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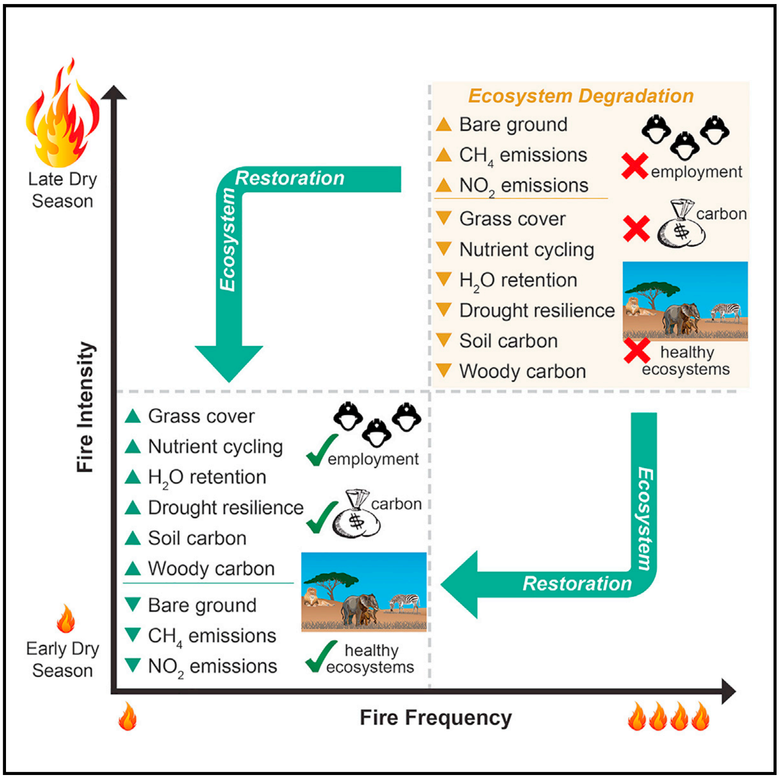
# Savanna fire management can generate enough carbon revenue to help restore Africa's rangelands and fill protected area funding gaps

## Graphical abstract




## Highlights

- Savanna burning methodologies could generate carbon revenues for many protected areas in Africa
- When combined with soil and woody carbon pools the potential is significantly greater
- Potential carbon revenues from fire management could substantially reduce protected area funding gaps
- Greater investment is needed in Africa to achieve multiple benefits from improved fire management

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## In brief

Carbon emissions from savanna burning contribute to global climate change. Improved fire management in Africa could dramatically reduce carbon emissions and build ecosystem resilience, reduce threats to biodiversity and provide much needed financial support to local economies. Potential carbon revenues could substantially reduce protected area funding gaps that are in crisis due to COVID-19 and diversify income to augment tourism. More funding to pilot projects is needed to realize this potential and accelerate the UN's Decade of Ecological Restoration.

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# Savanna fire management can generate enough carbon revenue to help restore Africa's rangelands and fill protected area funding gaps

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**SCIENCE FOR SOCIETY** The United Nation's launched the Decade of Ecological Restoration in response to planet-wide land degradation. This study analyses the potential for savanna fire management programs to reduce carbon emissions, restore fire regimes, and generate new revenue sources from carbon financing for chronically underfunded protected areas in Africa. We estimated the amount of carbon emissions reduced by shifting fires that normally burn in the late dry season (and emit more carbon) to the early dry season (that accrue more carbon in the soil and woody vegetation). Based on current carbon market values we found substantial potential to eliminate or significantly reduce the estimated US$ >1–2 billion annual funding gap for protected areas in Africa. Given additional benefits for nature and people from new savanna fire programs, we recommend integrated conservation and development projects direct more funding to fire management programs that support some of the least developed countries with high biodiversity in Africa.

## SUMMARY

Many savanna-dependent species in Africa including large herbivores and apex predators are at increasing risk of extinction. Achieving effective management of protected areas (PAs) in Africa where lions live will cost an estimated US$ >1–2 billion/year in new funding. We explore the potential for fire-management-based carbon financing programs to fill this funding gap and benefit degrading savanna ecosystems. We demonstrate how introducing early dry season fire management programs could produce potential carbon revenues (PCRs) from either a single carbon financing method (avoided emissions) or from multiple sequestration methods ranging from US$ 59.6–655.9 million/year (at US$ 5/ton) or US$ 155.0 million/year to US$ 1.7 billion/year (at US$ 13/ton). We highlight variable but significant PCRs for savanna PAs from US$ 1.5–44.4 million/year per PA. We suggest investing in fire management programs to jump-start the United Nations Decade of Ecological Restoration to help restore degraded African savannas and conserve imperiled keystone herbivores and apex predators.

 

## INTRODUCTION

Africa's iconic savanna ecosystems are at a crossroads, as many wildlife species are in precipitous decline, and the protected areas (PAs) intended to conserve them for future generations are facing extreme financial crises. While predators have been thought to have the highest extinction risk, herbivores have recently been shown to have the highest rates of extinction among mammals, birds, and reptiles.[1] The loss of large wild herbivores has potentially cascading effects on other species, including carnivores, as well as on key ecological processes, especially fire.[2]

African savannas support a higher diversity of ungulate species than in any other biome or continent.[3] Large mammalian herbivores, particularly megaherbivores, are known to exert strong effects on tropical savannas, especially in high diversity Africa savannas.[4] However, many large herbivore populations are declining, which is predicted to have significant impacts on human well-being from a variety of direct and indirect pathways, especially in low productivity areas common in Africa.[5] Livestock now outnumber wildlife in Africa,[1,6] which has profound implications for the continent in general, and savanna habitats in particular.[7] Not only are herbivores in trouble, but so too are many African savanna predators, in particular the lion (*Panthera leo*), whose range and population numbers have precipitously declined over the past two decades.[8–10] As African savannas are also at high risk of significant vegetative change due to a variety of global and local processes,[11] the combination of changing vegetation structure with altered grazing pressures in the context of a shifting climate patterns makes the future of this critical yet transitional ecosystem uncertain.

While PAs are recognized as one of the most effective conservation strategies in the world for protection of species and their habitats,[12–14] even in developing countries with intense human population and development pressures,[15] financing PAs remains a significant challenge,[16,17] notably in developing countries,[18] and especially in Africa.[19] The funding crisis has only been exacerbated by the global COVID pandemic, as it wreaked havoc on the global tourism industry, with catastrophic consequences for African PA systems that relied primarily (and in some cases, almost exclusively) on tourism revenue.[20,21] Given that African PAs are chronically underfunded, a fundamental question remains: Where would new funding come from to address these financial shortfalls and reduce, stabilize, or potentially reverse the land degradation and associated species declines that face savanna PAs in Africa?

The search for sustainable financing for conservation-related efforts in general, and PAs in particular, has produced a plethora of innovative financing ideas, such as trust funds, debt financing, ecosystem service payments, blended financing, and offsets.[22–24] As the global degradation of ecosystems is now well documented and linked directly to increasing impacts of climate change,[25] there is an important opportunity to directly connect the work needed to improve African savanna habitats with efforts to mitigate the impacts of climate change; and this opportunity is perhaps best captured within the socio-political context of the UN's Decade of Ecological Restoration.

The United Nation's Decade of Ecological Restoration began following recent reports highlighting that nearly a quarter of the earth's productive lands have been degraded, negatively impacting over 3 billion people.[26] Additional impacts of human-induced climate change further contribute to land degradation and human suffering, highlighting the need to address this increasing trend.[27] Amid this urgent call for restoration are cautious reminders that important lessons learned from decades of restoration efforts must be strategically applied to reduce risk and increase effectiveness.[28,29] Although ecological restoration can be prohibitively expensive, careful design can triple conservation benefits while halving the costs.[30,31] Such cost-benefit improvements will be necessary for meeting global conservation targets to reverse land degradation and biodiversity loss.[32]

A key component of ecological restoration is the recovery of ecological processes that will allow ecosystems to once again become self-sustaining (e.g., represented by the presence of ecologically functional populations of top predators such as the African lion, or the return of less frequent fire regimes that support more ecosystem services such as in Miombo woodlands[33]). A focus on ecological processes is particularly important when confronting habitat transformation—the combination of habitat loss, fragmentation, and degradation[34] that face many PA systems in Africa, and create complex ecological and management challenges. Changes in two dominant and interconnected ecological savanna ecosystem processes—fire and grazing—are having substantial and variable impacts. While there is a global decline in fire in many ecosystems,[35] some African ecosystems appear to be experiencing an elevated frequency of fire as a result of fire setting by poachers for the purposes of easing access to long grass and attracting wildlife to ensuing green flushes.[36] Increasing fire frequency may contribute to the loss of key elements in forage, such as N and P, and may promote stands of low-nutritive-quality forage species (e.g., *Themeda triandra*), which could negatively affect herbivore biomass.[37] Fire may also intensify competition for forage between grazers, including between wild ungulates and cattle.[38] Equally, exclusion of fire has resulted in an increase in bush encroachment[39] and the displacement of wild ungulates.[40] These complex interactions can occur within the same PA system, complicating management responses. Recent studies in the Serengeti-Mara ecosystem in East Africa highlighted that habitat loss and degradation on the outside of the PA network had significant negative impacts deep into the protected core of the PAs, further degrading the entire ecosystem.[41,42] Fire exclusion in some areas was driven by increases in sedentary domestic livestock outside the park, which alter the grazing impacts of migratory herbivores inside the park (e.g., wildebeest and zebra), reducing fuel loads and the ability of some areas to support fire.[42] Loss of fire as a result of fuel load decline and increasing amounts of bare earth have been linked to increased soil erosion, decreased soil carbon storage, and desertification,[43,44] as well as increases in human-wildlife conflict[45] that only exacerbates existing threats to species conservation.

The use of biodiversity offsets[46] and the global voluntary carbon market via Reducing Emissions from Deforestation and Forest Degradation (REDD/REDD+)[47] have been suggested as ways to alleviate chronic financing shortfalls in PA networks. Carbon financing from REDD+ has provided added revenue for some PA management systems, such as in Peru where benefit sharing for local communities was included.[48] While criticism of poorly conceived and monitored biodiversity offset projects have merit,[49] the vast majority of carbon financing has been focused on forested landscapes, with relatively little to no investment in grassland, rangeland, or savanna ecosystems in most parts of the globe.[50] However, by the end of 2018, emissions trading schemes raised a total of US$ 57.3 billion in auction revenues, demonstrating convincingly the scope and scale of the compulsory carbon market.[51] The voluntary carbon market has seen sales rise steadily since 2010, reaching an estimated US$ 48 million in global sales of land use change and forestry carbon credits by 2018.[52] A growing focus on natural climate solutions,[53] as well as new commitments to achieve carbon-neutral or Net Zero targets by countries and businesses has further increased global carbon market transactions. The development of new formal methodologies (e.g., Verra) for carbon accounting has created a credible, previously underutilized pathway to generate new and innovative income for savanna PAs by harvesting the oldest tool available to humans—fire.

While fire has shaped the diversity of life for millennia, there is growing recognition that fire can and should play a more important role in biodiversity conservation.[54] This study asks how much of the funding shortfall could be met by new and emerging carbon-based opportunities focused on savanna habitats and improved fire management. A recent global assessment highlighted how savanna fires mostly burn in the late dry season (LDS), resulting in more intense fires that produce greater emissions and damage human-built infrastructure.[55] This analysis concluded that globally significant emission reductions are possible by shifting from a current pattern of LDS fires to a pattern of cooler, early dry season (EDS) fires, and that the vast majority of global savanna fire emissions (74%) occur in Africa across 20 least developed countries (LDCs). Other studies suggest that similar fire abatement can increase soil and woody carbon sequestration,[56–58] suggesting additional carbon pools (e.g., soil, living and non-living woody carbon) should be accounted for in fire management programs.

Here, we investigate the potential for a well-managed EDS fire management program to generate carbon credits for African savanna PAs, and create a new, sustainable financial revenue stream. We demonstrate that this financing could indirectly support species conservation efforts both inside and outside PAs through habitat restoration (by reducing catastrophic fires and associated impacts to soils and vegetation) and directly support species conservation via other PA management actions (e.g., increased anti-poaching efforts and improved human-wildlife conflict resolution). We used greenhouse gas (GHG) emission abatement from methane ($CH_4$) and nitrous oxide ($N_2O$) to serve as a baseline, a relatively conservative estimate of potential carbon revenue (PCR) that could be generated from an EDS fire program.[55] We then combined emission abatement potential with estimates of carbon sequestration from three other carbon pools (i.e., non-living above ground biomass,[59,60] living above ground biomass,[61] and soil carbon[62]) to produce an upper estimate of carbon credit revenue-generating potential. We combined these estimates to produce a range of PCRs to determine how much of the PA financial shortfall recently estimated for savanna protected areas with lions (lion PAs)[16] could be met from carbon credits generated by EDS savanna burning programs. We discuss limitations of this approach in the context of land degradation trends, the challenges of fire management, and the stark realities of economic recovery from COVID-19 in some of the LDCs on the planet. We conclude by proposing a series of lion-centric pilot projects to launch the UNs Decade of Ecological Restoration and envision savanna fire management programs (such as successful northern Australia examples) as natural climate solutions and conservation-development investments that could reap multiple environmental and societal benefits in Africa.

## RESULTS

### PCR from savanna fire management for lion PAs in Africa

PCR from an EDS savanna fire management program could partially or entirely close the estimated US$ 1–2 billion funding shortfall for managing protected areas with lions (lion PAs) in Africa. We found that an EDS fire management program could generate PCR ranging from US$ 59.6 million to US$ 655.9 million per year (Table 1) based on the lower voluntary market average price (US$ 5/ton). At a higher price of US$ 13/ton, such a program could generate US$ 155.0 million to US$ 1.7 billion per year (Table 2).

In countries with the greatest potential for emissions reduction, five of seven (71%) are also countries with the greatest funding needs for PA management (Figure 1). As all seven of the countries with the greatest emissions reduction potential are also characterized as LDCs, there is substantial opportunity for this additional, new funding to provide significant co-benefits to national and local economies.

There is substantial potential for emission reductions benefits for the majority (65%; 198 of 303 in additional data in Table 1) of all lion PAs (Figure 2B). There is also substantial variability in the amount of local emissions produced within most landscapes (Figure 2A), and a significant trend ($R^2 = 0.61$, $p < 0.001$) that the larger the PA the greater the emissions reduction potential and therefore greater PCR (Figure 3). The PCR for each PA will be a product of the emissions reduction generated and the market price of carbon credits. As would be expected, larger PAs with a history of LDS wildfires and higher productivity generally demonstrate greater revenue-generating potential (Figures S1 and S2). Emissions reductions alone for all lion PAs across all countries could generate annual revenues between a median of US$ 825,562 per country (Table 1 at US$ 5/ton) to a median of US$ 2.1 million per country (Table 2 at US$ 13/ton).

However, the same EDS fire management program could also generate additional carbon credits from sequestration across the three remaining carbon pools: (1) above ground non-living biomass, (2) above ground live woody biomass, and (3) soil carbon. Our estimates suggest that, by shifting to cooler, patchier EDS fires, significantly more PCR would be accrued by combining the carbon sequestration and abatement across all carbon pools (Tables 1 and 2). This would reduce the financial shortfall for each lion range country by 4%–9% (median) for emissions abatement alone as compared with 45%–98% (median) by combining all carbon pools (at US$ 5–13/ton, Tables 1 and 2). While PCR from credits associated with living and non-living biomass are higher than for avoided emissions or soil carbon, they also introduce higher relative risk (Tables 1 and 2). These

**Table 1. African lion range states and lower estimate of carbon revenue potential from fire management in relation to PA funding gaps**

| Africa lion range-state country | No. of PAs with lions | GHG emission reduction potential (US$) | Soil carbon sequestration potential (US$) | Live woody biomass carbon sequestration potential (US$) | Non-living woody biomass carbon sequestration potential (US$) | Multiple carbon methods combined (US$) | % of annual PA finance gap from emissions reduction potential | % of annual PA finance gap from multi-method carbon revenue |
|---|---|---|---|---|---|---|---|---|
| | | Carbon project relative risk | | | | | | |
| | | Lower | Lower | Higher | Higher | Lower | | |
| Angola | 1 | 7,788,312 | 23,364,935 | 27,259,091 | 27,259,091 | 85,671,428 | 8.0 | 88.2 |
| Benin | 1 | 36,114 | 108,341 | 126,398 | 126,398 | 397,252 | 1.8 | 20.1 |
| Botswana | 47 | 3,075,543 | 9,226,628 | 10,764,399 | 10,764,399 | 33,830,968 | 1.2 | 12.8 |
| Burkina Faso | 1 | 2,960 | 8,880 | 10,360 | 10,360 | 32,560 | 0.3 | 3.0 |
| Cameroon | 1 | 6,215 | 18,645 | 21,752 | 21,752 | 68,364 | 0.4 | 4.3 |
| Central African Republic | 4 | 7,916,898 | 23,750,694 | 27,709,143 | 27,709,143 | 87,085,878 | 14.9 | 163.6 |
| Chad | 1 | 54,223 | 162,669 | 189,780 | 189,780 | 596,453 | 3.4 | 37.8 |
| Democratic Republic of the Congo | 4 | 1,864,276 | 5,592,828 | 6,524,966 | 6,524,966 | 20,507,037 | 5.1 | 56.0 |
| Ethiopia | 11 | 350,941 | 1,052,823 | 1,228,293 | 1,228,293 | 3,860,350 | 1.0 | 11.4 |
| Kenya | 12 | 57,058 | 171,174 | 199,703 | 199,703 | 627,638 | | |
| Malawi | 4 | 248,240 | 744,720 | 868,840 | 868,840 | 2,730,641 | 8.9 | 97.6 |
| Mozambique | 19 | 10,236,644 | 30,709,933 | 35,828,255 | 35,828,255 | 112,603,088 | 5.9 | 65.0 |
| Namibia | 6 | 825,562 | 2,476,685 | 2,889,466 | 2,889,466 | 9,081,178 | 2.9 | 32.2 |
| South Africa | 6 | 425,009 | 1,275,027 | 1,487,531 | 1,487,531 | 4,675,098 | | |
| South Sudan | 4 | 970,010 | 2,910,029 | 3,395,034 | 3,395,034 | 10,670,107 | 4.1 | 45.1 |
| Uganda | 4 | 612,433 | 1,837,298 | 2,143,515 | 2,143,515 | 6,736,760 | 7.5 | 82.3 |
| Tanzania | 25 | 10,424,509 | 31,273,526 | 36,485,781 | 36,485,781 | 114,669,596 | 4.9 | 53.7 |
| Zambia | 31 | 13,494,810 | 40,484,431 | 47,231,836 | 47,231,836 | 148,442,912 | 8.0 | 88.2 |
| Zimbabwe | 16 | 1,238,281 | 3,714,842 | 4,333,983 | 4,333,983 | 13,621,089 | 3.7 | 40.3 |
| Median | 4 | 825,562 | 2,476,685 | 2,889,466 | 2,889,466 | 9,081,178 | 4 | 45 |
| Total | 198 | 59,628,036 | 178,884,108 | 208,698,126 | 208,698,126 | 655,908,397 | | |

The potential for EDS fire management programs to generate carbon revenue in relation to protected area (PA) finance gaps for all PAs (with >0 GHG reduction potential). The rate of US$ 5/ton was applied as a lower estimate based on the current average of voluntary market values. Multiple methods include four existing carbon methodologies that could generate carbon credits from implementing an EDS fire management program focused on emissions reduction and carbon sequestration. PA finance gaps were based on cost estimates for effective PA management according to Lindsey et al.[16]

**Table 2. African lion range states and upper estimate of potential carbon revenue from fire management in relation to PA funding gapss**

| Africa lion range-state country | No. of PAs with lions | GHG emission reduction potential (US$) | Soil carbon sequestration potential (US$) | Live woody biomass carbon sequestration potential (US$) | Non-living woody biomass carbon sequestration potential (US$) | Multiple carbon methods combined (US$) | % of annual PA finance gap from emissions reduction potential | % of annual PA finance gap from multi-method carbon revenue |
|---|---|---|---|---|---|---|---|---|
| | | Carbon project relative risk | | | | | | |
| | | Lower | Lower | Higher | Higher | Lower | | |
| Angola | 1 | 20,249,610 | 60,748,831 | 70,873,636 | 70,873,636 | 222,745,714 | 20.9 | 229.4 |
| Benin | 1 | 93,896 | 281,688 | 328,636 | 328,636 | 1,032,855 | 4.8 | 52.4 |
| Botswana | 47 | 7,996,411 | 23,989,232 | 27,987,437 | 27,987,437 | 87,960,517 | 3.2 | 35.3 |
| Burkina Faso | 1 | 7,696 | 23,088 | 26,936 | 26,936 | 84,655 | 0.7 | 7.8 |
| Cameroon | 1 | 16,159 | 48,476 | 56,555 | 56,555 | 177,746 | 1.0 | 11.1 |
| Central African Republic | 4 | 20,583,935 | 61,751,805 | 72,043,772 | 72,043,772 | 226,423,284 | 33.9 | 372.4 |
| Chad | 1 | 140,980 | 422,939 | 493,429 | 493,429 | 1,550,777 | 8.9 | 98.4 |
| Democratic Republic of the Congo | 4 | 4,847,118 | 14,541,354 | 16,964,913 | 16,964,913 | 53,318,297 | 10.1 | 111.2 |
| Ethiopia | 11 | 912,446 | 2,737,339 | 3,193,562 | 3,193,562 | 10,036,910 | 2.1 | 23.6 |
| Kenya | 12 | 148,351 | 445,053 | 519,228 | 519,228 | 1,631,859 | | |
| Malawi | 4 | 645,424 | 1,936,272 | 2,258,984 | 2,258,984 | 7,099,666 | 24.4 | 268.5 |
| Mozambique | 19 | 26,615,275 | 79,845,826 | 93,153,464 | 93,153,464 | 292,768,029 | 21.6 | 237.6 |
| Namibia | 6 | 2,146,460 | 6,439,381 | 7,512,611 | 7,512,611 | 23,611,063 | 5.7 | 62.2 |
| South Africa | 6 | 1,105,023 | 3,315,070 | 3,867,581 | 3,867,581 | 12,155,255 | | |
| South Sudan | 4 | 2,522,025 | 7,566,076 | 8,827,088 | 8,827,088 | 27,742,277 | 7.9 | 86.8 |
| Uganda | 4 | 1,592,325 | 4,776,975 | 5,573,138 | 5,573,138 | 17,515,576 | 34.2 | 376.3 |
| Tanzania | 25 | 27,103,723 | 81,311,168 | 94,863,030 | 94,863,030 | 298,140,951 | 15.0 | 164.5 |
| Zambia | 31 | 35,086,507 | 105,259,520 | 122,802,773 | 122,802,773 | 385,951,572 | 18.0 | 198.2 |
| Zimbabwe | 16 | 3,219,530 | 9,658,590 | 11,268,355 | 11,268,355 | 35,414,830 | 7.4 | 81.4 |
| Median | 4 | 2,146,460 | 6,439,381 | 7,512,611 | 7,512,611 | 23,611,063 | 9 | 98 |
| Total | 198 | 155,032,894 | 465,098,681 | 542,615,128 | 542,615,128 | 1,705,361,832 | | |

The potential for EDS fire management programs to generate carbon revenue in relation to PA finance gaps for all PAs (with >0 GHG reduction potential) with lions. The rate of US$ 13/ton was applied as an upper estimate based on an average of Western Climate Initiative Carbon Auction Settlement prices.[63] Multiple methods include four existing carbon methodologies that could generate carbon credits from implementing an EDS fire management program focused on emissions reduction and carbon sequestration. PA finance gaps were based on cost estimates for effective PA management according to Lindsey et al.[16]

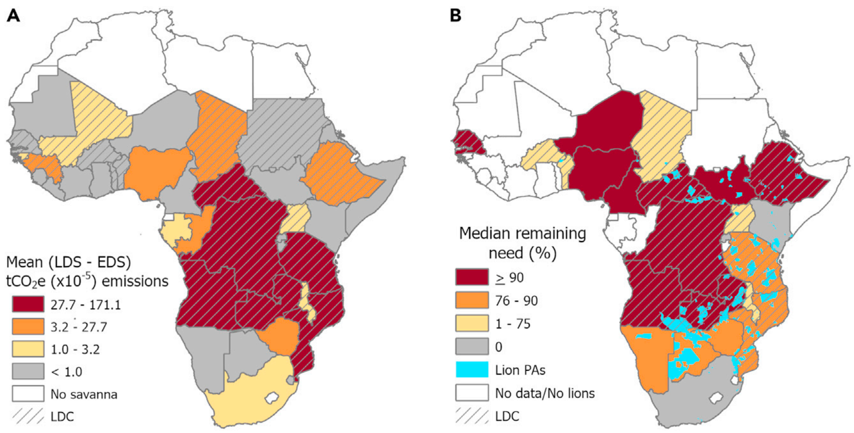


**Figure 1. Carbon emission reductions from improved fire management and the estimated financial need for effective management of protected areas with lions**

(A and B) The country-level relationship between (A) carbon emission reductions (in tons of carbon dioxide equivalents, t$CO_2$-e) resulting from instituting a fire management plan that shifts fires from the late dry season (LDS) to the early dry season (EDS) compared with (B) countries with lions and the financial need estimated for effective protected area (PA) management. The potential benefit of launching EDS savanna burning activities (A) are scaled by mean country-level abatement potential (LDS-EDS) emissions (using terciles on GHG values >0), and countries with crosshatching are least developed countries (LDC) (from Lipsett-Moore et al.[55]). See also Figure S1.

estimates do not account for other ecosystem services and local employment benefits or costs produced from implementing an EDS fire management program.

### Potential revenue for the top 20 lion PAs

While there is significant variability in the potential for fire management-generated emissions reductions across all lion PAs in Africa, a fire-based carbon project could have a significant and positive impact on some of the largest and most important savanna habitats and lion populations. When we ranked the top 20 PAs prioritized by the greatest PCR, such carbon financing could generate between US$ 2.0 million/year on average for each lion PA (at US$ 5/ton via emissions abatement only) and US$ 57.5 million/year (at US$ 13/ton combining all carbon pools) (Table 3). Using lions as an indicator of improved savanna ecosystem health, such funding could potentially restore lion populations and collectively conserve up to 23,191 lions with an average of 1,160 lions per PA (Table 3; SD = 1,196, n = 20). Similarly, when we ranked the top 20 lion PAs prioritized by lion population size, their PCRs could potentially support up to 30,563 lions with an average of 1,528 lions per PA (Table 4; SD = 1,028, n = 20), generating on average US$ 1.5 million/year per lion PA (at US$ 5/ton via emissions reduction) and US$ 44.3 million/year (at US$ 13/ton via multiple methods) (Table 4).

Given that total lion recovery potential (i.e., carrying capacity) for the 198 lion PAs with the potential to generate fire-carbon revenue is estimated at approximately 60,000 lions (see supplemental information; Table 2), prioritizing investments on a small subset—i.e., the 20 lion PAs with the greatest PCR potential—would capture one-third of the total lion recovery potential versus half of total lion recovery potential if the 20 lion PAs with the greatest lion carrying capacities were selected. Furthermore, the top 20 PAs when ranked by PCR (Table 3) occurred in half as many countries (7) as when PAs were ranked by potential lion numbers (14 countries, Table 4). Two countries (Zambia and Tanzania) emerged as having the greatest PCR potential for range-wide lion conservation, as they contained more than half of the lion PAs prioritized by PCR. When the lion PA rankings from both lists were combined (Table S1), only 10 lion PAs occurred on both prioritized lists, of which the top 5 combined rank sites each occurred in different countries (illustrating that no country was prioritized). However, Zambia emerged as a clear country-level priority from the complete combined rank prioritization list, as it occurred multiple times (5), capturing half of all the top 10 priority sites.

## DISCUSSION

Savannas are the world's most fire prone landscapes, contributing 30% of terrestrial net primary production[65] and covering 20% of the Earth's terrestrial surface.[66] Given the global focus on decreasing land degradation to address climate change[25] paired with greater attention on finding natural climate solutions,[53] our results suggest that fire management could play a critical role in financing conservation of and directly improving savanna habitats. As 20 LDCs in Africa account for nearly three-quarters (74%) of the mitigation potential from an EDS savanna fire management program,[55] there is clearly potential for launching local fire management programs as a bona fide natural climate solution that would directly contribute to national and local economies as well as to national GHG emission reductions. This climate-smart strategy is starkly different from many other better-known climate mitigation strategies, such as emissions reductions and afforestation in the developed world. Most notably, this type of natural climate solution intends to generate multiple additional benefits including biodiversity conservation (i.e., large herbivore and lion conservation), ecosystem and economic resilience, and enhanced ecosystem services that will improve human well-being of climate vulnerable local economies in under-developed countries.

Recent analysis of World Bank and Global Environment Facility funding—the largest international donor for biodiversity funding—revealed that integrated conservation and development projects in the tropics did not favor high biodiversity areas, nor countries with the greatest development needs.[67] Furthermore, they found that while Sub-Saharan Africa is stated as a top priority for World Bank funding, African countries have been largely underserved in comparison with other continents in receiving integrated conservation and development project funding. There is great potential for fire management programs to improve local livelihoods by not only hiring local community members, but also acting as a venue to incorporate local ecological knowledge into habitat management programs. Well protected and managed

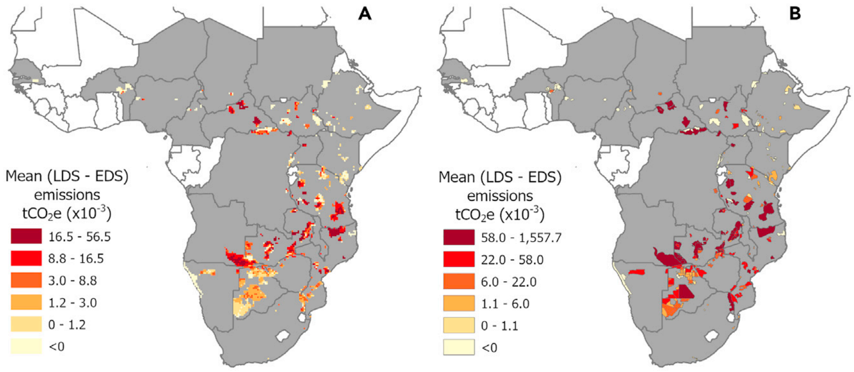


**Figure 2. Greenhouse gas emissions reduction potential for 256 PAs with lions**

Estimated mean annual emissions abatement from an effective LDS-EDS fire management approach in African savannas.

(A and B) PAs with lions are illustrated by (A) pixels within lion PAs, and (B) summed for the entire lion PA. Classes were based on quintiles (for all values >0). Twenty-three countries (gray) contain at least 1 of the 256 PAs. All greenhouse gas emissions are presented as tons of carbon dioxide equivalents ($tCO_2$-e) multiplied by $10^{-3}$. See also Figure S1.

natural habitats help conserve key ecosystem services, such as clean water provision, and PAs also have potential to act as hubs for tourism industry development and other forms of service provision to communities.[20] As the most significant savanna burning occurs in some of the world's most vulnerable countries, this presents an untapped opportunity to invest in integrated conservation-development projects that also contain the vast majority of the world's remaining free-ranging, but rapidly declining, African lion populations[8] and the most imperiled species group, the herbivores.[3] Herbivores, both large (e.g., megaherbivores) and small (e.g., dung beetles and termites) play key roles in distributing nutrients in African savanna ecosystems at a scale comparable with regional atmospheric nutrient fluxes.[68] Improved grassland management has been shown to increase soil carbon stocks via multiple pathways,[69] including the use of domestic herbivores (i.e., livestock) which historically have played an important role in enriching and diversifying predominantly nutrient-limited but productive African grasslands and savannas.[70] Recent research has shown that rangeland restoration efforts that involve more wildlife-livestock rangeland management could actually improve rangeland quality in African savannas, but only if wild megaherbivores are included.[71,72]

We used lions as an important indicator of restoration success, and selected lions because the best data on Africa's PA funding challenges have been generated in service of lion conservation efforts. We recognize that it would be possible and useful to select a different set of savanna PAs and focus on a different suite of species. However, the emphasis on lions already captures many of the large and important PAs that also contain critical large herbivore populations, and the management actions associated with the fire management program and associated activities would equally benefit large herbivores as well as lions. The analysis also captures those areas in Sub-Saharan Africa with some of the highest fire frequencies (e.g., Zambia) and therefore provides a reasonable proxy for how a fire management program could help support PA systems at the national level. From a monitoring and evaluation perspective, selecting a narrow focus on one species presents a clear management goal to help evaluate the effectiveness of the fire management program. In this context, we acknowledge that our predicted lion numbers and PCR estimates could be affected by biases that exaggerate the stated potential for lion population recovery. For example, the lion carrying capacity model was based on biological estimates that do not factor in human habitation within and around many of these lion PAs that will reduce potential lion population size regardless of fire programs and within-PA management. However, to estimate the potential for lion recovery, we believe that having a consistent index of lion potential to apply across all lion PAs was more appropriate for this study than accommodating the high uncertainties associated with current lion population estimates.[73]

For PCR estimation, some recent voluntary carbon market rates (US$ 2–3/ton) are lower than the 13-year voluntary market average used in this study (US$ 5/ton), and we did not include the cost of setting up carbon projects in each of these lion PAs as they are highly variable and difficult to estimate consistently. The current compulsory carbon market rates in Australia average approximately US$ 7.68/ton and recently sold for US$ 10.27/ton and, with the introduction of the Carbon Offsetting Scheme for International Aviation, future carbon prices may far exceed those used in this study.[52] Hence, our PCR estimates may be underestimating the carbon values over 5- to 15-year horizons, especially considering that over a million soil carbon credits recently sold in Northern Kenya for US$ 6–8/ton (M.E. Ritchie, personal communication).

Finally, there is increasing recognition that carbon projects in general, and REDD+ projects in particular, carefully assess the measurement, reporting, and verification (MRV) requirements as they can result in prohibitively high costs that ultimately render the project financially unsustainable.[74] Unfortunately, as these rangeland carbon projects are so new (both in Africa and for the different carbon methodologies), there is not enough information to model the optimal cost/benefit ratios as has been done for REDD+ forest carbon projects. It is our assumption that larger projects have better cost/benefit ratios in relation to MRV costs than small projects, which in turn must be balanced with sufficient carbon credits from either reduced emissions and/or carbon sequestration. To appropriately assess these trade-offs, more location-specific information is needed, and as this is a continental assessment, it is outside the scope of this effort. Assuming our estimates represent a credible and appropriate balance between current and future voluntary and compulsory carbon market prices, our analysis confirms that there is significant potential for an effectively run fire management program to provide substantial sources of revenue that would be offset to greater or lesser amounts by the kind of carbon financing chosen, the productivity of the landscape, and the associated MRV costs.

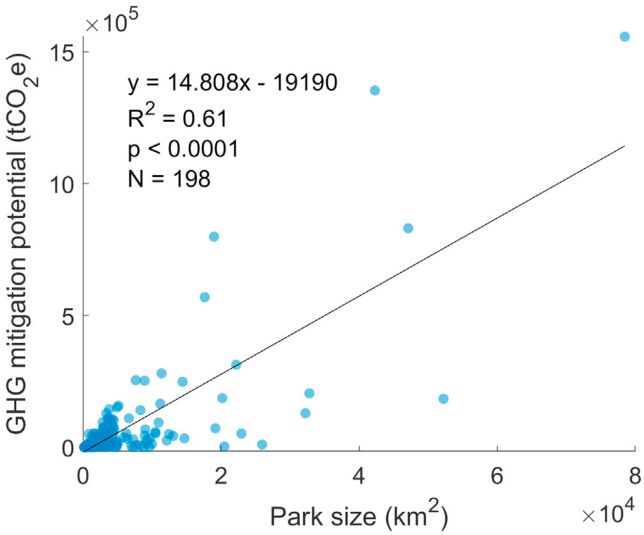


**Figure 3. Linear regression showing the significant relationship between protected area size and greenhouse gas emissions reduction potential (>0 tons of carbon dioxide equivalents, $tCO_2$-e) from effective LDS-EDS fire management**

We further recognize that, while savanna burning projects in Australia have made a substantial contribution to Australian conservation—generating multiple benefits for PAs and local communities[75]—it will take significant investment for similar benefits to be realized in Africa. A key constraint to the large-scale derivation of carbon revenues in Africa is for African countries to have appropriate regulatory frameworks that guide the generation and reinvestment of carbon revenues in a manner that results in strengthened management of PAs—rather than the funds being captured by the central government. A savanna burning program clearly presents the potential for "new and sustainable financing," as little carbon financing is currently being generated for lion PAs in Africa. Such projects have been slow to start due to the fact that they reside in savannas, not forests where most of the carbon project investments have been made (although some projects have been started in Kenya, Tanzania, and Zambia). As each of the three carbon sequestration methods introduced in this study are projected to generate revenues for two to three decades,[59,60,62] this type of carbon financing offers a vastly more sustainable alternative to most short-term development aid programs. However, given the multiple socio-cultural and economic benefits of these fire management-based carbon financing projects, we suggest that funding the start-up costs for establishing such a long-term, sustainable financing program could be viewed as a credible, integrated conservation and development project that further supports the global call for ecological restoration.

There are multiple ways such a project can benefit iconic African savanna species in crisis. The revenue generation provided by these carbon projects that is above the costs of implementing the fire management program (and its associated MRV costs) could be used to support other conservation activities. We recognize that the provision of more money, alone, will not directly result in greater wildlife populations unless it is provided in the context of sound governance and management structures. For example, surplus resources could be used to support anti-poaching patrols or projects that improve human-wildlife co-existence, such as those delivered by a growing number of effective public-private partnerships for PA management.[76] These activities would further augment the potential for altered fire management to improve savanna habitat by increasing forage quality and quantity for large herbivores and lion prey species. Land managers have used prescribed burning in African savannas to prevent catastrophic fires that negatively impact vegetation (e.g., riparian forests) and infrastructure, and to create benefits for wildlife and livestock, including improving forage quality, controlling bush encroachment, reducing tick-borne diseases in livestock, and attracting higher densities of grazers.[77] More productive African savannas (based on rainfall and soil nutrients) support greater herbivore biomass, which in turn supports greater carnivore biomass,[78–80] and lion density in PAs is closely related to prey biomass.[64] Furthermore, EDS fires could improve lion fitness by leaving taller grass in the LDS, as lions hunt more frequently and with greater success with increased cover.[81,82] While such effects are uncertain and difficult to predict,[83] the presence of fire management teams can also become an additional deterrent to poachers by their presence and their ability to remove snares that are an important source of mortality for lions and their prey. More research and monitoring of lion response to any fire management is needed to ensure that management objectives are being achieved. Carbon projects provide critical funding for monitoring and evaluation to enable these kinds of evidence-based adaptively managed projects to be established.

Despite all these positives, the potential for carbon credits and lion recovery alone will not be enough to overcome the current challenges to implementation.

First, there are hurdles to implementing successful fire management programs at scale in Africa. A recent review by Nieman et al.[84] highlighted several challenges related to fire management programs focused on improving forage quality and removing less palatable and more combustible grass material. For example, they highlighted that burning in the EDS would force grasses to regrow in the dry season when they would be water-stressed, reducing forage that could sustain grazing animals through the dry season. They also highlighted that such impacts would vary depending on the amounts of rainfall, with drier areas requiring a more restrictive fire management program. However, data from the Serengeti ecosystem of applying such a fire management program over a decade, when combined with increased anti-poaching efforts, resulted in dramatic increases in herbivore biomass and lion sightings.[85] This suggests that positive wildlife responses to EDS fire management programs in the context of well-funded PA management are possible. In addition, recent modeling efforts for Miombo woodlands suggest that a shift from annual burning to a longer 3.3-year mean fire return interval could generate significant carbon returns,[58] which for Niassa Special Reserve in Mozambique would apply to nearly half of the 42,000 ha PA.[86] This longer fire return interval is considered "optimal" in comparison with annual burning as it has been shown to increase multiple ecosystem service benefits to people and nature in Miombo habitat.[33]

**Table 3. Top 20 lion PAs in Africa estimated to gain the most carbon revenue generated from a fire management program**

| Rank | Africa lion range-state country | Africa lion protected area | Low PCR/year US$ | Middle PCR/year US$ | High PCR/year US$ | Predicted lion population estimate |
|---|---|---|---|---|---|---|
| 1 | Angola | Luengue-Luiana | 7,788,312 | 85,671,428 | 222,745,714 | 5,633 |
| 2 | Mozambique | Niassa | 6,765,565 | 74,421,213 | 193,495,153 | 1,881 |
| 3 | Tanzania | Selous | 4,153,721 | 45,690,931 | 118,796,419 | 2,157 |
| 4 | Central African Republic | Manovo-Gounda-Saint Floris | 3,993,089 | 43,923,982 | 114,202,353 | 1,457 |
| 5 | Central African Republic | Chinko | 2,846,294 | 31,309,238 | 81,404,020 | 359 |
| 6 | Zambia | Kafue | 1,564,726 | 17,211,987 | 44,751,166 | 1,714 |
| 7 | Tanzania | Moyowosi | 1,401,352 | 15,414,870 | 40,078,663 | 762 |
| 8 | Zambia | Lunga-Luswishi | 1,271,273 | 13,984,003 | 36,358,407 | 416 |
| 9 | Zambia | South Luangwa | 1,260,617 | 13,866,785 | 36,053,640 | 1,104 |
| 10 | Zambia | Musalangu | 1,242,875 | 13,671,622 | 35,546,217 | 1,594 |
| 11 | Democratic Republic of the Congo | Bili-Uere | 1,022,510 | 11,247,608 | 29,243,781 | 638 |
| 12 | Tanzania | Ruaha | 930,825 | 10,239,071 | 26,621,585 | 540 |
| 13 | Botswana | Central Kalahari | 918,503 | 10,103,529 | 26,269,176 | 1,616 |
| 14 | Central African Republic | Bamingui-Bangoran | 826,465 | 9,091,120 | 23,636,912 | 413 |
| 15 | Tanzania | Ugalla | 788,381 | 8,672,195 | 22,547,707 | 269 |
| 16 | Democratic Republic of the Congo | Garamba | 754,720 | 8,301,918 | 21,584,987 | 95 |
| 17 | Zambia | Kafinda | 719,328 | 7,912,603 | 20,572,767 | 257 |
| 18 | Zambia | Luano | 702,844 | 7,731,285 | 20,101,341 | 800 |
| 19 | Zambia | West Zambezi | 642,913 | 7,072,043 | 18,387,312 | 1,254 |
| 20 | Tanzania | Lwafi | 640,308 | 7,043,384 | 18,312,799 | 231 |
| Mean | | | 2,011,731 | 22,129,041 | 57,535,506 | 1,160 |
| SD | | | 2,029,972 | 22,329,691 | 58,057,198 | 1,196 |
| Total | | | 40,234,620 | 442,580,815 | 1,150,710,118 | 23,191 |

The low estimate of potential carbon revenue (PCR) was based on emissions reduction (Lipsett-Moore et al.[55]), and valued at an average voluntary carbon market rate of US$ 5/ton. The higher end of the range added in three carbon sequestration estimates, and was valued at the higher voluntary market average rate of US$ 13/ton. The middle PCR estimate used multiple methods (emission reduction and sequestration) at the lower market rate. Predicted lion population estimates (i.e., carrying capacity) were created from Loveridge and Canney.[64]

**Table 4. Top 20 PAs in Africa with the largest estimated lion populations, and the amount of potential carbon revenue generated from a fire management program**

| Rank | Africa lion range-state country | Africa lion protected area | Low PCR/year US$ | Middle PCR/year US$ | High PCR/year US$ | Predicted lion population estimate |
|---|---|---|---|---|---|---|
| 1 | Angola | Luengue-Luiana | 7,788,310 | 85,671,410 | 222,745,666 | 5,633 |
| 2 | Tanzania | Selous | 4,153,720 | 45,690,920 | 118,796,392 | 2,157 |
| 3 | Mozambique | Niassa | 6,765,565 | 74,421,215 | 193,495,159 | 1,881 |
| 4 | South Sudan | Zeraf | 467,260 | 5,139,860 | 13,363,636 | 1,779 |
| 5 | Tanzania | Serengeti | 214,030 | 2,354,330 | 6,121,258 | 1,776 |
| 6 | Zambia | Kafue | 1,564,725 | 17,211,975 | 44,751,135 | 1,715 |
| 7 | Botswana | Central Kalahari | 918,505 | 10,103,555 | 26,269,243 | 1,616 |
| 8 | Zambia | Musalangu | 1,242,875 | 13,671,625 | 35,546,225 | 1,594 |
| 9 | Central African Republic | Manovo-Gounda-Saint Floris | 3,993,090 | 43,923,990 | 114,202,374 | 1,457 |
| 10 | South Sudan | Badingilo | 221,070 | 2,431,770 | 6,322,602 | 1,455 |
| 11 | Zambia | West Zambezi | 642,915 | 7,072,065 | 18,387,369 | 1,254 |
| 12 | Kenya | Tsavo East & West | 14,525 | 159,775 | 415,415 | 1,169 |
| 13 | Zambia | South Luangwa | 1,260,615 | 13,866,765 | 36,053,589 | 1,104 |
| 14 | Ethiopia | Gambella | 226,705 | 2,493,755 | 6,483,763 | 958 |
| 15 | South Africa | Kruger | 359,400 | 3,953,400 | 10,278,840 | 908 |
| 16 | Burkina Faso | Arli | 2,960 | 32,560 | 84,656 | 890 |
| 17 | South Sudan | Meshra | 79,130 | 870,430 | 2,263,118 | 869 |
| 18 | Zambia | Luano | 702,845 | 7,731,295 | 20,101,367 | 800 |
| 19 | Zimbabwe | Hwange | 168,295 | 1,851,245 | 4,813,237 | 779 |
| 20 | Namibia | Etosha | 260,675 | 2,867,425 | 7,455,305 | 769 |
| Mean | | | 1,552,361 | 17,075,968 | 44,397,517 | 1,528 |
| SD | | | 2,228,922 | 24,518,145 | 63,747,177 | 1,028 |
| Total | | | 31,047,215 | 341,519,365 | 887,950,349 | 30,563 |

The low estimate of potential carbon revenue (PCR) was based on emissions reduction (Lipsett-Moore et al.[55]), and valued at an average voluntary carbon market rate of US$ 5/ton. The higher end of the range added in three carbon sequestration estimates, and was valued at the higher voluntary market average rate of US$ 13/ton. The middle PCR estimate used multiple methods (emission reduction and sequestration) at the lower market rate. Predicted lion population estimates (i.e., carrying capacity) were created from Loveridge and Canney.[64]

Second, it is also paramount that fire management programs are adaptable to local context in space and time. For example, due to the relatively ubiquitous global increase in savanna woody encroachment,[11] concerns that changing fire seasonality may lead to increased woody encroachment, wildlife migration, or any other unintended consequence of altering fire regimes, are important to address in any fire management program. However, several studies suggest increases in woody biomass in African savannas are not driven by changes in fire regimes, but instead by other factors, most notably the impact of browsing pressure from herbivores,[87] but also elevated $CO_2$ levels, changing land management, and precipitation.[11,88] In some African savannas, large grazing herbivores have been shown to modulate the impact and spatial extent of fire,[89] which in turn can impact tree cover, although the relationship between large herbivore influence on trees in savannas is complex and can produce both positive and negative impacts.[90] As the diversity of canopy cover in African savannas is directly linked to animal diversity and ecosystem functionality,[91] careful assessment of vegetative responses to changes in fire management can and should be incorporated into the monitoring and evaluation programs of any carbon projects involving fire management. However, if woody encroachment is a management concern, a brief shift to early wet season burning has been shown to reverse woody encroachment,[92] and Nieman et al.[84] highlight that fire management programs that focus on both early dry and early wet season fires provide the most practical approach to balancing ecological and societal goals. Similarly, patch mosaic burning has been shown to be a successful technique for shifting away from LDS fires, which ultimately could improve habitat heterogeneity and associated biodiversity responses,[93,94] although carbon gains would likely be lower due to more intense fires than if fires were shifted exclusively to the EDS.

Third, there must be lasting capacity to implement fire management and carbon stock evaluation programs in the form of expertise, governance structures, and tools for management and assessment to effectively implement EDS burning. In Australia, the savanna fire management program has benefited immensely from indigenous knowledge and implementation capacity.[95] In Africa, while similar knowledge exists, there needs to be greater investment to support broader, more cohesive governance structures to administer safe and effective burning programs over large areas.[96] We urge the bilateral and multilateral development and aid sectors to conceptualize this type of project like the UN's Land Degradation Neutrality program describes it—as a way to leverage progress on meeting the sustainable development goals and reducing the biodiversity crisis.[97]

Fourth, a major challenge is overcoming an under-appreciation of the importance of soil carbon in the fundamental health of ecosystems, adaptation to climate change, and as a sink for GHGs.[50] EDS fire management aligns with broader objectives to build healthier soils and restore productive terrestrial ecosystems. Healthier soils capture more carbon, and in turn improve nutrient cycling and water storage capacity.[50] These outcomes have direct benefits for local communities. For example, Miombo woodlands in Africa—like those in Niassa-Selous—are of global importance for carbon storage and sequestration[98] and support the daily needs of more than 100 million people,[99–101] yet are likely to experience increased pressure[102–104] and need more sustainable land management practices.[56,99] Already available carbon methodologies[105] provide a way to finance and functionally achieve such practices, and much more awareness is needed in the bilateral and multilateral aid sectors to spur greater investment in this kind of nature-based solution.

Finally, our results demonstrate a fundamental need for improved technology transfer to develop the full suite of carbon methodologies for EDS burning for Africa. A simplified platform that maps management actions onto complex formal methodologies and that convert actions into ecosystem services and economic values such as carbon credits is needed to enable potential carbon project developers to overcome multiple technical tasks in delivering PCRs. These tasks include estimating baselines, potential emissions reduction and sequestration rates, and demonstrating compliance with applicability conditions and additionality for fire management-based carbon projects. Concurrently, there is also the need for technical capacity to track changes in additional socio-cultural co-benefits. In Australia, such tools have greatly enhanced the uptake and development of projects across northern Australia's savannas resulting in contracts to secure 13.6 million tons $CO_2$-e over the next decade.[106] The availability of such tools (e.g., NAFI and SavBAT) for savanna burning carbon projects greatly enhanced savanna burning uptake and adoption.[107]

Despite the significant potential, there are currently no fire management-based carbon projects in Africa. Identifying priority pilot projects will be a key part of moving forward,[55] which can take advantage of recent advances in technology and extensive experience in fire management around the world that has identified key implementation challenges and opportunities.[108] Our analysis suggests that initiating projects in Zambia could result in a significant return on this investment, as there are substantially more high-priority lion carbon projects in Zambia than any other country. It is notable that Zambia already has successful lion carbon projects that provided significant revenues to local communities during the pandemic (e.g., in 2020 and 2021, BioCarbon Partners injected direct cash payments of US$ 4.76 million dollars from carbon revenues by the sale of offsets into 12 Chiefdoms).[109] As there are many socio-political, economic, and bureaucratic issues that would need to be resolved to ensure that, in each country, carbon revenues were re-invested into PA management, prioritizing initial investments to demonstrate a proof-of-concept is critical. This must include developing fire management policies that can address conflicting goals and trade-offs needed to balance the socio-cultural, political, and economic demands on any fire management program developed in the context of a PA system as well as the lands and land use practices that surround them. Creating new carbon financing mechanisms that allow existing carbon projects to add-in fire management that emphasize different carbon pools are desperately needed.

Finding new sources of funding for conservation is often overtaken by other competing societal needs. The lion is considered Africa's most iconic apex predator, and a critical link to developing more robust economies in some of the LDCs on the planet.[110] Large herbivores have emerged as one of the most imperiled species groups that also exert cascading effects on savanna ecosytems.[4] If current trends are allowed to continue, many African countries will lose their most iconic wildlife species before they have the chance to benefit significantly from them.[16] Our results suggest that investments in natural climate solutions that improve ecosystem health are complementary rather than competitive with other societal priorities. Carbon projects may significantly diversify the conservation revenue portfolio. Such diversification might mitigate extensive COVID-19-related economic impacts, including the catastrophic collapse of tourism revenue essential for most of these savanna PAs while also building economic resilience to future, unforeseen crises. Carbon projects offer potential "win-win-win" solutions that address the existential threat of climate change, improve the resilience of local communities, and reduce the loss of biodiversity and degradation of land at the same time.

## Concluding comments

We have shown how a more strategic approach to fire management in Africa has considerable potential to produce a cascade of positive, self-reinforcing impacts for savanna PAs and the local communities that rely on them. Exploiting the natural climate solution potential of savannas can unlock sufficient long-term revenue to close budget gaps for enduring and effective management of savanna PAs. That revenue would allow curtailing of the primary short-term drivers of lion and large herbivore declines, particularly poaching and encroachment by people and livestock on PAs. Concomitantly, increased primary productivity arising from changed fire management practices can reverse habitat degradation, build soil carbon and greater resilience to climate change-induced drought, and augment the recovery of large herbivores and lions as well. That in turn unlocks the potential for local communities and national governments to benefit from healthy functioning landscapes with thriving wildlife populations.

The mechanism underlying all these impacts also has substantial potential to reduce carbon emissions at a large scale with obvious benefits for the warming climate. Revenues generated from PAs via carbon financing are likely to help offset some of the opportunity costs associated with savanna PAs and increase the political will for the retention of such lands. Africa is facing explosive human population growth, and countries, such as Zambia and Tanzania with above-average proportions of their land area devoted to PAs and high-priority lion populations, will experience greater pressure to reallocate land for agriculture and settlement. In this Decade of Ecological Restoration, we suggest restoring EDS fire regimes in African savannas by launching pilot projects in areas with the greatest potential for restoring lion and associated large herbivore populations for reducing GHGs and carbon credit generation. The latter could also satisfy global conservation and development priorities, as these areas also occur in LDCs with high biodiversity that have until now not received nearly enough support. And without urgent action, this opportunity may soon be lost.

## EXPERIMENTAL PROCEDURES

### Resource availability

#### *Lead contact*

Further information and requests should be directed to and will be fulfilled by the lead contact, Timothy H. Tear (timothy.tear@briwildlife.org).

#### *Materials availability*

Data generated in this study have been deposited at Zenodo (https://doi.org/10.5281/zenodo.5722347).

#### *Data and code availability*

Information about analytical procedures can be found at Zenodo: https://doi.org/10.5281/zenodo.5722347.

### LDS-EDS GHG estimates

We followed the methods detailed by Lipsett-Moore et al.[55] that applied a savanna burning approach adopted by the Australian government[107] and applied them to all savanna habitats globally.

To test the applicability of this Australian EDS method in Africa, we used emissions data and its relationship to woody biomass and fire frequency from Niassa Special Reserve (Niassa) in Northern Mozambique. At 42,000 $km^2$, Niassa is one of Africa's largest PAs, containing one of the most intact and least disturbed areas of Africa's deciduous Miombo woodlands in Africa.[111] It occurs within the Eastern Miombo Woodlands terrestrial ecoregion, which is rated as globally outstanding for both its large, intact ecosystems and high biological distinctiveness index, with a conservation status of "relatively stable"[112] as well as receiving the highest conservation priority category for terrestrial ecoregions across Africa.[113] As Niassa also has some of the most extensive information on fire ecology,[108] and contains one of Africa's largest unfenced lion populations (which until recently was only one of eight populations with more than 1,000 lions[10]), it represents a critical case study for other potential carbon projects. Fifty sampling plots were established and data were collected on vegetation and fire (see Methods in Ribeiro et al.[33]). In particular, emissions data were collected by using the IPCC protocol,[114] which estimates emissions as a function of biomass. Woody biomass was estimated by calibrating the ALOS-PALSAR (L band SAR data, 30 m spatial resolution), Sentinel 2 (20 m spatial resolution), and Landsat 8 (30 m spatial resolution) images. Fire frequency data were collected by using a combination of burned area (MCD64A1, 500 m spatial resolution) and active fire (MCD14DL, 1 km spatial resolution) products from the Moderate Resolution Image Spectoradiometer. Linear regression was performed to assess the strength of the relationships between emissions and the presence of fire (fire frequency) and its potential impact on above ground carbon sequestration (live woody biomass) for both the EDS and LDS (defined by Lipsett-Moore et al.[55]).

### Testing cross-continental model assumptions

To test if the Australian-derived EDS model assumptions are applicable to lion PAs in Africa, we analyzed fire frequency, average emissions, and woody biomass data from Niassa Special Reserve in Northern Mozambique, as this PA was one of the highest priority lion PAs in this study (Table S1), and one of the few with emissions data. In Niassa (Figure S1), LDS fires produced significantly higher average emissions and were associated with greater mean number of fires ($p < 0.001$) and less woody biomass (mg/ha) ($p < 0.02$), suggesting LDS fires burned hotter and covered more area and produced greater emissions. In contrast, there were no significant relationships ($p > 0.05$) among EDS emissions or their variability for either fire frequency or woody biomass, suggesting that EDS fires were "cooler" and/or patchy enough that they had weaker, if any effects on woody carbon and emissions. This supports the prediction that LDS fires in Niassa would create more emissions and be more damaging than EDS fires. A fire management program designed to reduce this risk is therefore expected to generate similar PCR benefits predicted by the Australian EDS approach; however, this assumption would need further testing on site following implementation of the desired fire management prescription.

### Carbon credit estimates for multiple methodologies

Significant potential has already been identified to greatly expand the geographic scope of EDS fire management opportunities.[115] The Australian government continues to develop methods that account for the sequestration of the non-living woody carbon pool,[116] and recently approved a new methodology.[60] To estimate the potential for combining these mitigation methodologies from the same EDS fire management program, we relied on estimates from the only existing protocol that has been applied globally—the emissions reduction potential from an EDS fire management program.[55] In Africa, additional carbon credit-generating methods have been for avoided emissions in Miombo woodlands[105] and soil carbon.[62]

To estimate the amount of carbon sequestration potential from EDS fire management from the non-living woody carbon pool, we adopted the

3.5× conversion rate from the emission abatement potential recently adopted by the Australian government for high rainfall areas with poor fire histories.[60] We adopted the middle (3.5×) of the living woody biomass range (3–4× the emissions abatement potential).[61] Our soil carbon estimate of 3× abatement potential is derived from data collected in Miombo woodlands in Zambia,[57] which suggest significantly higher estimates from altered fire management than global soil carbon estimates for grasslands.[50] All of these are broad estimates for the explicit purpose of identifying PCR in this study, and would need to be refined at regional and local scales for use in a carbon project.

### Carbon credit values and relative risk

The range of carbon credit values were based on two general benchmarks. As carbon values vary widely, our lower estimate (US$ 5/ton) was based on the average value of carbon credits on the voluntary market over the past 14 years (US$ 4.9/ton; 2006–2018, n = 13, SD = 1.47).[117] The higher value (US$ 13/ton) was based on Western Climate Initiative Carbon Auction Settlement prices over a similar time frame (US$ 13.5/ton; 2012–2018, n = 17, SD = 1.12).[63] Recently, soil carbon credits using a VCS methodology from the Northern Rangelands Trust in Kenya sold for US$ 6–8/ton (M.E. Ritchie, personal communication, June 2021), suggesting that our range (US$ 5–13/ton) reasonably estimates the price range for existing carbon markets. With the rise in interest of nature-based solutions over the past 2 years, and the increased volume of VCS credits, both the lower and higher estimates are considered conservative estimates as prices are expected to increase in the near future for multiple reasons.[114]

All carbon projects must evaluate risk. While the vast majority of carbon projects focus on forested habitat, grassland carbon projects may produce more reliable carbon sinks than forest carbon projects primarily because catastrophic fires can do more damage to forest carbon stores than to grasslands[118]. Any sequestration project in Australia (including savanna burning projects) have a 25- or 100-year permanence obligation.[60] In this study, we generally categorized the relative risk of different savanna carbon projects based on the chance that the carbon credits produced by each different methodology could be lost once they were accrued. There is a relatively low risk for activities that produce emissions reduction and soil carbon because they are less likely to be lost than living and non-living woody biomass carbon pools that could be destroyed by catastrophic fires. Combining multiple methods and diversifying strategies was considered a lower relative risk because it contains two sources of lower risk methods.

### Lion PA financial assessments and carrying capacity estimates

The median funding shortfall for lion PA management was assessed for 23 of 27 lion range countries and for each lion PA based on methods detailed by Lindsey et al.[16] For this study, we used the middle of three PA area cost estimates (i.e., Lindsey et al.[16] method US$ 1,271/km$^2$) that was based on modeled costs of managing lion PAs at ≥50% of carrying capacity. Given the challenges of consistently and accurately assessing lion population sizes in Africa,[73] we chose to rely on a range-wide model of carrying capacity estimates presented in Lindsey et al.[9] developed by Loveridge and Canney.[64] Loveridge and Canney's[64] biologically based predictive model was based on published relationships among rainfall, soil nutrient, and herbivore biomass in African savannah ecosystems that were combined to predict prey biomass. Then, using prey biomass data from relatively undisturbed and protected sites only, they developed a model to predict lion biomass and density within lion PAs.

## SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.oneear.2021.11.013.

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## AUTHOR CONTRIBUTIONS

T.H.T. and G.J.L.-M. designed the study. T.H.T., N.H.W., L.S.P., N.S.R., and A.J.L. provided the data analysis. T.H.T., N.H.W., G.J.L.-M., M.E.R., N.S.R., L.S.P., P.A.L., L.H., A.J.L., and F.S. interpreted the data and wrote the paper.

## DECLARATION OF INTERESTS

One of the authors owns a company called Soils for the Future that develops carbon projects.

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