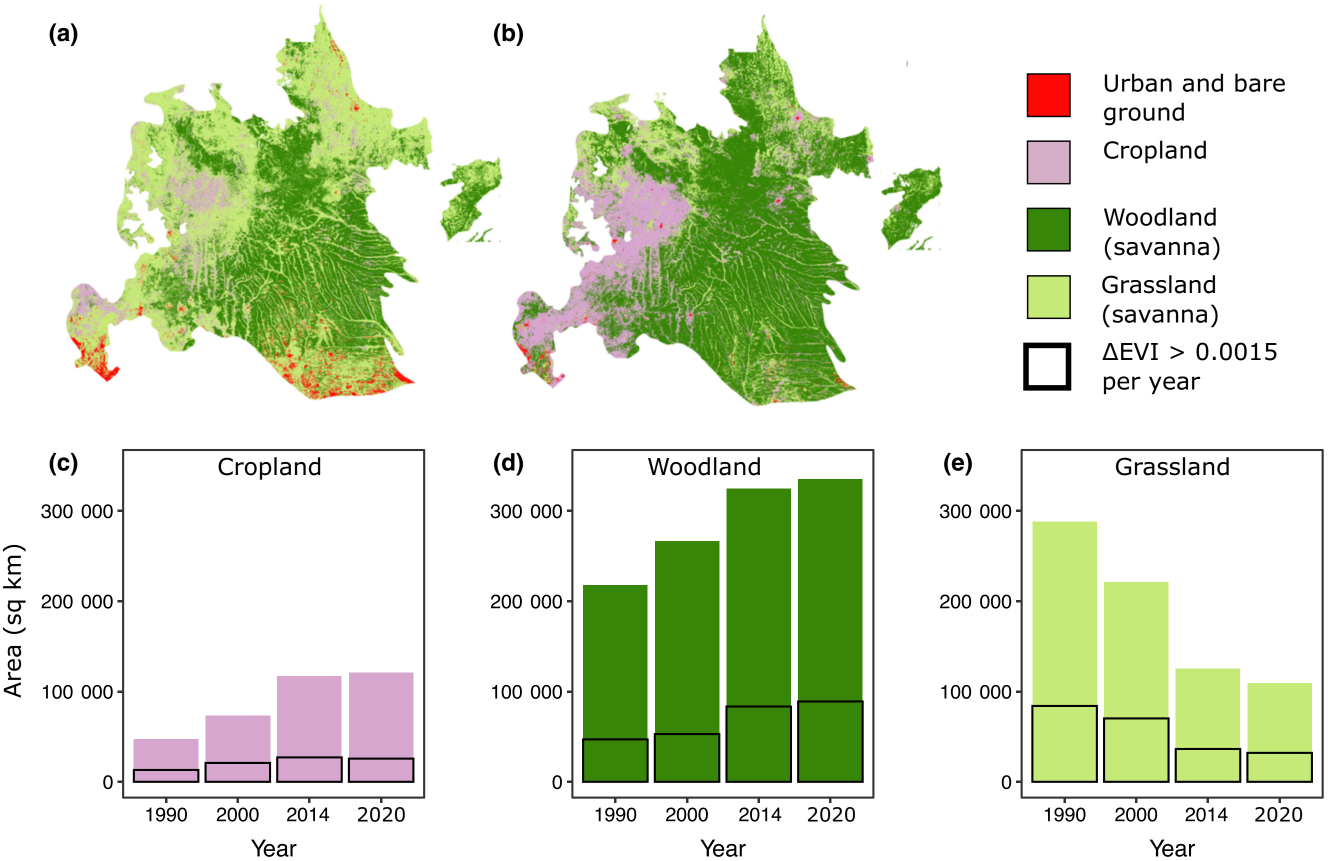

FIGURE 2 Mapping and quantifying land use change in the Angolan miombo woodlands. (a, b) show landcover of open savanna, closed savanna, cropland, and urban areas/bare ground in (a) 1990 and (b) 2020. Open savanna is defined as having <10% woody cover. Classifications were generated from Landsat imagery using a random forest classification trained on 5000 manually classified pixels. (c–e) Quantify the change in area since 1990 of the dominant landcover classes within the Angolan miombo woodlands, displayed in the maps above. The panels display changes in (c) cropland (d) open savanna (e) closed savanna. The bars outlined in black indicate areas of each land use class experiencing canopy greening according to the enhanced vegetation index (EVI) trend analysis. Data were extracted from a supervised classification of landcover in the ecoregion.

We also examined EVI trends in pixels that transitioned land use classes between 2000 and 2020 (Figure 4c–e). As expected, the greatest increase in canopy greenness occurred in pixels that transitioned from grassland to woodland (10.8%; $p<.001$, $r^2=.50$). In this vegetation class, the positive trend through time explained 50.3% of variation, the highest explanatory power of any land use class. Average canopy greenness also increased significantly in pixels that persisted as grassland between 2000 and 2020 (10.6% increase; $p<.01$; $r^2=.41$); in pixels that persisted as woodland (7.0% increase; $p<.01$; $r^2=.49$); and in pixels that experienced succession from cropland into woodland (9.4% increase; $p<.01$; $r^2=.37$). In this last category, less variation (37%) was explained by the positive trend through time than in other land use transition classes. Canopy greenness did not increase significantly in pixels that remained cropland between 2000 and 2020, or in pixels that transitioned from cropland and woodland to grassland ($p>.05$; Table 1).

Areas with positive EVI trends were concentrated along the ecoregion's periphery, in the northeast, southeast, and northwest (Figure 3). These positive trend areas border the higher rainfall Congolian savanna-forest mosaic to the north, and the lower rainfall *Baikiaea* savanna woodlands to the south. Areas with decreasing EVI were concentrated in the ecoregion's southwest and along the central agricultural frontier. Pixels showing no change were concentrated in ecoregion's center and east.

3.3 | EVI trends were not impacted by frequent fires

To understand how WE trends related to fire frequency, we assessed average EVI trends within burn frequency classes (Figure 4b). These were designated based on how many years each pixel burned over the study period. To isolate fire's impact on natural vegetation, we masked cropland, urban, and mixed pixels. Canopy greenness increased significantly across pixels in every burn frequency class, when values were averaged across natural vegetation pixels (Figure 4b; Table 1). Canopy greenness as measured by mean May EVI_{med} increased most quickly in areas that burned 15–20 of 20 years (10.7% increase; $r^2=.38$; $p<.01$).

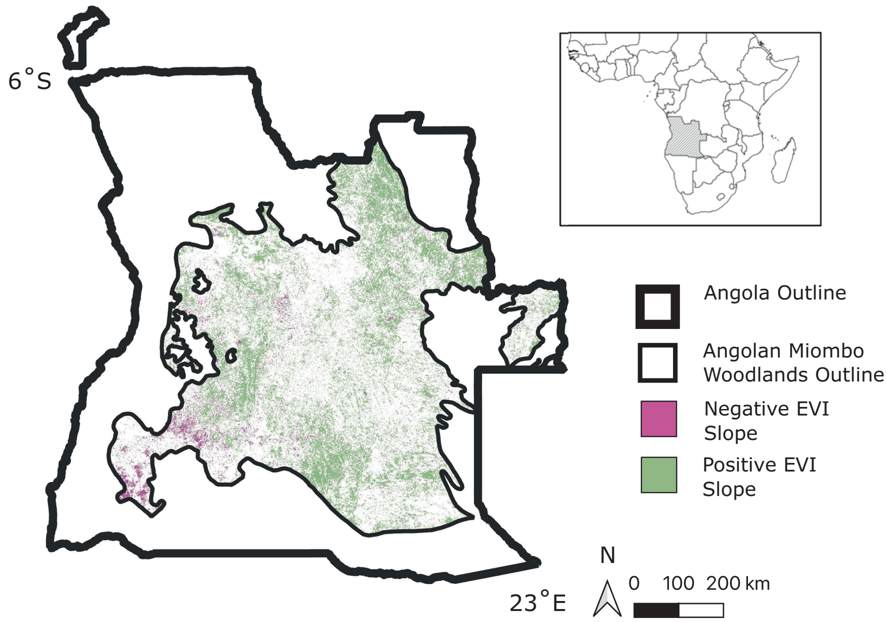

FIGURE 3 Trends of median May enhanced vegetation index (EVI), a proxy for canopy greenness, calculated within the Angolan miombo woodlands vegetation over the 2000 to 2022 study period. Trend values were calculated at 250m resolution. All the pixels presented on the map were masked at a level of confidence $p<.1$ and exhibited changes of at least 0.03 (positive trends) or −0.03 (negative trends) over the 20-year study period. 25.9% of pixels exhibited positive trends of least 0.03 ($p<.1$) and 2.8% of pixels exhibited negative trends of at least 0.03 ($p<.1$). The inset indicates Angola's location within sub-Saharan Africa. Map lines delineate study areas and do not necessarily depict accepted national boundaries.

May EVI_{med} increased least quickly in unburned pixels, although the positive trend was still significant (6.9% increase; $r^2=.47$; $p<.001$). That there was no significant relationship between burn frequency and May EVI_{med} trends suggests that even near-annual burning is not suppressing canopy greening in the Angolan miombo woodlands.

Pixels were distributed relatively evenly within burn frequency classes: 22.39% of the study area had no fire occurrence over the study period, and 32%, 18%, 13%, and 12% had fire occurrences of up to 5, 10, 15, and 20 years respectively (Figure S3). When assessed spatially, the most extensive area of high fire frequencies was in the ecoregion's northeast, a subregion exhibiting extensive WE, as measured both through canopy greenness trends and through conversion from grassland to woodland (Figure S3). The ecoregion's northwest, and southeast also exhibited high fire frequencies, while the central and southwest burned less frequently.

3.4 | Precipitation and temperature trends do not explain canopy greening

Finally, we assessed the relationship between canopy greenness and two relevant climatic variables: precipitation and temperature. There was no relationship between mean annual precipitation and mean annual canopy greenness, as measured through May EVI_{med} ($r^2=.03$; $p=.43$; Figure S5). There was a significant positive relationship between mean annual temperature and canopy greenness within natural vegetation ($r^2=.28$; $p=.01$). However, variation in canopy greenness was explained less well by rising temperature ($r^2=.28$) than by a linear trend over time ($r^2=.48$; Figure S5).

4 | DISCUSSION

The results reported here add to previous evidence that WE is combining with cropland expansion to alter a significant proportion of Africa's mesic savannas. We provide novel evidence that fire is not slowing WE in the Angolan miombo woodlands, one of Africa's least understood ecosystems. The analysis also highlights the unique threat to Angola's grasslands: between 1990 and 2020, 62% of the Angolan miombo woodlands' grasslands vanished, even as WE and cropland expansion altered just 34% of the ecoregion overall. Grassy ecosystems have a rich, unique, and threatened biodiversity unsuited to woodlands or forests (Murphy et al., 2016). The following discussion of the drivers of global change in the miombo woodlands can help policymakers conserve grassland biodiversity in Angola.

4.1 | Extent of Woody encroachment

Woody encroachment was found to be widespread in Angola, a result in line with previous continental and subcontinental-scale analyses. Two previous studies assessed WE across Africa by manually classifying canopy cover and by quantifying plant biomass using radar (McNicol et al., 2018; Venter et al., 2018). Both found

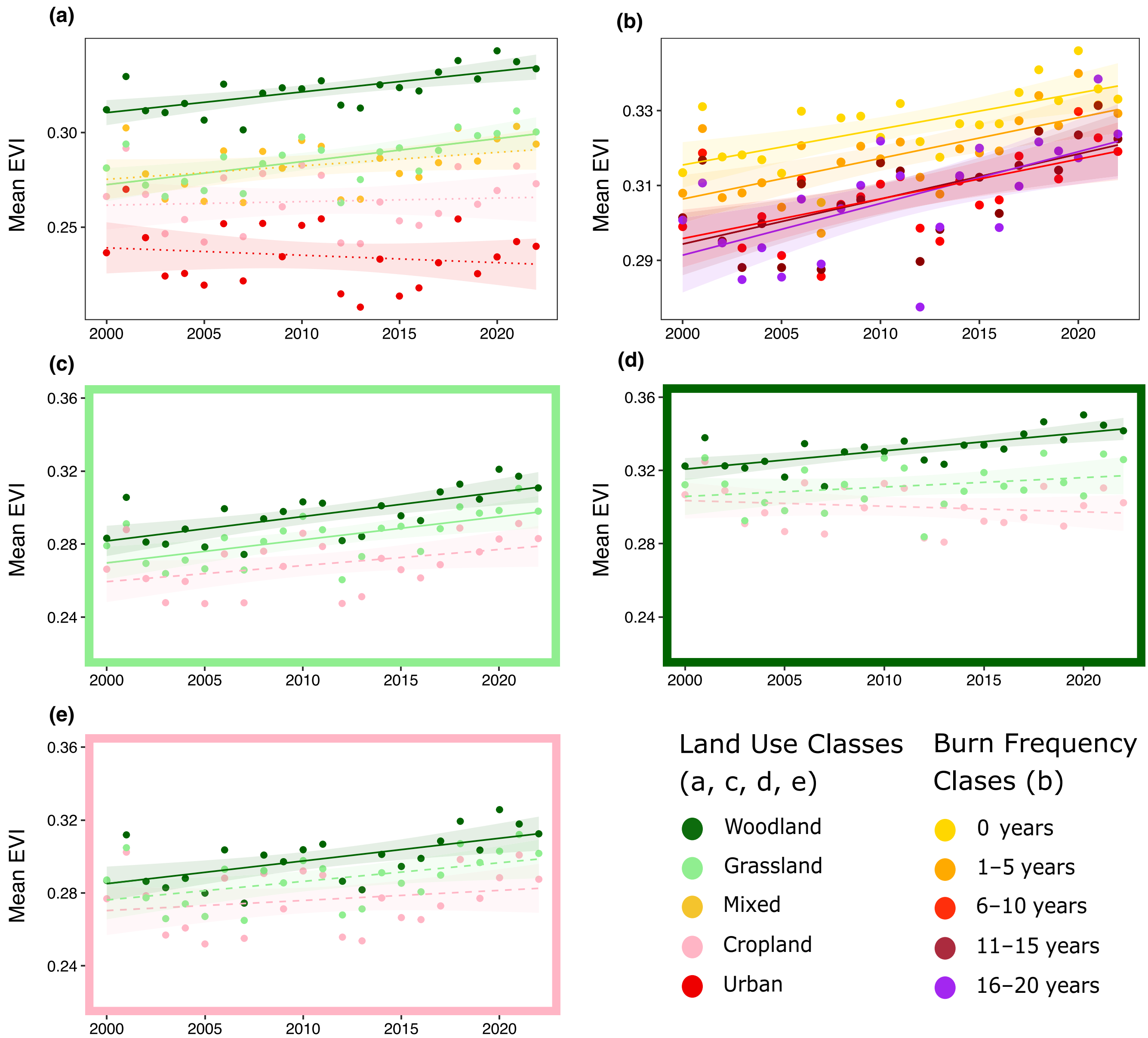

FIGURE 4 Time-series data for mean May enhanced vegetation index (EVI), a proxy for canopy greenness, averaged over pixels of different land use classes (a, c, d, e) and burn frequency classes (b). Points represent average annual values, solid lines represent significant linear trends ($p < .01$) and dashed lines represent insignificant linear trends. Shading represents 95% confidence intervals. Colored lines in (a, c, d, e) represent the 2020 land use classes of analyzed pixels. The panel outlines in (c, d, e) represent the 2000 land use classes of analyzed pixels. Mixed pixels in (a) include upscaled 250 m pixels comprising ≥10% 30-m pixels of both natural vegetation and cropland. For the burn frequency class analysis in (b), only pixels of pure natural vegetation were analyzed.

widespread WE in the Angolan miombo woodlands. A third study found decreasing woody cover in Angola from 1982 to 2006, but analyzed imagery from seasons inappropriate for capturing miombo canopy foliage (Mitchard & Flintrop, 2013). The results reported here provide further evidence of widespread WE using two additional independent methods: vegetation index analysis and landcover classification. We found that canopy greenness increased by 0.36% per year between 2000 and 2022, broadly in line with findings by Venter et al. (2018) that tree cover increased by 0.7% per year between 1986 and 2016 across Angola. We have further confidence that WE is occurring due to the concurrence between our independent landcover change and canopy greenness analyses: we found that canopy greenness increased most rapidly and consistently in pixels that transitioned from grassland to woodland. This agreement suggests that the satellite-derived proxies for WE are recording real ecological change.

The joint analysis of WE, landcover change, and fire frequency reveals three key features of WE's distribution in Angola. First, WE has overwhelmingly occurred within remaining natural vegetation. Canopy greenness increased rapidly in grassland and woodland, increased moderately in recovering fallows, and did not increase in mixed-used pixels and cropland. Second, WE occurred across the

TABLE 1 May EVI_{med} trends, a proxy for canopy greenness, were averaged across 2020 landcover classes, 2000–2022 landcover transition classes, and burn frequency classes. Values for burn frequency classes were calculated within pixels of pure natural vegetation. Trends were calculated using weighted linear regressions.

2020 Landcover	2000 Landcover	Burn Freq.	R^2	*F* stat	*p* value	Slope	Change in EVI (annual)	Change in EVI (total, 2000–2022)
By 2020 landcover								
Urban			.04	.80	.3822	−0.0004	−0.18%	−4.03%
Cropland			.01	.13	.7225	0.0002	0.06%	1.43%
Mixed			.13	3.21	.0876	0.0007	0.24%	5.61%
Grassland			.40	14.24	.0011	0.0012	0.44%	10.09%
Woodland			.50	20.59	.0002	0.0011	0.34%	7.85%
Natural			.48	19.12	.0003	0.0011	0.36%	8.27%
By landcover transition								
Grassland	Grassland		.42	14.96	.0009	0.0013	0.46%	10.62%
Woodland	Grassland		.50	21.22	.0002	0.0014	0.47%	10.82%
Cropland	Grassland		.20	5.20	.0332	0.0009	0.35%	7.96%
Woodland	Woodland		.49	20.54	.0002	0.0010	0.30%	6.97%
Cropland	Woodland		.03	.62	.4406	−0.0003	−0.09%	−2.12%
Grassland	Woodland		.12	2.87	.1053	0.0006	0.20%	4.64%
Cropland	Cropland		.05	1.07	.3132	0.0005	0.18%	4.12%
Woodland	Cropland		.37	12.41	.0020	0.0012	0.41%	9.38%
Grassland	Cropland		.24	6.64	.0176	0.0010	0.35%	8.04%
By burn frequency class								
Natural		0	.47	18.82	.0003	0.0010	0.30%	6.94%
Natural		1–5	.49	20.33	.0002	0.0011	0.34%	7.80%
Natural		6–10	.40	14.29	.0011	0.0011	0.35%	7.99%
Natural		11–15	.44	16.2	.0006	0.0012	0.40%	9.30%
Natural		16–20	.38	13.07	.0016	0.0014	0.46%	10.65%

gradient of tree cover and fire frequency. Canopy greenness increased significantly across pixels of both grassland and woodland and across all burn frequencies. Third, WE was distributed widely but unevenly within the ecoregion. The ecoregion-sized scale of the analysis allowed us to analyze the spatial distribution of WE in greater detail than in previous studies (e.g., Cabral et al., 2011; Palacios et al., 2015). Both the classification and EVI trend analysis suggest that greening was concentrated near the ecoregion's northern and southern borders, and rarer in the ecoregion's center. The only region experiencing negative greenness trends was the southwest. This region's reliance on cattle ranching is unique within the Angolan miombo woodland (Huntley, 2023). Our results support evidence that cattle overstocking, charcoal gathering, and drought are transforming this region's woodland into shrubland (Huntley, 2023).

The ability to ground truth this study's results is constrained by the absence of long-term plot data and the limited accessibility of rural Angola. Few roads and numerous landmines make a rigorous ground-truthing protocol difficult to carry out. We validated our classification results against high-resolution satellite imagery available. However, high-resolution time-series imagery is inconsistently available on Google Earth, so we were unable to verify EVI trends using it. This gap raises the possibility that long-term changes in tree or grass phenology over the study period could affect the results reported here. Such changes have not to our knowledge been reported in the miombo woodlands but the ecosystem is understudied (SEOSAW, 2020).

4.2 | Drivers of Woody encroachment

While a consensus has emerged that WE is widespread across the miombo woodlands, its causes remain contested, with previous studies proposing both global, climatic factors and local, disturbance factors (Luvuno et al., 2018; Sagang et al., 2022; Venter et al., 2018). Hypothesized drivers of WE include changes to fire, landscape fragmentation, temperature, precipitation, herbivory, and atmospheric CO_2 concentrations.

The results here suggest that fire is unlikely to be controlling WE in the Angolan miombo woodlands. This finding contrasts with the outcomes of fire experiments in the miombo woodlands, which have suggested that frequent fires inhibit woody vegetation cover (Furley et al., 2008; Ryan & Williams, 2011). It also contrasts with findings that fire suppressed WE in Cameroonian mesic savannas (Sagang et al., 2022). What explains these discrepancies? One explanation is that fire experiment results have been distorted by pre-clearing treatments. Without such treatments, fire effects alone are unlikely to maintain open ecosystems under elevated CO_2 conditions (Veenendaal et al., 2018). Future work should systematically analyze the long-term impacts of fire regimes on WE across mesic African savannas. If, as these results suggest, other drivers are constraining fire's capacity to maintain the miombo's grasslands, global change would threaten fire-dependent biodiversity and ecosystem services.

A second set of hypotheses suggests that landscape fragmentation is driving WE. Expanding cropland suppresses fire and herbivory in remaining patches of natural vegetation, releasing woody vegetation from disturbance. If landscape fragmentation were driving WE, we would expect to see canopy greening in mixed pixels, where natural vegetation and cropland are interspersed. Instead, canopy greenness advanced most quickly in pixels of pure natural vegetation. Moreover, greening areas were concentrated in the ecoregion's northeast and southeast, regions with little agriculture, low population densities, and unfragmented vegetation cover. Woody encroachment appears to be advancing in areas of natural vegetation relatively unimpacted by human land use change, suggesting that a global rather than local driver may be responsible.

An exception is the western highlands, a densely populated region showing positive greenness trends but little conversion of grassland to woodland. What explains this discrepancy? One possibility is that positive greenness trends in this region are explained by recovering fallows. This zone has experienced rapid agricultural expansion since 1990, and perhaps some abandoned fields have not been adequately captured by the land use classification (Safarik, 2020). Alternatively, the positive trend pixels may be capturing regional changes in crop phenology or in crop greenness. Investigating the factors driving positive EVI trends within this cropland-savanna mosaic is a rich area for future study.

This study did not directly assess the impact of herbivory on WE in the study area, as little accurate data on herbivory in Angola exists. However, we can infer from other analyses that changes to herbivory are unlikely to be driving the observed WE. Biomass in the Angolan miombo woodlands is overwhelmingly consumed by fire, not by herbivores (Archibald & Hempson, 2016). Previous work has found that historical herbivore biomass in the Angolan miombo woodlands was low and that contemporary biomass has not changed much in the ecoregion (Archibald & Hempson, 2016). Moreover, in the Mozambican miombo woodlands, where wartime hunting did significantly decrease herbivore populations, suppressed herbivory was not associated with increasing woody cover (Daskin et al., 2016).

If disturbance is not driving WE in the study area, climatic factors may be. This study found that changing precipitation was not associated with canopy greenness in the ecoregion. Rising temperature was weakly associated with canopy greenness. Time, a proxy for rising CO_2 concentrations, was strongly associated with increasing canopy greenness within areas of natural vegetation. There is some evidence that trees in the miombo woodlands will benefit disproportionately from rising CO_2 due to their root-suckering propagation strategy. By enhancing root-suckering, miombo trees directly benefit from increasing belowground CO_2 reserves (Kgope et al., 2010; Wakeling & Bond, 2007). Climatic factors are less easily manipulated than disturbance factors at plot scales, so it is difficult to experimentally validate relationships between rising temperature, rising CO_2 and WE. If fire and herbivory cannot arrest WE, conservation management strategies would need to manipulate anthropogenic disturbances such as charcoal gathering and to focus on adaptation.

Like WE's causes, its ecological character remains contested and understudied in the miombo woodlands (SEOSAW, 2020). It is unclear whether the canopy greening trends observed through satellite imagery indicate (a) increases in the canopy cover of savanna tree species; (b) increases in the cover of shrubby vegetation or thicket; or (c) the transition of savanna woodland into a closed canopy forest formation comprising Congolian rainforest or Zambezian *Cryptosepalum* dry forest species. The analyses found that WE is concentrated discontinuously on the ecoregion's peripheries. This raises the possibility that different forms may be occurring in different subregions. For example, the wetter northern portion might be experiencing transformation into closed canopy forest and the drier southern portion encroachment by shrubs or thicket, a common process in arid savannas (Stevens et al., 2016). Fieldwork-based studies are needed to assess how different forms of WE impact the miombo woodland's biodiversity and ecosystem services.

4.3 | Drivers of cropland expansion and deceleration

In addition to woody cover, land cover changed dynamically over the last 30 years. Cropland expanded rapidly in Angola's miombo woodlands until 2014 and decelerated afterward. In all, cropland was found to have expanded by 155% in 30 years, just below the 160% expansion reported by Potapov et al. (2022). Cropland expansion was distributed unevenly in the ecoregion. Until 2000, expansion was concentrated in the western highlands, which historically supported intensive agriculture but saw output collapse by 70%–95% during the 1975–2002 civil war (Safarik, 2020). Since 2000, an agricultural frontier has developed, with cropland expanding northeastward out of the highlands (Figure 2). The development of a post-conflict agricultural frontier has been reported by previous field-based and remote-sensing studies of Angolan agriculture (Mendelsohn, 2019; Schneibel et al., 2017).

The deceleration in cropland after 2014 has not been reported before, and contrasts with warnings that cropland expansion will accelerate in Angola, the miombo woodlands, and savannas globally (e.g., Tilman et al., 2017; World Bank, 2019). We provide three hypotheses to explain the slowdown. First, the collapse of oil prices in 2014, which account for 89% of Angola's export revenues, decreased the fertilizer and seed subsidies paid to subsistence farmers (OPEC, 2021; Safarik, 2020). Costlier inputs may have slowed expansion. Second, Angola's well-documented and rapid rural-to-urban migration may be slowing expansion, as a stagnant rural population needs less new cropland (Safarik, 2020). Third, the agricultural frontier may be physically limited by the Kalahari Sands soil formation. The Kalahari sands' low nutrient concentration likely hinder agriculture to the east of the present agricultural frontier (Huntley, 2023).

4.4 | Conservation and governance implications

Both cropland expansion and woodland expansion occurred at the expense of grasslands. The unique biodiversity within Angola's grassy ecosystems are likely to be especially threatened by global change (Huntley & Ferrand, 2019). This threat may be moderated by the low commercialization of Angola's agricultural system, with just 2%–3% of Angolan cropland farmed industrially (Safarik, 2020). In addition, some cropland expansion over the study period may be the recultivation of colonial-era plots, given the collapse in agricultural production during the 1974–2002 Angolan civil war (Safarik, 2020). Nevertheless, conservation strategies should highlight the biodiversity within Angola's rapidly vanishing grassy ecosystems. Because Angola is experiencing both food insecurity and biodiversity loss, decision-makers will need to balance conservation with food production (Becker-Reshef et al., 2020; Huntley, 2023) There is an urgent need to understand the causes of Angola's agricultural expansion and deceleration, in order to attain that balance. Decision-makers will also need to actively manage woody cover in protected areas spared from agriculture, if they are to successfully conserve grassland species. Combining remote sensing with a sociological study of Angola's agricultural systems and protected areas is an important area of future research (Vijay & Armsworth, 2021).

Finally, the comprehensive scope of ecoregion-wide remote sensing results can usefully challenge assumptions about ecosystem change based on individual perceptions. Across the miombo woodlands, there exists a widespread perception that logging and charcoal production are converting the miombo woodlands to grassland and shrubland (Huntley, 2017; Mendelsohn, 2019; World Bank, 2019). In Angola, deforestation and charcoal are consistently mentioned as threats to the miombo woodlands in policy reports (e.g., National Biodiversity Strategy And Action Plan, 2019–2022; 5th National Report on Biodiversity in Angola, 2007–2012). Yet to the best of our knowledge, no government reports, laws, or policies discuss WE. We suggest that the spatial distribution of WE may be obscuring its extent from practitioners, as research on Angolan ecology is concentrated in southwest Angola, the sole subregion exhibiting widespread negative EVI trends (Figueira & Lages, 2019). Additionally, casual and scientific observations of the miombo woodlands are concentrated around roads and towns, the areas most affected by logging and charcoal gathering (Mendelsohn, 2019). In contrast, WE is concentrated in remote areas difficult for research teams to access (Figueira & Lages, 2019). Ecoregion-scale remote sensing analyses can complement empirical fieldwork by providing data on these inaccessible, under-researched landscapes.

5 | CONCLUSIONS

Our results indicate that widespread WE and cropland expansion are simultaneously transforming the Angolan miombo woodlands. Global change has significantly altered over one-third of the ecoregion in the last 30 years, while an additional 8% of the ecoregion was converted to cropland before the study's timeframe. The results corroborate previous studies finding widespread greening in African savannas (García Criado et al., 2020; Venter et al., 2018), while extending results into one of the world's least-studied and understood ecoregions (Russo et al., 2019).

In addition, WE is occurring in areas that burn extremely frequently (>15 of the last 20 years), suggesting that global drivers such as rising temperature and CO_2 concentrations may be outweighing local drivers such as fire and land use change. While increasing woody cover can enhance savanna carbon sequestration, it degrades ecosystem functions such as grazing capacity and water provision (Luvuno et al., 2018; White et al., 2022). The uncertainty around WE's impacts in the miombo woodlands highlights the need for fieldwork. We affirm calls to dramatically expand research on global change in neglected, misunderstood, and threatened grassy ecosystems (Bond & Parr, 2010; Parr et al., 2014).

These results have implications for ecosystem management and biodiversity conservation in the miombo woodlands. First, the results complicate calls to manage WE by manipulating disturbance, as they suggest that neither fire nor herbivory are likely to arrest WE in the Angolan miombo woodlands. Second, the results highlight the need to address cropland expansion and WE jointly, as dual threats to savanna biodiversity (Abreu et al., 2017; Tilman et al., 2017). Analyses premised solely on habitat loss driven by land use conversion will underestimate risk to endemic savanna species. Instead, biodiversity risk assessments must account for the ways disturbance, rising CO_2, and climate change interact to shift species composition within savannas. These findings will be useful as Angola rebuilds its conservation system post-conflict and coordinates with neighboring countries to conserve Africa's largest savanna.

Finally, we emphasize the value of focused, ecosystem-level, and national-level analyses as a complement to global and local studies, including the continental scale analyses prominent in global change ecology (Xiong et al., 2017). By focusing on a single ecoregion, we were able to improve the accuracy of long-term cropland mapping in the miombo woodlands from ~60% to 86% (Xiong et al., 2017). The creation of land cover classifications with highly accurate cropland classes is essential for mapping habitat loss and WE, key drivers of biodiversity loss and carbon emissions. We suggest future researchers coordinate creating ecoregion-scale maps of African savannas. Another advantage of national-level analyses is that they expose the ways a country's unique history and geography can moderate how global change affects its ecosystems. For example, we hypothesize that in Angola, low oil prices and post-conflict, urban-to-rural migration dynamics contributed to the deceleration of cropland expansion since 2014. Angola's oil dependence and post-conflict politics are unique in the miombo region and likely shape its global change ecology in distinctive ways. However, the nature of these relationships between politics and ecology in Angola is poorly understood and is a rich area for future study.

AUTHOR CONTRIBUTIONS

Ty Loft: Conceptualization; data curation; formal analysis; investigation; methodology; validation; visualization; writing – original draft; writing – review and editing. **Nicola Stevens:** Supervision; writing – review and editing. **Francisco Maiato Pedro Gonçalves:** Validation; writing – review and editing. **Imma Oliveras Menor:** Methodology; supervision; writing – review and editing.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available on Google Earth Engine at https://earthengine.google.com/. The datasets used are the MCD64A1.061 MODIS Burned Area Monthly Global 500m (https://doi.org/10.5067/MODIS/MCD64A1.061); USGS Landsat 5 Surface Reflectance Tier 1; USGS Landsat 7 Level 2, Collection 2, Tier 1; and USGS Landsat 8 Level 2, Collection 2, Tier 1. The processed data is available from Figshare at https://doi.org/10.6084/m9.figshare.c.7036589.v1.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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