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Mapping Human-Fire Interactions: Challenges and Innovations

Belief Network Assessment of Fire Management in East African Savannas Under Socioeconomic and Climate Change

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ABSTRACT

Fire regimes across East Africa's savanna conservation landscapes increasingly reflect interconnected ecological and biocultural breakdown, reinforcing systemic vulnerabilities. Yet colonially inherited fire suppression and exclusionary tenure arrangements continue to overlook the ecological value of pyrodiversity and the stewardship roles of Indigenous and local actors. This study presents a novel probabilistic systems model for evaluating seven predictive, exploratory, and normative fire management approaches across best-, intermediate-, and worst-case socioeconomic–climate futures. The SAV Belief Network (SAV BN) advances BN modelling by explicitly incorporating system complexity and future uncertainty through systemic feedbacks, bidirectional interactions, and high node complexity, supporting rigorous scenario analysis in data-limited contexts. Grounded in empirical data from the Tsavo Conservation Area, the model reflects relational epistemologies that emphasise human–nature interdependencies and place-based knowledge. No approach proved capable of simultaneously achieving wildfire mitigation, ecological integrity, and livelihood resilience. Most reduced wildfire risk and, under best-case trajectories, improved livelihoods; however, even highly normative approaches only slowed, rather than halted or reversed, ecological degradation. Fire suppression and carbon-oriented strategies focused on above-ground biomass accounting intensified ecological decline, particularly under inequitable futures, while locally conceptualised bottom-up strategies failed to confront entrenched colonial legacies and reproduced exclusionary power structures and degradation narratives. These findings highlight the need to reimagine fire regimes as products of multi-scalar, path-dependent dynamics shaped by institutional erosion, political–economic preferences, and contested land claims. Addressing this complexity requires moving beyond 'integrated' or 'community-based' framings towards historical institutional and environmental justice approaches that centre representation and equity.

Abbreviations: AGB, above-ground biomass; ALL, protected area and community lands; BBN, Bayesian Belief Network; BGB, below-ground biomass; BN, Belief Network; CBFiM, Community-Based Fire Management; CDI, Climate Delay and Inequality; CL, community lands; EDS, early dry season; ENSO, El Niño-Southern Oscillation; FFCD, Fossil-Fuelled Climate Denial; FHS, fuel harvesting scheme; FSP, fire suppression and prevention; GCA, Green Climate Ambition; GDP, Gross Domestic Product; HGS, Holistic Grazing Scheme; IOD, Indian Ocean Dipole; LDS, late dry season; MAP, mean annual precipitation; OS, overshoot; PA, protected area; PFM, Participatory Forest Management; RCP, representative concentration pathway; REDD+, reducing emissions from deforestation and forest degradation in developing countries; SAV BN, Savanna Belief Network; SBEA, Savanna Burning Emissions Abatement; SES, social–ecological systems; SSP, shared socioeconomic pathway; TCA, Tsavo Conservation Area.

1 | Introduction

Wildfires are complex 'wicked problems', marked by inherent uncertainty and limited data availability, which constrain the accurate prediction of ecosystem trajectories and contribute to ongoing mismanagement of global public goods and natural resources (Sills and Jones 2018; Geary et al. 2020). In Sub-Saharan Africa, over 80% of large savanna fires occur in the late dry season (LDS), primarily in sparsely populated protected areas and plantations (Archibald 2016; Lipsett-Moore et al. 2018). Compared to early dry season (EDS) fires, LDS fires are hotter, drier, and more intense and are associated with higher greenhouse gas emissions and woody cover loss (Russell-Smith et al. 2021). Consequently, they are often framed as intentional 'hungry beasts' on which to wage war against (Marghetis and Matlock 2024).

Across East African conservation landscapes dominated by fire-adapted savannas, colonially inherited fire suppression policies and exclusionary land reforms have precipitated a pyric transition away from heterogeneous, small-scale burning regimes towards a homogeneous, wildfire-dominated system. Within protected areas, suppression has driven fuel accumulation, resulting in extreme wildfires that exceed current firefighting capacities, thereby reinforcing the 'wildfire paradox' (Tedim et al. 2019; Croker et al. 2023a). Conversely, outside protected areas, livestock have replaced fire as the dominant fuel consumer. Overgrazing and the overexploitation of herbaceous vegetation have driven a marked decline in total burned area, accelerating biodiversity loss, soil erosion, and the expansion of fire-resistant woody species (Osborne et al. 2018; Coverdale et al. 2021). These dynamics are further reinforced by population growth, urbanisation, agricultural intensification, and the sedentarisation of historically mobile pastoralists (Korf et al. 2015; Archibald 2016; Andela et al. 2017).

This juxtaposition of opposing fire regimes within and outside protected areas reflects a broader wildfire paradox in complex adaptive systems; one that is symptomatic of coupled ecological–biocultural hysteresis (Holling 2001; Gunderson and Holling 2002; Lyver et al. 2019). This refers to the erosion of interconnected ecological and biocultural processes that historically sustained diverse savanna ecosystems and sociocultural communities; therefore, amplifying systemic vulnerabilities related to resource depletion, biodiversity loss, conflict, and reduced carbon sequestration (Gil-Romera et al. 2011; Pyne 2018; Loehman 2020; Osborne et al. 2018). While most wildfire paradox framings emphasise ecological hysteresis, the spatial and temporal reorganisation of local communities has also given rise to forms of subaltern politics rooted in resource inequalities perpetuated by colonial and post-independence governance structures (Otero and Nielsen 2017). Fire regimes are, therefore, often reminiscent of asymmetrical biopolitical configurations or, in other words, the systematic marginalisation of local worldviews and claims to land and resources based on ancestral precedence, cultural histories, and adaptive livelihoods (Rasmussen and Lund 2018; Lyver et al. 2019; Sharifian et al. 2022).

These challenges underscore the need for equitable, bottom-up fire governance that recognises the dual ecological role of fire in savanna ecosystems and centres Indigenous representation in decision-making. Such approaches aim to empower local communities in defining fire objectives and implementing prevention, control, and burning practices, thereby fostering cooperation and reducing conflict (Tedim et al. 2019; Ganz et al. 2003; FAO 2011; Croker et al. 2023a).

Despite growing interest in bottom-up fire management, its conceptualisation and implementation have largely been led by Western researchers and external agencies seeking a globally standardised, extractable approach (Croker et al. 2023a). This has often assimilated diverse fire-user communities into a singular epistemic tradition, limiting their meaningful participation (Mapaure et al. 2009; Pollini 2010; Alvarado et al. 2018). Attempts to revitalise traditional fire practices through 'cultural burning' and 'good fire' initiatives have coincided with a rise in market-based climate mitigation projects (Petty et al. 2015; Neale et al. 2019). Under the banner of nature-based solutions and carbon offsetting, these initiatives aim to increase above-ground carbon sequestration and reduce emissions by suppressing LDS fires, thereby supporting national and global climate goals.

Today, 'bottom-up fire management' refers both to interventions that devolve significant legal rights and authority to local communities, and to state-led projects in which select local actors who traverse subsistence, social, and political economies are enlisted in centrally organised burning programs designed to strengthen state control over rural affairs (Smith et al. 2024; McKemey et al. 2020). These divergent interpretations reflect a broader discursive landscape in which the term is strategically mobilised to legitimise competing governance models (Krah et al. 2020). Across East Africa and the scientific literature, such framings are shaped by cultural heritage, land-use values, and the intended aims of research, policy, and development agendas, typically prioritising fire suppression (Croker et al. 2023a). This reveals an enduring structural asymmetry between political–economic institutions and local governance systems, where contested biopolitical relationships risk undermining equitable and effective resource management and sustainable development (Bluwstein 2018; Millhauser and Earle 2022).

Recognising these limitations, we evaluate the potential of seven alternative fire management approaches to address the wildfire paradox, improve savanna health, and reduce livelihood vulnerabilities across a savanna-dominated conservation landscape in East Africa. We develop a novel Belief Network (BN) to probabilistically model their outcomes under best-, intermediate-, and worst-case socioeconomic and climate trajectories up to 2100.[1] Grounded in data derived from extensive fieldwork informed by principles of decolonisation (Croker and Ford 2022; Croker et al. 2022, 2024), our regionally scalable BN integrates insights from both published literature and the relational experiences of local actors in Kenya's Tsavo Conservation Area. It expands on our previous work on Community-Based Fire Management (CBFiM) and Indigenous-led Savanna Burning Emissions Abatement (SBEA) in East and Southern Africa (Croker et al. 2023a, 2023b), while prioritising actor representation within the model's algorithm to mitigate the reproduction of hegemonic fire governance narratives (Star and Griesemer 1989; McCann et al. 2006; Hulme 2016).

This study demonstrates the value of BNs in data-limited, highly uncertain social–ecological contexts (Stafford et al. 2015; Tedim et al. 2019), particularly in post- and settler-colonial contexts where fire-user communities remain socially, politically, and geographically marginal. By evaluating how alternative fire management approaches navigate and address local expressions of fire's future 'wicked problems', we reveal the trade-offs and synergies among desired outcomes and within the network's underlying relationships (Epstein et al. 2013; Marshall 2015; Croker et al. 2023a). This framework can also be adapted to model site-specific conditions (e.g., protected areas, arid–eutrophic savannas), supporting the implementation of contextually grounded and locally meaningful policy and management interventions.

2 | Theoretical Framework

Our analysis integrates social–ecological systems (SES) thinking, historical institutionalism, and decolonising methodologies to recentre fire as an adaptive, path-dependent, and politically contested phenomenon. Together, these complementary frameworks form a bricolage architecture for analysing fire regimes, enabling a holistic and contextually grounded assessment of modelled wildfire, ecological, and livelihood outcomes across divergent futures.

SES thinking recognises East African savannas as dynamic, non-equilibrium systems shaped by pyrogeographic interactions among climatic, ecological, and sociocultural processes across nested 'panarchies', through which disturbances and related externalities propagate over space and time (Gunderson and Holling 2002; Ostrom et al. 2007). Fire suppression and exclusionary tenure regimes have eroded the self-organised governance systems that co-evolved with human fire-use practices and biodiverse grasslands over millennia (Bond and Keeley 2005; Pooley 2021), weakening ecological–biocultural feedbacks. SES thinking recentres institutional diversity, trust, and local agency as foundations for adaptive, bottom-up fire management (McGinnis and Ostrom 2014). Furthermore, it conceptualises human-induced climate change as an endogenous component of the fire regime rather than an external or separate driver, recognising how biogeophysical conditions interact with topography and sociocultural dynamics to generate emergent and increasingly novel fire behaviour (Ratter 2012; Bacciu et al. 2022).

Historical institutionalism examines how path dependencies and institutional legacies shape the political 'action situation': the rules, norms and organisations that determine who participates in fire management and what strategies are available (Fioretos 2011). Viewing institutions as choice domains that structure strategic behaviour across Tsavo Conservation Area reveals how past interventions continue to influence how local actors interpret challenges, negotiate authority, and evaluate governance options (Thelen 1999; Bucheli and Wadhwani 2013; Fioretos et al. 2016). Because institutional rules evolve unevenly across space and time, understanding actor behaviour as an emergent property of contingent interactions among agency, context, and institutional change helps to conceptualise the research context as a temporally layered configuration of institutional dynamics that simultaneously enable and constrain alternative fire governance approaches (Schmidt 2008; Jackson 2009).

Decolonising methodologies inform the epistemic dimension of this lens by recognising research as a political act and knowledge production as embedded within global power hierarchies (Smith 2021). They challenge the presumed universality of Western scientific frameworks, advocate for the unassumed inclusion of diverse knowledge systems (Thambinathan and Kinsella 2021), and reveal how, in the absence of continuous reflexivity, they can reproduce disciplinary norms and colonial paradoxes (Croker et al. 2024). Applied to fire governance, decolonial principles highlight how narratives of 'community-based' approaches have often been shaped by external researchers, assimilating heterogeneous local fire practices into a single, extractable epistemic frame. Insights from a recent Decolonising Fire Science workshop series (Croker et al. 2022, 2024; Croker and Ford 2022) underscore the importance of positionality, legitimacy, and justice in shaping inquiry and representation in contested fire contexts.

3 | Methods

Bayesian Networks model conditional dependencies among system variables, enabling probabilistic reasoning under uncertainty (Hulme 2016). By integrating heterogeneous datasets with local and expert knowledge, Bayesian Networks act as boundary objects that support dialogue across stakeholders with divergent management aspirations (Star and Griesemer 1989), helping identify plausible pathways to desired outcomes and quantify how changes propagate through social–ecological systems (Newton 2009; Barbrook-Johnson and Penn 2022).

Building on established applications of Bayesian Belief Networks (BBNs) in environmental science (Aguilera et al. 2011), we present a BN (herein referred to as 'SAV BN') co-developed with local actors and experts to model complex systems dynamics in data-limited fire management contexts, for example where interactions are experiential rather than formally documented, evidence for alternative management approaches is limited, and future social–ecological trajectories remain highly uncertain. Relative to traditional BBNs, key advances include: (i) the incorporation of feedbacks and bidirectional interactions, (ii) inclusion of variables without well-documented causal relationships, and (iii) support for >80 nodes without compromising model integrity. In the absence of robust empirical data, BNs also facilitate computational sensitivity analyses to identify influential edges in the network, whose parameters encode both certainty and magnitude of effect (Stafford et al. 2015; Dominguez Almela et al. 2024). This addresses a common limitation whereby sensitivity analyses are omitted due to concerns over reliance on expert-informed parameters (Barton et al. 2012; Busch et al. 2012; Landuyt et al. 2013).

The model was developed through a four-step mixed-methods process integrating participatory elicitation, expert

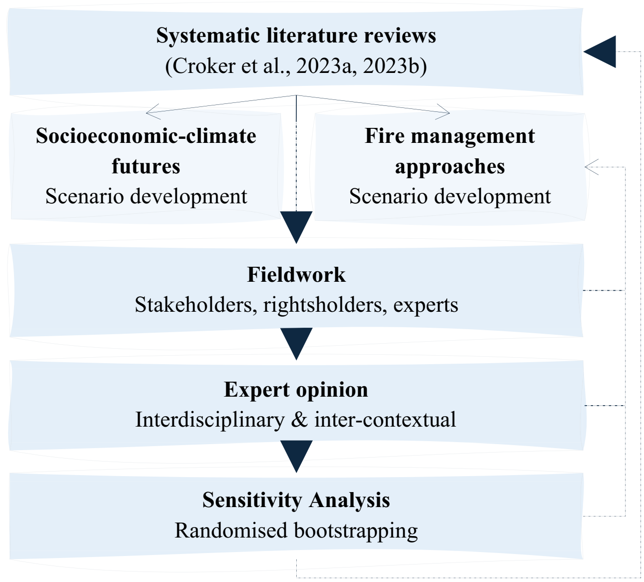

FIGURE 1 | Iterative four-step model parameterisation and scenario development process for SAV BN.

judgement, and computational modelling, grounding conditional independence assumptions in experiential knowledge systems (Figure 1). The model evaluates spatially explicit, landscape scale wildfire, ecological and social dynamics under seven predictive, exploratory, and normative fire management approaches across an East African savanna conservation landscape (750–1500 mm MAP) spanning protected areas (PAs) and community lands (CLs). Although BNs are typically non-temporal[2] (May et al. 2019), fire management outcomes are path dependent, shaped by interacting pyrogeographic processes across nested panarchies (Ostrom et al. 2007; Garmestani et al. 2023). SAV BN was therefore parameterised to project system dynamics to 2100, and each approach was simulated under three socioeconomic–climate futures using the *BBNet* package in R (Dominguez Almela et al. 2024).

The full model database, including detailed node descriptions, interactions, scenario narratives, and intervention measures, is available online (Croker 2024), while extended methodological information can be found in the Supporting Information and in Croker (2025).

3.1 | Case Study Site

Fieldwork was conducted in July–December 2022. Tsavo Conservation Area spans precipitation-limited grassy savannas in the lowlands and disturbance-driven woody savannas in the highlands, where pyrodiverse fire regimes sustain bistable tree–grass dynamics (Staver and Levin 2012; Schertzer et al. 2015; Laris et al. 2016). As a social–ecological frontier and wildlife–livestock interface (Jori et al. 2021), it contains overlapping yet contested tenure regimes, including private ranches, Maasai group ranches, and three national parks. The region's fire regime reflects competing land-use values and rapid livelihood transitions amid ongoing land reforms (Kenya's Community Land Act 2016). Proximity to the port of Mombasa has intensified land pressures, exposing customary systems to illegal activities and reterritorialisation, reinforcing an ecological–biocultural wildfire paradox (Catley et al. 2012; Scoones 2021; Croker 2025).

3.2 | Data Collection

Data collection followed decolonial principles to avoid reproducing externally constructed governance narratives, particularly framings of ‘bottom-up’ fire management that impose new top-down prescriptions (Croker et al. 2023a, 2023b). Ensuring diverse participation was essential for embedding locally grounded knowledge into the model's algorithm (Hulme 2016; Croker and Ford 2022).

A triangulated mixed-methods approach facilitated participatory futures thinking and supported the co-development of scenarios and model variables (Table SI1) (Biggs et al. 2015; Nowell et al. 2017; Johansson 2021; Croker 2024). Cross-examination also informed the interpretation of modelled outcomes, resituating modelled abstractions within their real-world social–ecological context (Patton 2002; Gibson 2017).

Methods included questionnaires ($n=225$), semi-structured interviews ($n=28$; 58 individuals), three focus groups, and a two-day inter-cultural workshop (Croker et al. 2024). Questionnaires captured fire-related attitudes and mitigation strategies; interviews elicited insights from individuals with decision-making authority or epistemic influence (sampling strategy in SI1); and focus groups (elders, women and youth, land managers) supported consensus-building (Prochazka and Hajek 2015; Devisscher et al. 2016). An inter-cultural workshop used rich pictures, world cafés, and participatory art to generate exploratory and normative fire management approaches, directly informing scenario development. Full protocols are in SI1–SI3 and Croker (2025).

3.3 | Joint Socioeconomic-Climate Scenarios

Three scenarios were developed to model alternative fire management pathways to year 2100: Green Climate Ambition (GCA), Climate Delay and Inequality (CDI), and Fossil-Fueled Climate Denial (FFCD). These core SSPX-Y scenarios, where *X* denotes the shared socioeconomic pathway (SSP) and *Y* the approximate representative concentration pathway (RCP) reached by year 2100, represent best-, intermediate-, and worst-case futures, informed by the IPCC (IPCC 2021) and adapted to East African socioeconomic and ecological conditions[3] (e.g., poverty, institutional fragility, land-use change, food security, compound risks) (Hulme et al. 2001; GECHS 2008; Engelbrecht et al. 2015; IPBES 2019; Hao et al. 2020; Weber et al. 2020; WMO 2021). Scenarios further integrated regionally relevant literature (O'Neill et al. 2017; van Vuuren et al. 2017; Riahi et al. 2017; Harrisson 2019) and were reviewed by domain experts for coherence and relevance. Table 1 summarises each scenario's key features, while full narratives are provided in Croker (2024).

TABLE 1 | Overview of joint socioeconomic–climate scenarios developed in SAV BN: (i) scenario type depending on climate policy action; (ii) mitigation and adaptation challenges; (iii) global warming value above pre-industrial levels in 2100 based on RCP trajectories and SSPX-Y equivalents; (iv) brief warming summary outlining the quantitative data used to construct each scenario, including estimated temperature range based on policy action and population dynamics, GDP and market trajectories (Finney et al. 2019; WMO 2021), aerosol emissions and projected frequency of hot temperature extremes, agricultural and ecological drought, and heavy precipitation events under each degree of warming (IPCC 2021).

Scenario title	Scenario type	Mitigation and adaptation challenges	Global warming value	Equivalent SSPX-Y scenarios	Brief warming summary
Green Climate Ambition (GCA)	Best-Case Scenario—additional climate policy action	Low mitigation and adaptation challenges	1°C–2°C	SSP1-1.9 and SSP1-2.6	Warming to approx. 1.5°C. In the medium and long-term, overshoot up to 2.6°C across East Africa. Net-zero emissions are reached after 2050. Annual GDP across East Africa declines by approximately 2%–4.5% per year and there is greater dependency on external markets. The frequency of hot temperature extreme events over land increases from 4.1 times in a 10-year period under 1.5°C of warming to 5.6 times under 2°C of warming, causing a temperature increase of +1.9°C to +2.6°C (1850–1900 baseline). Agricultural and ecological drought events are 2 and 2.4 times more likely to occur under 1.5°C and 2°C, respectively. In the wet season, heavy precipitation events are 1.5 and 1.7 times more likely to occur under 1.5°C and 2°C of warming, causing an increase in wetness by +10.5% and +14.0%, respectively.
Climate Delay and Inequality (CDI)	Intermediate Case Scenario—current policy action	Medium mitigation and adaptation challenges	2°C–4°C	SSP4-3.4, SSP2-4.5 and SSP4-6.0	Warming to at least 2.7°C and up to Warming of 3°C–4°C by 2100 is very likely. Annual GDP across East Africa declines by approximately 4.5%–11.2% per year and there is greater dependency on external markets. The frequency of hot temperature extreme events over land increases from 5.6 times in a 10-year period under 2°C of warming to 9.4 times under 4°C of warming, causing a two-fold temperature increase of +2.6°C to +5.1°C (1850–1900 baseline). The number of warm nights could increase by 50%. Agricultural and ecological drought events are 2.4 and 4.1 times more likely to occur under 2°C and 4°C, respectively. In the wet season, heavy precipitation events are 1.7 and 2.7 times more likely to occur under 2°C and 4°C of warming, causing a two-fold increase in wetness by +14% and +30.2%, respectively.

(Continues)

TABLE 1 | (Continued)

Scenario title	Scenario type	Mitigation and adaptation challenges	Global warming value	Equivalent SSPX-Y scenarios	Brief warming summary
Fossil-Fuelled Climate Denial (FFCD)	Worst-Case Scenario—no additional policy action/retraction of certain policy	High mitigation and adaptation challenges	4°C–6°C	SSP7-3.0 and SSP5-8.5	Warming to 3°C by mid-century and 5°C by 2100. Reinforcing feedback loops cause warming of 6.3°C by 2100. Warming might stay below 6°C due to the cooling effects of increased aerosol emissions. Annual GDP across East Africa declines by more than 11.2% per year, with an exponentially increasing rate of decline for every 0.1°C of warming. By 2050, this figure could reach more than 15% per year. There is greater dependency on external markets. Under 6°C of warming, the frequency and intensity of hot temperature extreme events over land, agricultural and ecological droughts and heavy precipitation events in the wet season over a 10-year period, are likely to be double or even triple that experienced at 4°C.

Note: See Croker (2024) for detailed information.

3.4 | Fire Management Scenarios

Seven fire management scenarios were developed from systematic reviews (Croker et al. 2023a, 2023b), participatory field data and expert consultation: Fire Suppression and Prevention (FSP), REDD+, Savanna Burning Emissions Abatement (SBEA), Flexible Prescribed Burning (FPB), Holistic Grazing Scheme (HGS), Fuel Harvesting Scheme (FHS), and Community-Based Fire Management (CBFiM). These capture diverse governance trajectories and are characterised by eight core management dimensions (Table 2; Croker 2024).

During fieldwork, participants frequently used back-casting to link desired outcomes to present interventions (Robinson et al. 2011). Policy actors favoured predictive or exploratory scenarios within existing structures (e.g., FSP, REDD+), while normative scenarios (e.g., FPB, CBFiM) were mostly articulated by local actors lacking formal governance responsibilities. Integrated exploratory-normative approaches (e.g., decentralised HGS, FHS) offered innovative yet grounded solutions. Where governance pathways diverged (e.g., SBEA, HGS, FHS), we modelled the version supporting decentralisation and local agency, while recognising their differing objectives and the perceived risks of expanding local access to protected areas.

3.5 | Model Development and Parameterisation

The structure of SAV BN was built on conditional independence assumptions that quantify relationships between system variables, specifically the degree of belief that a *strong increase* in a parent node (Y) would drive either a *strong or weak* increase ($Y_i = X_i$) or decrease ($Y_i = X_d$) in a child node (X) under projected conditions to 2100. Each directed edge ($Y \rightarrow X$) was assigned a belief weight ($w \in [-4, 4]$) to represent the perceived direction and magnitude of influence, reflecting both certainty and magnitude of effect relative to a 'no-policy' baseline. This baseline captures current fire suppression and response practices without additional interventions or resourcing (Trendowicz and Jeffery 2014; Frías et al. 2017) (Table 3).

Edge parameters were iteratively derived and refined as new evidence emerged (Figure 1). First, variables and causal pathways were identified through systematic reviews, targeted searches, and expert knowledge. Second, median values for significant interactions were obtained from Likert-scale questionnaire data (e.g., between fire-use practices and perceived wildfire risk), informing preliminary edge strengths. Qualitative interview and focus group data were thematically analysed within a constructivist framework to elicit grounded understandings of fire governance, identify additional variables, and assign edge values based on agreement, conviction, and perceived magnitude of effect (SI1–SI2; Table SI1) (Hampshire et al. 2014; Braun and Clarke 2006; Stafford et al. 2020). Finally, interdisciplinary experts validated the draft network structure, identifying missing nodes, highlighting key causal pathways, and noting areas of alignment or disagreement with preliminary edge parameters (expert protocol in SI3). Their responses were standardised using a certainty–magnitude matrix (Table 3).

TABLE 2 | Overview of predictive (pr), exploratory (ex) and normative (nr) fire management scenarios modelled in SAV BN under future socioeconomic–climate change.

Fire management scenario	Scenario approach	Key management factors: Burning policy	Dominant view of fire	Dominant management strategy	Main fuel reduction strategy	Ecological objective	Finance mechanism	Opportunities for 'bottom-up' approach
Fire suppression and prevention (FSP) *(pr)*	Centralised	No policy change or by-laws	Negative [disaster]	Mostly reactive	Wildlife [possible incorporation of fire]	Forestation	n.a.	Very limited [community involved in firefighting]
REDD+ project *(pr)*	Centralised	No policy change or by-laws	Negative [disaster]	Mostly reactive	Wildlife [possible incorporation of fire]	Forestation	Carbon-based PES scheme	Very limited [community involved in firefighting]
Savanna burning emissions abatement scheme: Emissions Avoidance and Bio-sequestration (SBEA) *(ex)*	Decentralised	Requires policy change and creation of by-laws	Positive [regenerative]; negative [disaster]	Mostly proactive	Fire	Savanna conservation; forestation	Carbon-based PES scheme	Limited [community involved in implementing prescribed burns]
Flexible prescribed burning (FPB) *(nr)*	Centralised (+)	Requires policy change	Positive [regenerative]	Mostly proactive	Fire	Savanna conservation	Carbon-based PES scheme	Limited [community involved in implementing prescribed burns]
Holistic Grazing Scheme (HGS) *(ex)*	Decentralised	Requires policy change and creation of by-laws	Negative [disaster]	Mostly proactive	Livestock [possible incorporation of fire]	Forestation	n.a.	Yes [possible decentralisation of some management rights]
Fuel harvesting scheme (FHS) *(ex)*	Decentralised	Requires creation of by-laws	Negative [disaster]	Mostly reactive	Harvesting ground litter	Savanna conservation; forestation	Possible incorporation	Yes [possible decentralisation of some management rights]
Community-Based Fire Management (CBFiM) *(nr)*	Decentralised	Requires policy change and creation of by-laws	Positive [regenerative]	Mostly proactive	Livestock; fire	Savanna conservation	Possible incorporation	Yes [decentralisation of management rights]

Note: All scenarios are designed for implementation in an East African savanna-protected area context, investing in and resourcing, to varying degrees, three main intervention measures: Fire management systems, firefighting capacity and law enforcement. (+) signifies the inclusion of below-ground carbon in the scenario's carbon-accounting methodologies (implemented under the specified finance mechanism). Croker (2024) provides further information on each scenario and intervention measures.

TABLE 3 | Parameterisation values for edges and select nodes within the model, their corresponding probability equivalents used in calculations and the interpretation of resulting posterior values.

Integer value	Probability value equivalent	Edge parameter value	Overall posterior value (+) increase; (−) decrease
4 (or −4)	0.9 (0.1)	Strong relationship between parent and child node, with clear cause-and-effect relationship. High (> 95%) agreement between sources supporting the relationship	Large magnitude of change (75%–100%) under modelled scenario
3 (or −3)	0.8 (0.2)	Strong relationship between parent and child node, with clear cause-and-effect relationship. Moderately high (> 75%) agreement between sources supporting the relationship. OR Moderate relationship between parent and child node, with some difference detectable (might not be obvious) in cause-and-effect relationship. Full agreement (> 95%) agreement between sources supporting the relationship	Moderate to large magnitude of change (50%–75%) under modelled scenario
2 (or −2)	0.7 (0.3)	Moderate relationship between parent and child node, with some difference detectable (might not be obvious) in cause-and-effect relationship. Moderately high (> 75%) agreement between sources supporting the relationship. OR Weak relationship between parent and child node, with difference detectable (might not be significant) in cause-and-effect relationship. Full agreement (> 95%) agreement between sources supporting the relationship	Small to moderate magnitude of change (25%–50%) under modelled scenario
1 (or −1)	0.6 (0.4)	Weak relationship between parent and child node, with difference detectable (might not be significant) in cause-and-effect relationship. Moderately high (> 75%) agreement between sources supporting the relationship	Small magnitude of change (1%–25%) under modelled scenario
0	0.5	No relationship, or large disagreement between sources	No change

Edge parameters derived at each step were stored in separate calibration columns, with final values calculated as the modal value across methods and tested via sensitivity analysis. Interactions were then organised into a probability matrix, with rows representing parent nodes, columns representing child nodes, and blanks indicating no prior information (Dominguez Almela et al. 2024). Three versions of the interaction matrix were used to model variation across fire management scenarios, reflecting different carbon-accounting approaches: (1) no carbon financing; (2) above-ground biomass (AGB) + LDS emissions reductions; and (3) AGB + LDS + below-ground biomass (BGB).[4]

3.5.1 | Node Categorisation, Assignment and Modelling

To capture landscape-level dynamics and support inference across spatial configurations, nodes were:

i. Classified into five thematic groups: 'climate and environmental' (global and regional scale); 'wildlife'; 'socioeconomic' (landscape scale); 'protected area fire management and policy' (local scale); 'outcome';

ii. Precisely defined via literature review and expert elicitation (SI4.1) (Croker 2024);

iii. Assigned spatial classifications: entire modelled landscape ('ALL'), protected areas ('PA') and community lands ('CL') (SI4.2);

iv. Allocated a representation status: 'level', 'extent', 'occurrence' (SI4.3).

Fire management and policy nodes were further differentiated into 'permission measures', 'intervention measures', 'financing measures', and 'legal', 'illegal' and 'other' fire-related activities (Croker 2024). To capture variation in wildfire risk across fire management approaches, several activities were modelled as both legal and illegal to capture scenario-specific conditionalities (SI4.4).

'Intervention measures' were grouped into five operational categories: (i) plantation establishment and spatial expansion, (ii) enhancement of law enforcement capacity, (iii) investment in firefighting infrastructure, (iv) development of integrated fire management systems, and (v) formalisation of community-based fire governance within protected areas. Except for plantations, these are non-discrete, process-based interventions and were defined along implementation pathways informed by empirical and field data (Croker 2024).[5] Each measure was strictly defined to clarify its operationalisation in SAV BN and in the interpretation of modelled outcomes. Given the scope of this study, further disaggregating intervention measures into multiple nodes would have implied a level of precision not supported by the available data, thereby risking biased or unstable causal inference (Barton et al. 2012; Varis et al. 2012).

Casual interactions followed predefined spatial rules to facilitate analysis of wildfire regimes and savanna health within protected areas, as well as livelihood dynamics across the broader conservation landscape:

- ALL ↔ ALL, PA, CL
- PA ↔ ALL, PA; PA ← CL
- CL ↔ ALL, CL; CL → PA

While PA ↛ CL, indirect effects may still propagate through the network, for example when processes within the PA generate carbon credits that subsequently support investments in CL processes (Figure 2) (SI4.2).

Following these rules, ten 'scenario nodes' acted as input nodes in SAV BN, representing the three socioeconomic–climate and seven fire management scenarios. Each scenario node was linked to a set of key system variables ('select nodes') expected to change (Table SI2) (Croker 2024), allowing scenario effects to propagate through the network via feedbacks. This approach avoids fixing variables that are themselves subject to feedback and uncertainty (details in SI4.5; Croker 2025).

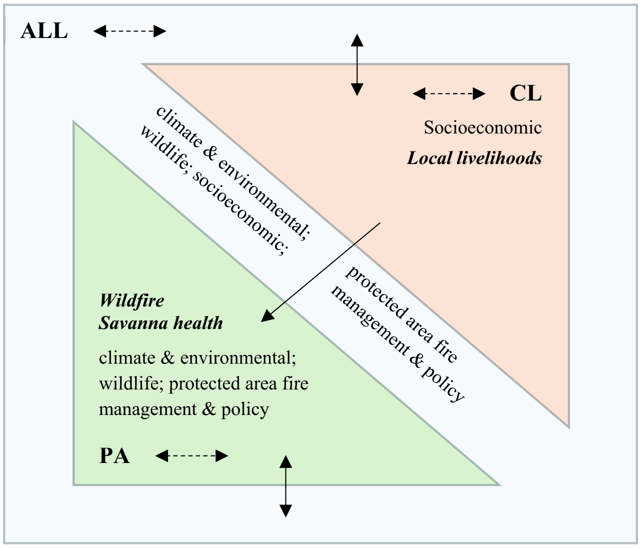

FIGURE 2 | Spatial interactions between thematically grouped nodes across protected areas (PA), community lands (CL) and the full modelled landscape (ALL). *ALL* nodes represent large-scale, transboundary processes; *PA* nodes capture ecological dynamics and fire management interventions; and *CL* nodes reflect socioeconomic processes shaping landscape conditions and the feasibility of alternative fire management. All 'wildlife' nodes are classified as PA nodes except 'spatial compression', and all 'protected area fire management and policy' sub-groups are classified as PA nodes except 'financing measures' (see SI4.2).

3.6 | Sensitivity Analysis

We conducted a bootstrapped sensitivity analysis using the BBN.sensitivity() function in *BBNet*. For each scenario, 10% of conditional probabilities were randomly adjusted by ±0.1 across 1000 iterations to identify edges with the greatest cumulative influence on wildfire, savanna health, and livelihoods (Dominguez Almela and Stafford 2024). Acknowledging structural uncertainty in causal pathways, as well as conflation between perceived certainty and magnitude of effect in edge parameters (Stafford et al. 2020), influential relationships were cross-validated with expert judgement and published evidence.

3.7 | Final Model Runs

The three joint socioeconomic–climate futures (GCA, CDI, FFCD) were first run without additional fire management to establish the 'no-policy' baseline. Seven fire management scenarios were then modelled under all three socioeconomic–climate futures to evaluate potential impacts on wildfire mitigation, savanna health, and livelihood resilience to 2100.

For each scenario, 1000 bootstrap replicates were generated and 95% CIs calculated by excluding the upper and lower 2.5% of simulated values (Crawley 2012). Edge parameters remained fixed for the first model run, producing the reported increase values, which represent the probability of a node increasing or decreasing under the scenario. Confidence intervals characterise the plausibility range of each posterior estimate and indicate how uncertainty propagates through the network (Dogan 2007; Rahmandad et al. 2015). Posterior values near zero indicate minimal deviation from the baseline (i.e., lack of influence; CI = 0.5), whereas wide or sign-crossing intervals indicate sensitivity to underlying assumptions, resilience, or response plasticity (CI ≠ 0.5) (Table SI3).

Network effects for each scenario were calculated following the methodology described in Dominguez Almela et al. (2024). All outputs were interpreted using the semi-quantitative certainty–magnitude matrix employed during parameterisation (Table 3).

4 | Results

SAV BN produced 24 scenario outputs, each generating posterior values and 95% confidence limits for all nodes included in the network.[6] Full model results are provided in the Supporting Information (Table SI3), and key outcomes for wildfires, savanna health and local livelihoods are summarised in Table 4, with red and blue cells indicating mathematically positive and negative outputs, respectively. In this context, positive outputs (red cells) represent beneficial outcomes for savanna health and local livelihoods, while negative outputs (blue cells) represent beneficial outcomes for wildfires (i.e., greater mitigation success). The results presented in this paper should be interpreted alongside the accompanying model database for full explanatory context (Croker 2024).

As shown in Table 4, all alternative fire management approaches enhanced wildfire mitigation relative to the 'no-policy' baseline, outperforming suppression frameworks that have dominated

TABLE 4 | Calculated probabilities of an increase (red) or decrease (blue) in wildfires (W), savanna health (SH) and local livelihoods (LL) under seven centralised (c) or decentralised (dc) fire management scenarios and future socioeconomic–climate change (GCA, CDI and FFCD futures).

Fire management scenario	Green Climate Ambition (GCA)			Climate Delay and Inequality (CDI)			Fossil-Fuelled Climate Denial (FFCD)		
	W	SH	LL	W	SH	LL	W	SH	LL
No-policy	**2.321**	**−0.711**	**0.064**	**4.073**	**−1.152**	**−3.059**	**4.344**	**−1.307**	**−3.192**
FSP (c; p)	*−0.849*	−2.363	−0.960	*−0.849*	−3.064	*−2.687*	*−0.849*	−3.160	*−2.755*
REDD+ (c; ex)	*−1.348*	−3.055	*0.064*	*−1.348*	−3.511	*−2.463*	*−1.348*	−3.556	*−2.489*
SBEA (dc; ex)	*−0.083*	−2.602	*0.414*	*−0.083*	−3.226	*−0.727*	*0.139*	−3.292	*−0.751*
FPB (+) (c; nr)	*−0.077*	*−0.397*	*0.064*	*0.164*	*−1.152*	*−2.610*	*0.246*	*−0.657*	*−2.650*
HGS (dc; ex)	*−1.348*	−1.555	*1.177*	*−1.348*	−2.644	*−0.434*	*−1.348*	−2.807	*−0.128*
FHS (dc; ex)	*−1.348*	−1.445	*1.177*	*−1.348*	−2.575	*−0.438*	*−1.348*	−2.744	*−0.128*
CBFiM (dc; nr)	*−1.782*	*−0.278*	*1.587*	*−1.782*	−2.594	*−0.256*	*−1.782*	−2.746	*0.402*

Note: Predictive (p), exploratory (ex) and normative (nr) fire management scenarios include: Fire suppression and prevention (FSP), Reducing Emissions from Deforestation and Forest Degradation (REDD+), savanna burning emissions abatement (SBEA), flexible prescribed burning (FPB), Holistic Grazing Scheme (HGS), fuel harvesting scheme (FHS) and Community-Based Fire Management (CBFiM). The 'No-policy' scenario serves as a baseline, reflecting the current fire suppression and response model without additional resourcing. Italics text indicates more favourable outcomes compared to the baseline (bold values).

in Sub-Saharan Africa since the late nineteenth century.[7] In a GCA future, shifts towards more inclusive governance alleviate several socioeconomic pressures that contribute to subversive ignitions. However, without additional and ambitious climate policies, projected warming under CDI and FFCD futures is expected to intensify wildfire activity beyond the capacity of existing suppression models, which are already constrained by limited fire legislation, real-time detection capacity, financial and human resources, and cross-stakeholder coordination (Rotich et al. 2025).

Savanna health declined across all modelled approaches, reflecting a diminishing capacity to sustain ecological integrity under projected socioeconomic–climate change. Notably, consistent with concerns raised by fire ecologists (Parr et al. 2024), 73% of participants perceived savannas as degraded forests, favouring stronger fire suppression to curb 'destructive' burns believed to maintain 'species-poor' and 'sub-climax' grasslands. Such perceptions continue to embed Clementsian views of ecological succession within predictive and locally constructed exploratory fire management approaches (Croker 2025). Although normative scenarios produced comparatively better outcomes for savanna health, their development remains constrained by cognitive and institutional legacies of entrenched anti-fire discourses rooted in colonial forestry and early fire ecology (Kobziar et al. 2024). Since SAV BN was parameterised to reflect recent empirical trends in Sub-Saharan Africa, including rapid ecological degradation[8] and a 76% decline in faunal biodiversity since 1970 (WWF 2024), our findings highlight critical threats to the persistence of fire-adapted savanna systems under suppression- and risk-oriented regimes that restrict high-intensity burning.

Livelihood outcomes showed the highest variability, driven largely by the distribution of management rights across fire management approaches and their interactions with socioeconomic and climatic conditions. All alternative approaches except for fire suppression and prevention enhanced at least one dimension of livelihood resilience amid increasing adaptation and mitigation pressures, generating net positive outcomes under a GCA future and attenuating vulnerability trajectories under CDI and FFCD futures relative to the baseline. Decentralised approaches consistently outperformed centralised ones, limiting vulnerability to a 1%–25% increase above current levels and, in some cases, improving resilience by 25%–50% (Table SI3).

No modelled approach reduced livelihood vulnerabilities under a CDI future marked by unequal investment in human capital, economic disparities, and exclusionary governance. Similar trends were projected under a FFCD future, further exhibiting how feedbacks among inter-group conflict, elite capture, and weakened management rights intensify biocultural hysteresis. The gradual loss of traditional fire knowledge and institutional legitimacy, coupled with increased competition for conservation-derived income, has promoted a chaotic fire regime shaped by individualistic burning practices, where short-term, personal incentives undermine opportunities for collective stewardship (Croker 2025). These dynamics deepen state resistance to devolving management rights, perpetuating exclusionary feedback loops and reproducing the very inequalities that decentralisation and 'community-based' reforms seek to address (Ostrom et al. 2007; Garmestani et al. 2023). Consistent with broader governance scholarship, the results show that decentralisation alone cannot ensure empowerment or equity without robust local institutions, social protection, and enabling human development conditions (Chasek and Downie 2020; Croker 2024; Van Zeben and Hilson 2025). In contexts where resurgent nationalism weakens multilateral cooperation, decentralised structures remain vulnerable to geopolitical and economic shocks, limiting their ability to sustain equitable and adaptive fire governance.

Overall, the modelled results demonstrate that no single fire management approach consistently delivers co-benefits across all outcomes. Persistent trade-offs, particularly between savanna health and local livelihoods, highlight the absence of a universal 'win–win–win' solution under intensifying climate and socioeconomic pressures (Croker et al. 2023a). The following sections discuss scenario-specific dynamics and their implications for wildfire mitigation, savanna health, and livelihood resilience.

5 | Discussion

5.1 | Wildfires

Fire management approaches that invested in both suppression capacity and the establishment of holistic, multi-stage management systems achieved the most substantial wildfire reductions relative to baseline. These approaches balanced centralised Incident-Command structures with proactive interventions across pre- (hazard identification, data collection, emergency planning), during- (crisis communication, evacuation systems), and post-fire (loss assessment, recovery planning) phases, enhancing preparedness and institutional learning across scales through data-driven multi-actor coordination.

As shown in Figure 3 and Table 4, normative, hybrid approaches combining top-down coordination with decentralised implementation, most notably CBFiM, achieved the greatest mitigation success under competitive and insecure geopolitical conditions (Croker 2024). Devolving fire-use authority strengthened institutional legitimacy and adaptive capacity by aligning management with local livelihoods and cultural aspirations (Lyver et al. 2019; Croker 2025). When coupled with broader shifts towards more inclusive development and state investment in suppression infrastructure (GCA future), CBFiM can reduce ignition risks tied to inter-group conflict, institutional fragmentation, and opportunistic fire regimes (Figure 3, left).

Yet consistent with critiques of partial decentralisation (Ribot et al. 2006; Larson and Soto 2008), centrally governed but locally implemented management activities risk reproducing dependency on external agencies, elite capture, and biocultural hysteresis, especially where statutory override limits legitimate community participation (Eriksen 2007; Dube 2013). This pattern mirrors broader trends in environmental governance where decentralisation reforms under global programmes such as REDD+ often reinforce administrative dependency, rather than fostering genuine local autonomy (Myers et al. 2018; Sarmiento and Larson 2020). Overall, the results show that long-term wildfire mitigation depends less on technical efficiency than on equitable, adaptive governance that embeds local decision-making within multi-scalar networks.

Prescribed-burning approaches (e.g., SBEA, FPB) illustrate these tensions. While LDS and wet season burning can reduce fuels and curb woody encroachment, limited local authority combined with stricter state law enforcement yielded only marginal mitigation benefits. In a FFCD future, these configurations projected an increase in uncontrolled fires symptomatic of agrarian resistance rooted in exclusionary governance legacies (Figure 4), echoing experiences from across Sub-Saharan Africa where the institutionalisation of fire has transformed it into a vehicle of protest and subaltern expression (Kull 2002).

Interestingly, centralised REDD+ and decentralised grazing and harvesting schemes (HGS, FHS) achieved comparable mitigation outcomes. REDD+, operating within the global carbon-market economy and adhering to the UNFCCC's

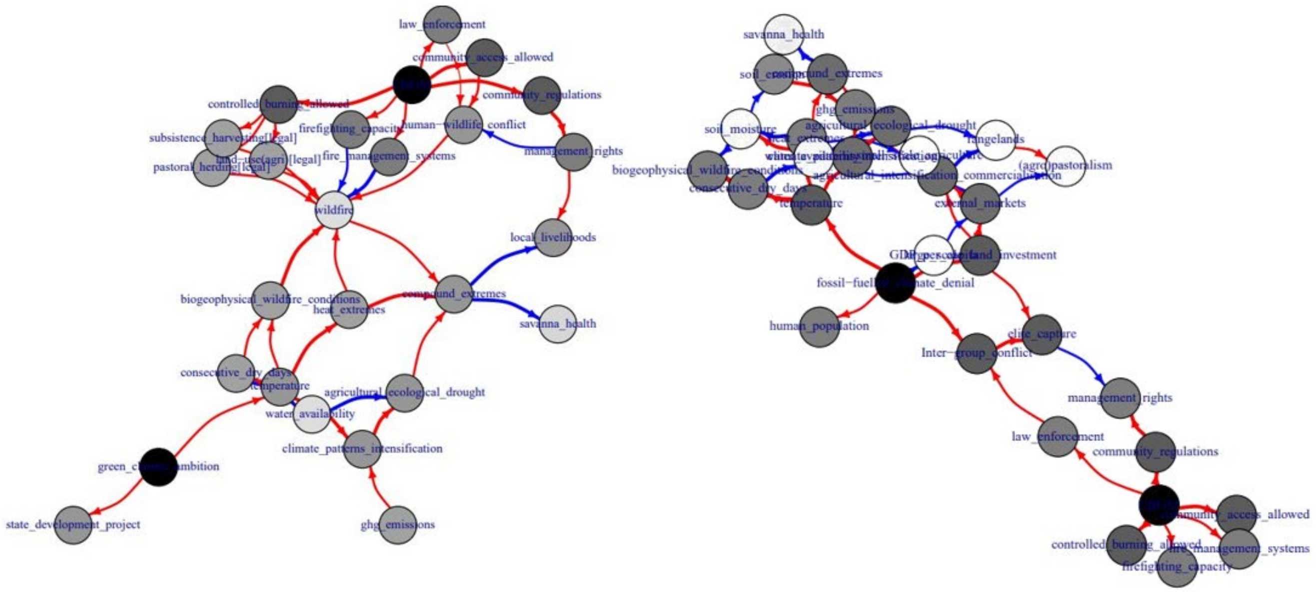

FIGURE 3 | Modelled network for a CBFiM approach in GCA (left) and FFCD (right) socioeconomic–climate future. Nodes with the highest probability of increasing are shown in dark circles, and those likely to decrease are shown in light circles (visualised probability distribution of child node X: $0.35 > X > 0.65$ (GCA); $0.25 > X > 0.75$ (FFCD)). Scenario nodes are shown as black circles (set to '4') and are directly linked to their corresponding select nodes. Red and blue arrows represent positive and negative mathematical relationships, respectively, with arrow width indicating relationship strength (i.e., perceived certainty × effect magnitude).

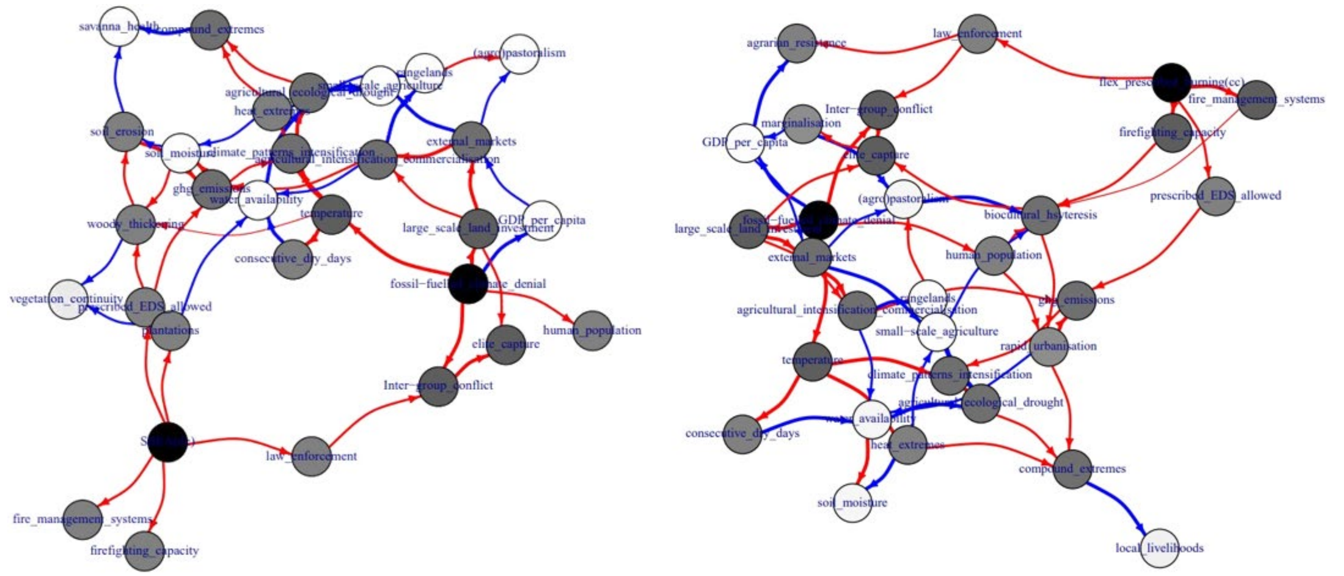

FIGURE 4 | Modelled networks for SBEA schemes (left) and FPB strategies (right) in a FFCD socioeconomic–climate future. Nodes with the highest probability of increasing are shown in dark circles, and those likely to decrease are shown in light circles (visualised probability distribution of child node X: $0.25 > X > 0.75$). Scenario nodes are shown as black circles (set to '4') and are directly linked to their corresponding select nodes. Red and blue arrows represent positive and negative mathematical relationships, respectively, with arrow width indicating relationship strength (i.e., perceived certainty × effect magnitude).

definition of a forest (10%–30% tree cover across 0.05–1 ha units) (UNFCCC 2009), prioritises above-ground carbon sequestration in its management framework. In contrast, HGS and FHS represent locally conceptualised fuel reduction schemes, which operationalise Articles 48–52 of Kenya's Forest Conservation and Management Act (2016) through Participatory Forest Management (PFM). Despite differing logics and engagement with subaltern politics (Croker 2025), both expose persistent tensions between carbon-oriented conservation and locally adaptive fire governance frameworks (Lehmann et al. 2011). Each constrains the emergence of normative fire futures through a disaster- and risk-centric framing that casts fire as both an ecological hazard and a competitor for increasingly extrinsically valued consumable biomass, exploited by humans, livestock, wildlife, and carbon-market economies (Archibald and Hempson 2016). Even where HGS by-laws permit regulated burns for pasture regeneration within protected areas, participants noted that ecological gains are often offset by spatial compression and intensified overgrazing in adjacent lands, driven by herders' perceptions of improved access (Veldhuis et al. 2019).

As shown in Figure 5, even 'participatory' mechanisms can reproduce colonial forestry rationalities and anti-fire epistemologies, perpetuating the very wildfire paradox they seek to resolve. Given that fire occurrence sharply declines beyond an ~40% tree cover threshold and herbivore habitat selection decreases with canopy density (Staver et al. 2011; Abades et al. 2014; Luvuno et al. 2018), both REDD+ and, over time, locally governed HGS and FHS are projected to promote woody encroachment (Dohn et al. 2013; Pringle et al. 2016), reducing ignition potential while simultaneously eroding the adaptive feedbacks sustaining fire-dependent savanna mosaics (Staver et al. 2011; Abades et al. 2014; Luvuno et al. 2018).

5.2 | Savanna Health

REDD+ and SBEA schemes focused on maximising carbon credit revenue via AGB metrics had the most adverse ecological effects (Table 4). Even decentralised SBEA schemes that prescribe low-intensity EDS burns to enhance sequestration and offset LDS emissions encouraged the spread of non-endemic, fire-sensitive woody species (Otieno and Kinyamario 2017; Mganga 2023).[9] Modelled results align with the *environmental stress-gradient hypothesis*, showing that woody thickening in dystrophic–mesic savannas heightens competition on sub-canopy grasses, increases water stress, and drives biodiversity loss, while also reducing soil carbon (Omoro et al. 2013; February et al. 2020; Coetsee et al. 2023; Zhou et al. 2023).

As shown in Figure 6, these ecological effects extend beyond protected areas, where carbon-financing mechanisms, both spontaneously and structurally, drive the emergence of new trade networks, the formation of market hubs, the expansion of agricultural frontiers, and the reorientation of food systems towards export markets, collectively reshaping rural economies (Kateka 2025). Though Corporate Social Responsibility (CSR) projects are often a celebrated component of market-oriented approaches, promoting social and environmental co-benefits, they are typically designed to meet certification standards, enhance investment appeal via non-financial performance indicators valued by donors, secure social licence among extrinsically motivated elites, and institutionalise 'private–indirect' governance that maintains external control over local fire users (Brockington et al. 2008; Scales 2016).

As these market logics embed within local institutions, they transform land-use values and livelihood strategies. Once opportunity-driven, diversification now increasingly follows

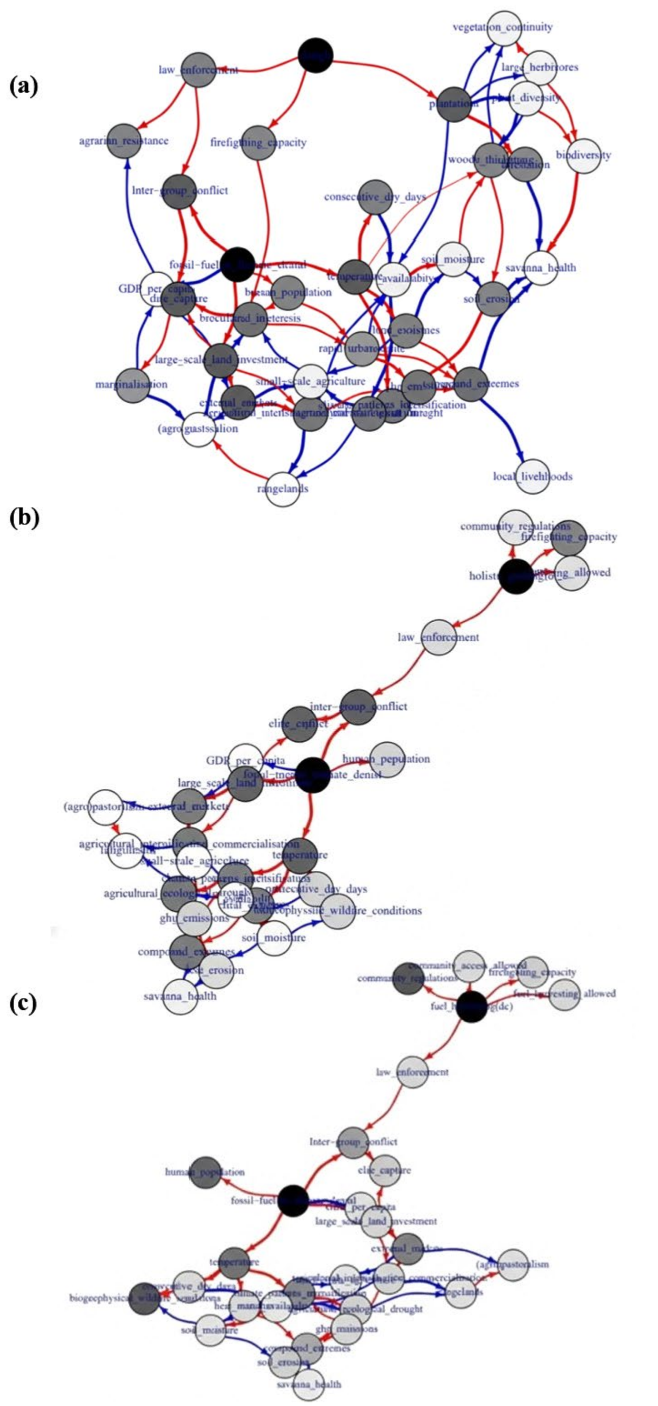

FIGURE 5 | Modelled networks for (a) REDD+, (b) HGS and (c) FHS in a FFCD socioeconomic–climate future. Nodes with the highest probability of increasing are shown in dark circles, and those likely to decrease are shown in light circles (visualised probability distribution of child node X: $0.25 > X > 0.75$). Scenario nodes are shown as black circles (set to '4') and are directly linked to their corresponding select nodes. Red and blue arrows represent positive and negative mathematical relationships, respectively, with arrow width indicating relationship strength (i.e., perceived certainty × effect magnitude).

international market incentives. Local participants expressed a growing preference for high-return land uses that deliver direct cash benefits linked to elevated market prices, such as commercial agroforestry and plantation systems, which are frequently funded through CSR initiatives and state development funding. The expansion of these projects across Sub-Saharan African and global savannas presents a multi-scalar economic dilemma (Parr et al. 2024), increasingly outcompeting incentives for long-term biodiversity conservation (Kirui et al. 2022; Mapaure et al. 2009; Alvarado et al. 2018). For example, the Amboseli Ecosystem Management Plan, co-developed with local stakeholders and envisioned as a blueprint for broader planning across Tsavo, prioritises nucleated settlements around emergent market hubs to streamline extension services and accelerate agrarian modernisation[10] (Croker 2024, 2025). However, this has also catalysed the sedentarisation of historically mobile pastoralists and eroded relational knowledge systems (Lind, Okenwa, and Scoones 2020). As elites 'move up' into capital-intensive commercial livestock systems or 'move out' into higher-return sectors, resource-constrained communities often 'drop out' into informal economies, engaging in perceived 'low-risk, high-return' illicit activities detached from customary norms and associated with unregulated fire use (Chege 2015). These practices jeopardise the integrity of carbon offset schemes by increasing leakage risks,[11] undermining long-term emissions goals, and accelerating biodiversity loss (Lind, Sabates-Wheeler, et al. 2020; Kirui et al. 2022).

Parallel dynamics emerge in HGS and FHS, where short-term livelihood needs override ecological objectives. As fuel becomes an economic commodity, fire is increasingly viewed as 'obsolete' (Croker 2025). While participants proposed integrating fuel harvesting into carbon frameworks to improve productivity via the removal of moribund materials (Zimmermann et al. 2010), they overlooked fire's ecological role in maintaining biodiversity (Van de Vijver et al. 1999; Van Langevelde et al. 2003). As shown in Figure 5, fire responds quickly to changing climate and environmental conditions, whereas herbivores and savanna flora equilibrate more slowly due to demographic and evolutionary constraints, with rates of change often exceeding adaptive capacity (Radchuk et al. 2019; Moore and Schindler 2022). Consequently, shifts in fire regimes and herbivore populations across ecological and evolutionary timescales risk destabilising the savanna adaptive cycle.

These risks are compounded by ENSO and Indian Ocean Dipole (IOD) variability, where multi-year La Niña and negative IOD phases suppress short rains following strong El Niño years characterised by above-average rainfall and high fuel loads (Wu et al. 2019; Anderson et al. 2023; Tao et al. 2024). Under such conditions, prescribed EDS burns increase heat and water stress, reduce productivity and expose bare ground to woody invasion, accelerating degradation (Lobell and Burke 2008; Palmer et al. 2023). Modelled results indicate that predictive and exploratory fire approaches, except HGS and FHS under a GCA future, push savannas towards critical ecological thresholds, signalling potential regime shifts towards asymptotic, functionally degraded closed-canopy states (Table SI3) (Dohn et al. 2013; Pringle et al. 2016).

Only FPB and, under GCA, CBFiM improved savanna health. Both challenge anti-fire paradigms and rigid carbon-accounting frameworks, and under broader equitable

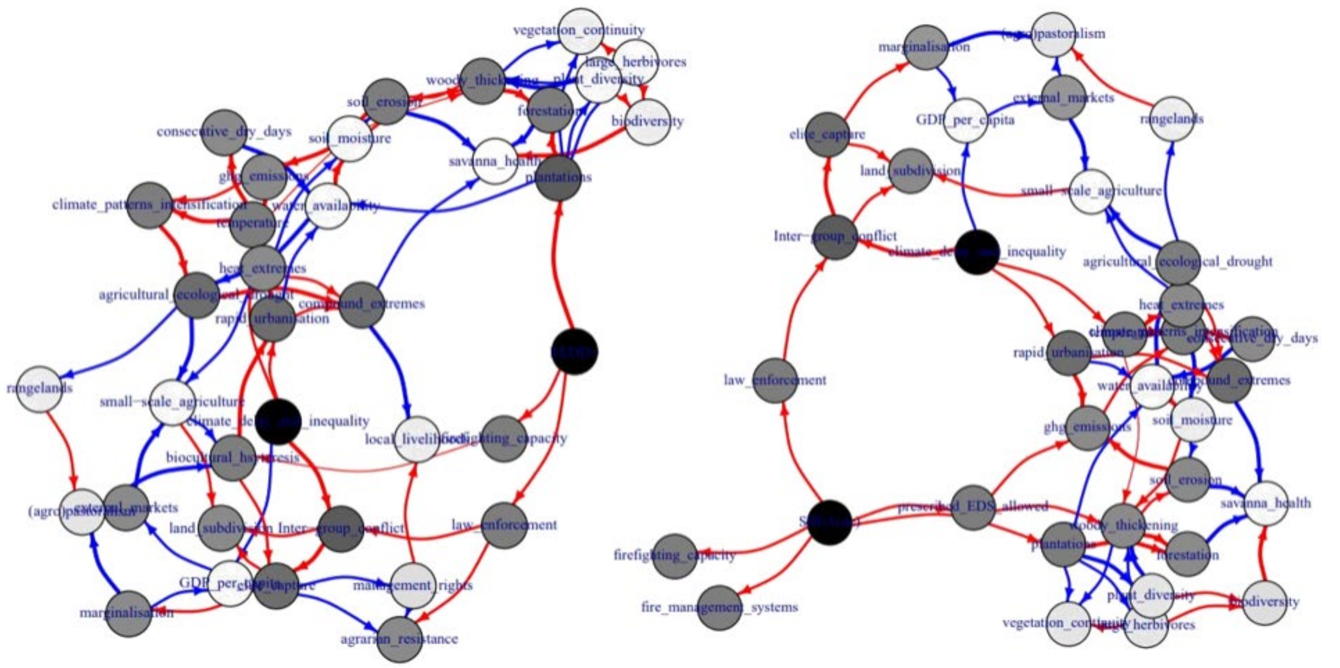

FIGURE 6 | Modelled networks for REDD+ projects (left) and SBEA schemes (right) under a CDI socioeconomic–climate future. Nodes with the highest probability of increasing are shown in dark circles, and those likely to decrease are shown in light circles (visualised probability distribution of child node X: $0.3 > X > 0.7$). Scenario nodes are shown as black circles (set to '4') and are directly linked to their corresponding select nodes. Red and blue arrows represent positive and negative mathematical relationships, respectively, with arrow width indicating relationship strength (i.e., perceived certainty × effect magnitude).

governance structures (GCA future), the decentralisation of fire rights in alignment with local livelihood objectives supported better ecological outcomes (Smith et al. 2024). Even under CDI and FFCD futures characterised by socioeconomic instability and conflict, FPB, which integrates BGB into its carbon accounting, halted degradation by recognising the role of pyrodiversity in sustaining C_4 grass productivity, megafaunal biodiversity, and carbon cycling (Beerling and Osborne 2006; Lindsey et al. 2017).

Emerging evidence shows that >70% of soil organic carbon in African savannas derives from frequently burned C_4 grasses (Handavu et al. 2021; Zhou et al. 2022), whereas C_3 tree-based sequestration and exclusive EDS burning may undermine long-term resilience (Croker et al. 2023b; Knowles et al. 2025). Thus, FPB provides a promising normative approach; by adaptively integrating LDS and wet season fires, which target woody seedlings at phenologically vulnerable stages when seed moisture enhances heat permeability, it can help maintain tree cover below ~40% (Abades et al. 2014; Laris et al. 2016).

This aligns with Articles 7 and 8 of the Convention on Biological Diversity and provides a foundation for integrated, long-term carbon–biodiversity schemes[12] beyond dual-certification models (e.g., CCB standards), which often lack empirical robustness (Parr and Andersen 2006; Croker et al. 2023b). However, BGB accounting remains poorly standardised, with current approaches frequently excluding fine root fractions and producing inaccurate estimates (Ravindranath and Ostwald 2008). Similarly, biodiversity credit markets remain nascent and underdeveloped. Realising FPB's potential requires re-embedding fire governance within local social–ecological contexts rather than treating fire solely as a global climate instrument. Encouragingly, recent iterations of REDD+ and other carbon programs are integrating biodiversity metrics and local participation, signalling progress towards more equitable, adaptive governance frameworks (Sharma et al. 2015; Harris et al. 2022; Arocha et al. 2024).

5.3 | Local Livelihoods

In FFCD futures, marked by high-technological land investments which override smallholder systems (Croker 2024), only CBFiM sustained livelihood resilience to 2100. This reflects the benefits of community participation in designing and enforcing fire-use regulations, contingent on inclusive decision-making and accepted procedures for conflict resolution (Croker et al. 2023a). While governance regimes grounded in self-organising, locally legitimate institutions are often assumed to promote adaptive resilience in the literature, such assumptions overlook the ongoing erosion of customary institutions and social norms through colonial and post-colonial influence and expropriation (Ribot et al. 2006; Agrawal et al. 2008; Smith et al. 2024).

In addition to HGS and FHS, CBFiM was envisioned as an extension of Kenya's PFM framework (FCMA 2016), yielding comparable livelihood outcomes. Under this framework, Community Forest Associations (CFAs) would facilitate the establishment of specialised fire-user groups to represent community interests, lobby for formalised fire rights, and co-design operational burning rules. Under a FHS, CFAs would also be responsible for overseeing a quota-based 'cut-and-carry' fuel management strategy, while under a HGS, grazing committees would establish rotational 'graze-and-rest' systems in line with the Wildlife

Conservation and Management Act (2013), which makes provisions for drought-time grazing within protected areas. These approaches were viewed as mechanisms to address governance challenges associated with ad hoc 'gentlemen's agreements'[13] and nocturnal agency[14] across Tsavo (Butt 2011; Hall et al. 2017; Croker 2025).

Although PFM remains the only legal avenue for decentralising management rights in Kenya, it lacks safeguards for procedural justice, equitable representation, and fair benefit-sharing. CFA members must pay annual fees to retain participation rights, yet the state retains ultimate ownership and can unilaterally revoke agreements. These fees often exclude poorer households, reinforcing existing power asymmetries and enabling a de facto transfer of exclusion rather than management rights to local elites (Saito-Jensen et al. 2010; Epstein et al. 2013; Arnall et al. 2013).

Carbon-finance approaches, particularly REDD+ and FPB, generated very negative livelihood outcomes. While decentralised SBEA schemes appeared to perform marginally better, they frequently exhibit managerial decentralisation without devolution, where Indigenous rangers replace customary custodians to enforce externally prescribed regimes (McKemey et al. 2020; Millhauser and Earle 2022; Croker et al. 2023b). Such processes of 'recentralising while decentralising' concentrate carbon benefits among privileged actors, often at the national level where they are then reinvested into security operations near park-community boundaries. The reinforcement of a 'fences and fines' conservation logic exposes local communities to volatile socioeconomic and climatic (CDI, FFCD futures), exacerbated by ecological hysteresis (Kapoor 2002; McCarthy 2005; Ribot et al. 2006; Fache and Moizo 2015). In turn, this has provoked demonstrations of agrarian resistance and fuelled intra-community antagonisms, exemplified by an increasing number of secretive arrangements between community members and conservation officials to report or criminalise neighbours engaged in illicit activities[15] (Peluso 1993; Adams and Hulme 2001; Adams and Mulligan 2002). The pursuit of individual advancement through external affiliations increasingly supersedes customary obligations, posing critical dilemmas for decentralised governance. These findings reaffirm contemporary governance insights: without procedural safeguards, transparent benefit-sharing, and genuine local agency, carbon-finance mechanisms risk entrenching structural injustices rather than redressing them (Ribot and Larson 2012; Myers et al. 2018; Sarmiento and Larson 2020).

6 | Conclusions

This study provides a probabilistic evaluation of seven fire management approaches under best-, intermediate-, and worst-case socioeconomic–climate futures in East African savannas. While most approaches reduced wildfire risk and, in a GCA future, improved livelihood resilience, no single strategy simultaneously achieved wildfire mitigation, ecological integrity, and livelihood benefits. Fire suppression, fuel reduction, and carbon-oriented approaches that prioritised AGB accounting consistently intensified ecological degradation, exposing climate–biodiversity trade-offs that constrain contemporary managers bound by annual reporting cycles (Croker et al. 2023a). These results reveal that modern fire regimes are not merely ecological outcomes but deeply political, institutional artefacts, underscoring the need to imagine and reorient governance systems towards more normative fire futures (Smith et al. 2024).

Bottom-up approaches conceptualised by local actors often failed to confront the (neo)colonial legacies embedded in land-use politics and participatory governance frameworks historically mobilised to extend centralised control over rural affairs (Kull 2002). In doing so, they reproduced anti-fire narratives and enabled state and elite consolidation through the instrumentalisation of 'community-based' reforms. The persistence of these path dependencies shows how colonial and postcolonial interventions continue to shape fire governance, eroding customary institutions, reshaping local knowledge systems, and fragmenting intra-community relations. Consistent with broader evidence showing that prolonged exposure to external intervention transforms land-use and heritage values (Croker et al. 2023a), these dynamics constrain pathways towards socially and ecologically just fire governance by accelerating biocultural hysteresis. In this process, degradation narratives are internalised and reproduced by the very communities positioned as stewards of traditional fire knowledge (Kull 2004; Butz 2009; Kamau and Medley 2014; Kneas 2016). In Kenya, this pattern is amplified by devolved county systems in which the national government retains control over land administration and revenue distribution, continuing to mediate participation and authority in resource management (Croker 2025).

Addressing these dynamics requires a paradigm shift in African fire governance, from a narrow emphasis on 'community participation' towards strengthening institutional legitimacy, accountability, and autonomy. A historical institutional lens can reveal how local governance systems interact with national political economies and are continuously renegotiated to shape outcomes (Nygaard 2008; Petty et al. 2015; Berkes 2017), thereby exposing governance asymmetries that undermine Indigenous and local political agency in fire management.

Translating these insights into policy demands reforms that embed local decision-making within multi-scalar governance networks that operationalise tripartite environmental justice frameworks, integrating representational, procedural, and distributional dimensions to secure genuine rights over land and fire. Formalising management rights, clarifying tenure, and re-establishing locally legitimate institutions, as defined by fire-using communities themselves, are essential for building adaptive and equitable governance.

External actors, including multilateral institutions, regional fire agencies, international funders, and carbon-market organisations, can play a catalytic role by resourcing and providing capacity for long-term, community-led fire management. This includes establishing enduring monitoring partnerships that bridge community, state, and transnational actors (Krah et al. 2020; Fisher et al. 2022). When co-designed with local stakeholders and underpinned by transparent benefit-sharing and biodiversity-linked metrics, carbon-finance mechanisms can advance these aims, enhancing democratic self-governance, reducing operational costs, and reconciling ecological and social priorities (Croker et al. 2023b; Croker 2025).

Yet transformative change must be understood within the realities of Sub-Saharan Africa's ongoing land rush, where land grabs, resource conflicts, and competing agrarian claims have reconfigured state–community relations and fractured local institutions. Without strong safeguards, decentralisation risks reproducing exclusionary governance systems under the guise of participation (Croker 2025). As biomass declines, the social–ecological drivers of degradation and ignition will persist, revealing the wildfire paradox as an ecological–biocultural phenomenon symptomatic of multi-systemic pressures. Addressing this paradox demands identifying conditions that preclude opportunities for sustainable, local fire management, as well as prioritising political and legal reforms necessary to formalise customary land rights and develop inclusive, locally legitimate fire governance arrangements (Domínguez and Luoma 2020).

Advancing this agenda will require models that integrate exogenous shocks and cross-sectoral linkages, such as trade dynamics, market volatility, and infrastructural expansion, into probabilistic analyses of social–ecological change. Embedding such complexity into spatially explicit Bayesian frameworks will enhance their explanatory and policy relevance in specific management contexts, supporting the transition towards historically informed, socially just and ecologically adaptive fire governance across African conservation landscapes under future anthropogenic change.

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Data Availability Statement

The data supporting this article is based in Croker (2024).

Endnotes

[1] Full descriptions for each of the fire management and socioeconomic–climate scenarios modelled in this study are provided in Croker et al. (2024).

[2] In data-rich environments, spatiotemporal BBNs have been developed to model network effects over time (Cain 2001; Aalders 2008; Bashari et al. 2024), such as how different types of forest fire impact vegetation at each evolutionary burning phase (Giretti et al. 2012).

[3] SSPX-Y extensions, such as SSP4-3.4 and SSP5-3.4 OS, were also included in scenario development due to contextual relevance. For example, SSP4-3.4 reflects an inequality-driven development trajectory with limited adaptive capacity, while SSP5-3.4 OS represents a delay–mitigate pathway in which fossil-fuel-intensive growth persists until 2040, followed by aggressive climate policy responses to escalating residual climate costs (Narain et al. 2011; Meyer and Trisos 2023).

[4] Most carbon projects account only for above-ground biomass (AGB); but recognising the importance of below-ground biomass (BGB) for soil carbon, especially in grassy savannas, some are beginning to incorporate BGB, though uptake remains limited. In SAV BN, matrix (3) therefore includes an edge between 'plant diversity' and 'carbon credits' to capture the influence of productive herbaceous species on soil carbon stocks. In these BGB-inclusive scenarios, the edge from 'forestation' to 'carbon credits' is reduced relative to AGB-only scenarios to reflect broader and more balanced accounting requirements.

[5] Because 'intervention measures' exist along a continuum, each was described in detail to clarify its conceptualisation and operationalisation in SAV BN, for example, what an increase or decrease in 'firefighting capacity' or 'law enforcement' represented. This improved model transparency and internal consistency, particularly given the regional scope of the analysis and the limited empirical basis for generalising the causal relevance of fire management interventions across East African contexts.

[6] Outputs were generated for 82 nodes in the non-carbon matrix and 83 in the carbon matrix.

[7] Direct causal links between 'intervention measures' and 'wildfire' amplified local effects in the model, diminishing the influence of broader systemic interactions. Given the study's scope, interventions were aggregated into operational categories (see Section 3.5.1), and 'wildfire' was modelled as a composite node representing frequency, intensity and severity. While this approach facilitated comparative analysis, it also reduced internal complexity and masked potentially non-linear dynamics, especially because wildfire dimensions respond differently to biogeophysical conditions such as vegetation structure. In site-specific applications (e.g., protected or management areas), intervention and wildfire nodes could be disaggregated to better capture system complexity and guide local management decisions.

[8] The Ecological Threat Report (Institute for Economics and Peace 2023) measures four key indicators of ecological degradation directly related to social resilience and drivers of conflict: (1) food insecurity, (2) natural disasters, (3) demographic pressures and (4) water risk. These findings support Croker et al. (2023b) contextual analysis of the social–ecological challenges that characterise East and Southern Africa and, in turn, influence the policy domain and action situations available to actors to implement alternative fire management approaches.

[9] Croker et al. (2023b) provide a full analysis of the opportunities and challenges for SBEA schemes in East and Southern African savanna-protected areas, such as in the Miombo Woodlands where SBEA schemes are recommended for implementation, despite MAP often exceeding 1000 mm and woody species often accounting for > 90% of total biomass.

[10] Intensive and commercial agricultural systems are high-input high-output systems which often prioritise export-based production; therefore, increasing reliance on external markets. They are typically characterised by minimal fallow periods, high livestock stocking rates and population density, increased nutrient pollution and run-off and large labour requirements—including the use of fertiliser, ploughing and weeding activities and the establishment of irrigation systems and fencing networks.

[11] Evidence shows that across tropical mesic savannas worldwide, such as the South American Chaco, Brazilian Cerrado, much of Southeast Asia and Miombo Woodlands, agricultural frontiers are closely correlated with the use of intentionally ignited, uncontrolled fires to

clear extensive areas for production. These fires pose a direct wildfire risk to adjacent protected areas, threatening the generation of carbon credits in climate financing projects and raising concerns about carbon leakage.

[12] Causality between fire management activities and biodiversity is not easily discernible in East Africa due to decadal environmental variability driven by dynamic climate patterns across the Pacific and Indian Oceans. Hence, species responses to fire within a 10-year interval are likely to express time-lags representative of phenotypic plastic adaptions, necessitating longer-term monitoring and data collection to inform management actions (see Croker et al. 2023b).

[13] Local participants used the term 'gentlemen's agreements' to describe informal, often bribery-mediated arrangements between park authorities and selected community members, permitting livestock grazing in protected areas. Although the WCMA (2013) allows such access during droughts and natural disasters, the absence of a legal implementation framework results in uneven access, typically favouring political–economic elites, including ranch officials.

[14] *Nocturnal agency* refers to the rise of illicit activities within exclusionary conservation zones at night, exploiting reduced surveillance and visibility to circumvent access restrictions. Participants linked this to the loss of legal grazing options and increasing environmental uncertainty. Such activities elevate wildfire risks. In Kenya, certain management plans permit the construction of temporary bomas at night in conservation areas to support steer fattening for market compliance. However, this has facilitated strategic encroachment, with herders residing near park boundaries to exploit ambiguities in enforcement, contributing to habitat compression and management challenges.

[15] In some cases, intra-community conflicts have surpassed negative relationships with government agencies and NGOs; local people are increasingly becoming 'informers to partners, [...] informing and sharing information on who is participating in illegal activity, checking on who is doing what'. This is likely due to individual ambition and the perceived benefits of working with these organisations (e.g., increased access to resources), further evidencing growing sociocultural antagonisms at the local level and presenting several dilemmas regarding the decentralisation of management rights (Croker 2025).

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Data S1:** geo270063-sup-0001-Supinfo.docx.