Title: A burning question: Can natural climate solutions and carbon financing save the lion from extinction?

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Abstract

Lions (*Panthera leo*) in Africa have lost nearly half their population in just the last two decades, and effective management of the protected areas where lions live will cost an estimated USD $1 B/year in new funding. We explore the potential for natural climate solutions to fill this funding gap by introducing early dry season fire management programs to generate carbon credits. Potential carbon revenue from a single method (avoided emissions) or from multiple sequestration methods could provide annual revenue of USD $59.6-$655.9 M (at USD $5/ton) or USD $155.0 M–$1.7 B (at USD $13/ton). The top twenty PAs with lions and the greatest PCR could generate annually between USD $2.0–$57.5 M per PA, and PAs with the greatest potential for lion numbers between USD $1.5–$44.4 M per PA. We highlight priorities for investments and pilot projects to realize this potential in Africa.

Introduction

The lion's decline over the past two decades has been staggering, with a ~43% decline in abundance within key populations, and nearly all historically large lion populations (≥~500) reporting size reductions[1]. It is noteworthy that within the protected areas (PA) sampled that contain many of the largest lion populations, less than a third supported ≥ 50% of their carrying capacity (K), and less than half supported ≥ 50% of lion prey at K[2]. Approximately ~56% of lion range has PA status[3], and as human pressures cause continued land conversion outside of PAs, the proportion of lion range falling inside PAs is likely to increase. Consequently, Lindsey et al.[2] suggest prioritizing increased funding to manage lion protected areas (lion PAs) to reverse the declining trend, and emphasized that unless something was done soon, lions could be lost from many savanna ecosystems in the next two decades.

Recent studies[4,5] highlighted that habitat loss and degradation on the outside of a PA network in the Serengeti ecosystem in East Africa have had significant and complex negative impacts deep into the

protected core of the PA. Changes in two dominant ecological savanna ecosystem processes - fire and grazing - have resulted in the complete loss of fire from some parts of the Serengeti ecosystem[5] that mirror a global decline in fire in many ecosystems[6]. Conversely, 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 through long-grass and attracting wildlife to ensuing green flushes[7]. To save lions, it will be necessary to reverse the degradation of PAs, which will require not only reducing the impact of poaching on lions and their prey, but also managing the ecological processes that ultimately influence the capacity of the land to support healthy lion populations.

Protected areas are recognized as one of the most effective conservation strategies in the world[8-10], even in developing countries with intense human population and development pressures, including Africa[11]. However, financing PAs remains a significant challenge[12,13], especially in developing countries[14], and notably in Africa[15]. Many African governments are tackling the significant financial challenges posed by large development needs such as building roads, bridges, and transportation systems via a strategy of public-private partnerships[16, 17]. Recent analysis[12] suggests that reversing lion decline by prioritizing more effective management of the PAs with the largest lion populations would require approximately ~USD $1B/year of new and sustainable funding. Public-private partnerships for the management of PAs have significant potential to confer improved management outcomes and to help attract funding[18]. Given that protected areas have been, and continue to be chronically underfunded, a fundamental question remains: Where would this new funding come from? The search for sustainable financing for conservation-related efforts in general, and protected areas in particular, has produced a plethora of innovative financing ideas[19-21]. As the global degradation of ecosystems is now well documented and linked directly to increasing impacts of climate change[22], there is an important opportunity to directly

connect the work needed to improve habitat in African savannas with efforts to mitigate the impacts of climate change.

The use of biodiversity offsets[23] and the global voluntary carbon market via Reducing Emissions from Deforestation and Forest Degradation (REDD+)[24] have been suggested as ways to alleviate chronic financing shortfalls. Carbon financing from REDD+ has provided added revenue for some PA management systems, such as in Peru[25] including benefit sharing for local communitie[26]. However, 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[27]. A growing focus on natural climate solutions[28], a continued rise in the global carbon market transactions, and the development of new formal methodologies for carbon accounting has created a credible, previously underutilized pathway to generate new income for savanna PAs. For example, by the end of 2018, emissions trading schemes raised a total of $57.3 billion in auction revenue, demonstrating convincingly the scope and scale of the compulsory carbon market[29]. The voluntary carbon market has seen sales rise steadily since 2010, reaching an estimated USD $48 million in global sales of land use change and forestry carbon credits by 2018[30].

As lions occupy savanna habitats, this study asks how much of the funding shortfall could be met by new and emerging carbon-based opportunities focused on that habitat. 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 to both human-built infrastructure as well as ecosystem structure and function[31]. Their 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 (LDC). Other studies suggest that similar fire abatement can increase soil and woody carbon sequestration[32,33].

We investigated the potential for a well-managed EDS fire management program to generate carbon credits for African lion PAs. We used greenhouse gas (GHG) emission abatement from methane (CH_4) and nitrous oxide (N_2O) to serve as a baseline, relatively conservative estimate of potential carbon revenue (PCR) that could be generated from an EDS fire program[31]. We then combined emission abatement potential with estimates of carbon sequestration from three other carbon pools (i.e., non-living biomass[34,35], living biomass[36], and soil carbon[37]) to produce an upper estimate of carbon credit revenue generating potential. We combined these estimates to produce a range of PCR to determine how much of the lion PA financial shortfall could be met from carbon credits generated by EDS savanna burning program that would support more effective PA management for lions.

Results

PCR from an EDS savanna fire management program could partially or entirely close the estimated US$1B funding shortfall for managing lion PAs in Africa. We found that for all lion PAs in Africa, an EDS fire management program could generate PCR ranging from USD $59.6 - $655.9 M per year (Table 1) based on the lower voluntary market average price (USD $5/ton). At a higher price of USD $13/ton, such a program could generate USD $155.0 M – $1.7 B 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 lion protected area management (Fig. 1). As all seven of the countries with the greatest emissions reduction potential are also characterized as Least Developed

Countries (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 Supplemental Table 1) of all lion PAs (Fig. 2b). There is also substantial variability in the amount of local emissions produced within most landscapes (Fig 2a), and significant trend (R^2=0.61, $p<0.001$) that the larger the protected area the greater the emissions reduction potential and therefore greater PCR (Fig. 3). The PCR for each lion 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 late dry season (LDS) wildfires and higher productivity generally demonstrate greater revenue generating potential (Fig. 4). Emissions reductions alone for all lion PAs across all countries could generate between a median of USD$ 825,562 per country (Table 1 at USD $5/ton) to a median of USD $2.1 M per country (Table 2 at USD $13/ton). However, the same EDS fire management program could also generate additional carbon credits from sequestration across the three remaining carbon pools: (1) non-living biomass, (2) live woody biomass and (3) soil carbon. Our estimates suggest that by shifting to cooler, patchier EDS fires, 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 to 45-98% (median) by combining all carbon pools (at USD $5-13/ton, Tables 1 and 2). While living and non-living biomass PCR are higher than for avoided emissions or soil carbon, they also introduce higher relative risk (Tables 1 and 2). This estimate does not account for other ecosystem services and local employment benefits produced from implementing a fire management program.

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 lion populations. When we ranked the top 20 PAs prioritized by the greatest PCR , such carbon financing could generate between USD $2.0 M/year on average for each lion PA (at USD $5/ton via emissions abatement only) and USD $57.5 M/year (at USD $13/ton combining all carbon pools) (Table 3). Such funding could potentially restore lion populations and collectively conserve up to 23,191 lions with an average of 1160 lions per PA (Table 3; SD 1196, n=20). Similarly, when we ranked the top twenty 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 1028, n=20), generating on average USD $1.5 M/year per lion PA (at USD $5/ton via emissions reduction) and USD $44.3 M/year (at USD $13/ton via multiple methods) (Table 4).

Given that total lion recovery potential (i.e., carrying capacity) for the 198 lion PAs that could generate fire-carbon revenue is estimated at approximately 60,000 lions (see Supplemental Information – Table 2), prioritizing investments on the 20 lion PAs with the greatest PCR potential would capture one third of the lion recovery potential versus half of recovery potential for the 20 lion PAs with the greatest lion carrying capacities. 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). Only two countries (Zambia and Tanzania) contained more than two lion PAs on both lists, and contained more than half of the lion PAs prioritized by PCR. Only ten (10) lion PAs occurred on both prioritized lists (Table 5). Combining the lion PA rankings from both lists illustrated that the top five sites occurred in different countries, and only Zambia occurred multiple times (5), capturing half of all the top priority sites.

To test if the Australian-derived EDS model assumptions are applicable to lion PAs in Africa, we analyzed data from Niassa National Reserve in Northern Mozambique (Fig. 5). This PA coincidentally also emerged as one of the highest priority lion PAs in this study (Table 5). In Niassa, higher average emissions 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 to produce greater emissions. In contrast, there were no significant relationships ($p>0.05$) among emissions or their variability for either fire frequency or woody biomass with EDS fires, suggesting that early fires were "cool" 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 would generate similar PCR benefits predicted by the Australian EDS approach.

Discussion

Savannas are the world's most fire prone landscapes, contribute 30% of terrestrial net primary production[38] and cover 20% of the Earth's terrestrial surface[39]. Given the global focus on decreasing land degradation to address climate change[22] paired with greater attention on finding natural climate solutions[28], our results suggest that fire management could play a major role in financing conservation of and directly improving savanna habitats. As 20 least developed countries in Africa account for nearly three quarters (74%) of the mitigation potential from an EDS savanna fire management program[31], there is clearly potential for fire management as a natural climate solution to contribute to national and local economies. Similarly, most lion populations in Africa occur in savanna habitats, and fire management, as a natural climate solution, could potentially fund direct protection from illegal hunting and support habitat improvement for lions[12]. There is great potential for fire management to improve livelihoods for

some of the world's most vulnerable countries that also contain the vast majority of the world's remaining free-ranging, but rapidly declining African lion populations[3].

We acknowledge our predicted lion numbers and PCR estimates could be affected by biases that exaggerate the stated potential. 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[40]. For PCR estimation, current voluntary carbon market rates (USD $2-3/ton) are lower than the 13-year voluntary market average used in this study (USD $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 ~USD $7.68/ton and recently sold for USD $10.27/ton, and the introduction of the Carbon Offsetting Scheme for International Aviation (CORSIA), future carbon prices may far exceed those used in this study[29]. Hence, our PCR estimates may be underestimating the carbon values over 5-15 year horizons. Assuming our estimates represent a credible and appropriate balance between current and future voluntary and compulsory carbon market prices, our analysis shows there is significant potential for an effectively run fire management program to provide significant sources of revenue.

We further recognize that while savanna burning projects in Australia have made a substantial contribution to Australian conservation – generating multiple benefits for protected areas and local communities[41], it will take significant investment for similar benefits to be realized in Africa. A savanna

burning program clearly presents the potential for "new and sustainable financing", as almost no carbon financing is currently being generated for lion PAs in Africa due to the fact that they reside in savannas, not forests. As each of the three carbon sequestration methods introduced in this study are projected to generate revenues for two to three decades[27,34,35], this type of carbon financing offers a vastly more sustainable alternative to most short-term aid programs.

In addition to revenue generation, there is potential for improved fire management to have indirect impacts on improving lion habitat by increasing forage quality and quantity for prey species. Land managers have used prescribed burning in Africa savanna's 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 tickborne diseases in livestock, and attracting higher densities of grazers[42]. More productive African savannas (based on rainfall and soil nutrients) support greater herbivore biomass, that in turn supports greater carnivore biomass[43-45], and lion density in protected areas is closely related to prey biomass[46]. Similarly, patchy burning may support higher total herbivore biomass, as many species of African herbivores are attracted to burned areas and their temporary green flush[47-49]. It is well known that burning is a tool frequently used by hunters and poachers to attract prey, often with significant large-scale impacts[49-51], and greater burning does not appear to reduce lion fitness [52]. It's possible that EDS fires could improve lion fitness by leaving taller grass in the late dry season, as lions hunt more frequently and with greater success with increased cover[53,54]. While such effects are uncertain and difficult to predict[55], the presence of fire management teams can 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.

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

First, there must be lasting capacity to implement fire management 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[56]. 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[4,5,57,58]. We urge the bilateral and multilateral development and aid sectors to conceptualize this type of project like the UNs Land Degradation Neutrality program describes it – as a way to leverage progress on meeting the Sustainable Development Goals (SDGs) and reducing the biodiversity crisis[59].

Second, 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[27]. 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[27]. These outcomes have direct benefits for local communities. For example, miombo woodlands in Africa – like those in Niassa - are of global importance for carbon storage and sequestration[60] and support the daily needs of more than 100 million people[61-63], yet are likely to experience increased pressure[64-66] and need more sustainable land management practices[32,62]. Already available carbon methodologies[67] 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.

Third, 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 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 reductions 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[68]. The availability of such tools (e.g., NAFI and SavBAT) for savanna burning carbon projects greatly enhanced savanna burning uptake and adoption[69].

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[31]. 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. Furthermore, only seven countries capture the top 20 potential lion carbon projects, which provides an important subset of socio-political contexts to prioritize initial investments. As there are many socio-political, economic, and bureaucratic issues that would need to be resolved to insure that in each country, carbon revenues were re-invested into PA management, prioritizing initial investments to demonstrate a proof-of-concept would be essential.

Finding new sources of funding for conservation is often overtaken by other competing societal needs. Lions already have been identified as not only Africa's most iconic apex predator, but also a link to

developing more robust economies in some of the least developed countries on the planet[70]. 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[12]. Our results suggest that investments in natural climate solutions that improve ecosystem health are complementary rather than competitive with other societal priorities. For example, 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 lion PAs. 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.

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 lion 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 PAs with lions. That revenue would allow curtailing of the primary short-term drivers of lion and lion-prey 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 and augment the recovery of lion prey species 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 are likely to help offset some of the opportunity costs associated with PAs and increase political will for the retention of such lands. Africa is facing explosive human

population growth, and some countries, such as Zambia and Tanzania with above-average proportions of their land area devoted to PAs, pressure will grow for the reallocation of land for agriculture and settlement.

Methods

LDS-EDS GHG estimates

We followed the methods detailed by Lipsett-Moore et al.[31] that applied a savanna burning approach adopted by the Australian government[67] and applied them to all savanna habitat 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 National Reserve (Niassa) in Northern Mozambique. At 42,000 km^2, Niassa is one of Africa's largest protected areas, contains one of the most intact and least disturbed areas of Africa's deciduous Miombo woodlands in Africa[71]. 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"[72] as well as receiving the highest conservation priority category for terrestrial ecoregions across Africa[73]. As Niassa also has some of most extensive information on fire ecology[74], and contains one of Africa's largest unfenced lion populations and only one of eight populations with more than 1,000 lions[3], it represents a critical case study for other potential carbon projects. Fifty sampling plots were established and collected data on vegetation and fire (see methods in Ribeiro et al.[75]). In particular, emissions data were collected by using the IPCC protocol[76] which estimates emissions as a function of biomass, woody biomass was estimated by calibrating the ALOS-PALSAR (L band SAR data, 30m spatial resolution), Sentinel 2 (20m spatial resolution) and Landsat 8 (30m spatial resolution) images. Fire frequency data were collected by using a combination of burned area (MCD64A1, 500m spatial resolution) and active fire (MCD14DL, 1km spatial resolution) products from the Moderate

Resolution Image Spectoradiometer (MODIS). 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 early and late dry seasons (defined by Lipsett-Moore et al.[31]).

Carbon credit estimates for multiple methodologies

Significant potential has already been identified to greatly expand the geographic scope of EDS fire management opportunities[78]. The Australian government continues to develop methods that account for the sequestration of the non-living woody carbon pool[77], and recently approved a new methodology[35]. 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[31]. In Africa, additional carbon credit generating methods have been for avoided emissions in miombo woodlands[66] and soil carbon[14].

To estimate the amount of carbon sequestration potential from EDS fire management from the non-living woody carbon pool, we adopted the 3.5x conversion rate from the emission abatement potential recently adopted by the Australian government for high rainfall areas with poor fire histories[35]. We adopted the lower end (3x) of the living woody biomass range (3-4x the emissions abatement potential)[36]. Our soil carbon estimate of 3x abatement potential is derived from data collected in miombo woodlands in Zambia[33] that suggests significantly higher estimates from altered fire management than global soil carbon estimates for grasslands[27,28]. 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 (USD $5/ton) was based on the average value of carbon credits on the voluntary market over the past 14 years (USD $4.9/ton; 2006-2018, n=13, sd = 1.47)[25]. The higher value (USD $13/ton) was based on Western Climate Initiative Carbon Auction Settlement prices over a similar time frame (USD $13.5/ton; 2012-2018, n=17, sd = 1.12)[79]. With the rise in interest of nature-based solutions over the past two 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[25].

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[80]. Any sequestration project in Australia (including savanna burning projects) have a 25-year or 100-year permanence obligation[35]. 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.[5]. For this study, we used the middle of three PA area cost estimates (i.e., Lindsey et. al.[5] method \$1,271/km^2) that was based on modeled costs of managing lion PAs at $\geq$ 50% of carrying capacity. Given the challenges of consistently and accurately assessing lion population sizes in Africa[40] we chose to rely on a rangewide model of carrying capacity estimates presented in Lindsey et al.[2] developed by Loveridge and Canney[46]. Loveridge and Canney's[46] 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, and 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.

Literature Cited:

1. Bauer H. et al. Lion (Panthera leo) populations are declining rapidly across Africa, except in intensively managed areas. *Proc. Natl Acad. Sci. USA* **112**,14894-14899 (2015).

2. Lindsey, P.A., et al. The performance of African protected areas for lions and their prey. *Biol. Cons.* **209**,137-149 (2017).

3. Riggio, J., et al. The size of savannah Africa: A lion's (*Panthera leo*) view. *Biod. and Conserv.* **22**, 17-35 (2012).

4. Velduis, M.P., et al. Cross-boundary human impacts compromise the Serengeti-Mara ecosystem. *Science* **363**, 1424-1428 (2019).

5. Probert J.R. et al. Anthropogenic modifications to fire regimes in the wider Serengeti-Mara ecosystem *Glob Change Biol.* **00,** 1−18 (2019).

6. Andela, N., et al. A human-driven decline in global burned area. *Science* **356**, 1356-1362 (2017).

7. Lindsey, P.A., et al. The bushmeat trade in African savannas: Impacts, drivers, and possible solutions. *Biol. Cons.* **160**, 80-96 (2013).

8. Bruner A.G., Gullison R.E., Rice R.E., & da Fonseca GAB. Effectiveness of parks in protecting tropical biodiversity. *Science* **291**,125–128 (2001).

9. Hilborn R., et al. Effective enforcement in a conservation area. *Science* **314**: 1266 (2006).

10. Watson, J., Dudley, N., Segan, D. *et al.* The performance and potential of protected areas. *Nature* **515,** 67–73 (2014).

11. Riggio, J., et al. How effective are the protected areas of East Africa? *Global Ecol. and Conserv.* **17**, e00573 (2019).

12. Lindsey, P.A., et al. More than $1 billion needed annually to secure Africa's protected areas with lions. *Proc. Natl Acad. Sci. USA* **115**, E10789 (2018).

13. Coad, L., et al. Widespread shortalls in protected area resourcing undermine efforts to conserve biodiversity. *Front Ecol Env* **17**, 259-264 (2019).

14. Bruner, A.G., et al. Financial costs and shortfalls of managing and expanding protected-area systems in developing countries. *BioScience* **54**, 1119-1126 (2004).

15. Chardonnet, B. Africa is changing: Should its protected areas evolve reconfiguring the protected areas in Africa. IUCN PAPACO. p 41. (2019).

16. Dykes, B.J. and Jones, C.D. Public-Private Partnerships in Africa: Challenges and Opportunities for Future Management Research, *Africa J. Manage.* **2**, 381-393 (2016).

17. Osei-Kyei, R., & Chan, A.P.C. Developing Transport Infrastructure in Sub-Saharan Africa through Public–Private Partnerships: Policy Practice and Implications, *Transport Reviews* **36**, 170-186 (2016).

18. Baghai, M., et al. Models for the collaborative management of African protected areas. Biological Conservation 218: 73-82 (2017).

19. Emerton, L., Bishop, J. & Thomas, L. *Sustainable Financing of Protected Areas: A Global Review of Challenges and Option*s. IUCN, Gland, Switzerland and Cambridge, UK. x + 97pp. (2006).

20. Kharas, H., & McArthur, J. Links in the chain of sustainable finance: Accelerating private investments for the SDGs, including climate action. *Global Views* **5**, 1-15 (2016).

21. Torsten, T., Gerber, L.R. Innovative financing for the High Seas. *Aquatic Conser: Mar Freshw Ecosyst*. **27**, 89-99 (2017).

22. IPBES. *The IPBES assessment report on land degradation and restoration*. (eds Montanarella, L., Scholes, R., & Brainich, A.) (Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Bonn, Germany 2018).

23. Githiru, M., King, M.W., Bauche, P., Simon, C., Boles, J, Rindt, C., & Victurine, R. Should biodiversity offsets help finance underfunded Protected areas? Biological Conservation 191:819-826 (2015).

24. Githiru, M., & Njambuya, J.W. Globalization and biodiversity conservation problems: Polycentric REDD+ solutions. Land 8:35 doi:10.3390/land8020035 (2019).

25. Forest Trends' Ecosystem Marketplace. *Financing Emission Reductions for the Future: State of Voluntary Carbon Markets 2019*. Washington DC: Forest Trends (2019).

26. Podvin, K., Sandoval, M., Gutiérrez, C., & Schneider, C. *Final project report: Facilitating REDD+ benefit sharing in Peru, implemented by IUCN, CI-Peru and AIDER*. Quito, Ecuador: IUCN. (2017).

27. Bossio, D.A., et al. The role of soil carbon in natural climate solutions. *Nat Sustain* (2020). https://doi.org/10.1038/s41893-020-0491-z

28. Griscom, B.W. et al. Natural climate solutions. *Proc. Natl Acad. Sci. USA* **114**, 11645-11650 (2017).

29. ICAP. *Emissions Trading Worldwide: Status Report 2018*. Berlin: International Carbon Action Partnership (ICAP) (2018).

30. Hamrick, K., & Gallant, M. *Voluntary Carbon Market Insights: 2018 Outlook and First Quarter Trends*. (Forest Trends' Ecosystem Marketplace, 2018).

31. Lipsett-Moore, G.J., Wolff, N.H., & Game, E.T. Emissions mitigation opportunities for savanna countries from early dry season fire management *Nat Commun* **9,** 2247 (2018).

32. Williams, M., Ryan, C., Rees, R., Sambane, E., Fernando, J., Grace J. Carbon sequestration and biodiversity of re-growing miombo woodlands in Mozambique. *For. Ecol. Manage*. **254,** 145-155 (2008).

33. Ritchie, M.E. *Prospects for Payments for Ecosystem Services through Carbon and Water Storage Projects in southwestern Zambia*. (The Nature Conservancy, 2014)

34. Cook G.D, Meyer C.P., Muepu, M., & Liedloff A.C. Dead organic matter and the dynamics of carbon and greenhouse gas emissions in frequently burnt savannas. *Int. J. Wildland Fire* **25,** 1252-1263 (2016).

35. Commonwealth of Australia. Carbon Credits (Carbon Farming Initiative—Savanna Fire Management—Sequestration and Emissions Avoidance) Methodology Determination 2 Minister for Environment and Energy, Canberra. (2018).

36. Russell-Smith, J. *Key research to assist the development of carbon sequestration methods for savanna fire management in Northern Australia*. (Meat and Livestock Australia, Ltd., 2020)

37. VCS. VM0032 methodology for the adoption of sustainable grasslands through adjustment of fire and grazing (2015b).

38. Grace, J., Jose, J. S., Meir, P., Miranda, H. S. & Montes, R. A. Productivity and carbon fluxes of tropical savannas. *J. Biogeogr*. **33**, 387–400 (2006).

39. Scholes, R. J., Hall D. O. in *Global Change: Effects on Coniferous Forests and Grasslands* (eds Breymeyer, A. I., Hall, D. O., Melillo, J. M. & Agren, G. I.) pages 69–100 (Wiley, Chichester 1996).

40. Braczkowski, A. et al. Restoring Africa's Lions: Start with good counts. Front. Ecol. Evol. doi:10.3389/fevo.2020.00138 (2020).

41. Ansell, J., et al. Contemporary Aboriginal savanna burning projects in Arnhem Land: a regional description and analysis of the fire management aspirations of Traditional Owners. *Int. J. Wildland Fire* https://doi.org/10.1071/WF18152 (2019).

42. Odadi, W.O., Kimuyu, D.M., Sensenig, R.L., Veblen, K.E., Riginos, C., & Young, T.P. Fire-induced negative nutritional outcomes for cattle when sharing habitat with native ungulates in an African savanna. *J. Applied Ecol.* **54**, 935-944 (2016).

43. Coe, M.J., Cumming, D.H., and Phllipson, J. Biomass and production of large African herbivores in relation to rainfall and primary production. *Oecologia* **22**, 341-354 (1976).

44. Bell, R.H.V. in *Ecology of Tropical Savannas* (eds Huntley, B.J., & Walker B.H.) 193-216 (Springer-Verlag, Berlin, Germany, 1982).

45. East, R.D. Rainfall, soil nutrient status and biomass of large African savanna animals. *African J. of Ecol.* **22,** 245-270 (1984).

46. Loveridge, A.J., & Canney, S. *Report on the Lion Distribution and Conservation Modeling Project*. Born Free Foundation (2009).

47. Mduma, S.A.R., & Sinclair, A.R.E. The function of habitat selection by oribi in the Serengeti, Tanzania. *Afr. J. Eco.* **32,**16-29 (1994).

48. Wilsey, BJ. Variation in use of green flushes following burns among African ungulate species: the importance of body size. *Afr. J. Eco*. **34**, 32-38. (1996).

49. Tomor, BM, Owen-Smith, N. Comparative use of grass re-growth following burns by four ungulate species in the Nylsvley Nature Reserve, South Africa. *Afr. J. Eco*. **40**,201-204 (2002).

50. Moe, S.R., et al. The influence of man-made fires on large wild herbivores in Lake Burungi area in northern Tanzania. *Afr. J. Eco*. **28**, 101-106 (1990).

51. Rowe-Roe, DT. Influence of fire on antelope distribution and abundance in Natal Drakensberg. *S. Afri. J. Wild.* **12**,124-129 (1982).

52. Eby, S, et al. The impact of burning on lion *Panthera leo* habitat choice in an African savanna. *Current Zool.* **59**, 335-339 (2013).

53. Hopcraft, J.G.C., et al. Planning for success: Serengeti lions seek prey accessibility rather than abundance. *J. Anim. Eco*. **74**: 559-566. (2005).

54. Van Orsdol, K.G. Foraging behavior and hunting success of lions in Queen Elizabeth National Park, Uganda. *African J. of Ecol.* **22**, 79–100 (1984).

55. Letnic, M., & Ripple, W.J. Large-scale responses of herbivore prey to canid predators and primary productivity. *Global Ecol. Biogeogr*. 26:860–866 (2017).

56. Russell-Smith, J. et al. Deriving multiple benefits from carbon market-based savanna fire management: an Australian example. *PLOS One* **10**, e0143426 (2015).

57. IFFN. *Impact of the Integrated Forest Fire Management Program on Rural Livelihoods in East Caprivi Region, Namibia* (Namibia: Forest Fire Management Program, IFFN No. 25, 2001).

58. Kamminga, E. M. *Impact of the Integrated Forest Fire Management Program on Rural Livelihoods in East Caprivi Region, Namibia*. (Namibia-Finland Forestry Program, Directorate of Forestry, Ministry of Environment and Tourism. Windhoek, Namibia 2001).

59. Global Mechanism of the UNCCD. *Land Degradation Neutrality Transformative Projects and Programmes: Operational Guidance for Country Support*. Bonn, Germany. (2019).

60. Ribeiro N.S., Matos C.N., Moura I.R., Washington-Allen R.A., Ribeiro A. Monitoring vegetation dynamics and carbon stock density in Miombo woodlands. *Carbon Balance and Manage* **8**, 11 (2013).

61. Syampungani, S., Chirwa, P.W., Akinnifesi, F.K., Sileshi, G., & Ajayi, O.C. The miombo woodlands at the cross roads: potential threats, sustainable livelihoods, policy gaps and challenges. *Nat. Resour. Forum*, **33**, 150-159 (2009).

62. Jew, E.K.K., Dougil, A.J., Sallu, S.M., O'Connell, J., & Benton, T.G. Miombo woodland under threat: Consequences for tree diversity and carbon storage. *Forest Ecology and Management* **361**, 144-153 (2016).

63. Gumbo, D.J., Dumas-Johansen, M., Muir, G., Boerstler, F., & Xia, Z. *Sustainable management of Miombo woodlands – Food security, nutrition and wood energy*. (Rome, Food and Agriculture Organization of the United Nations, 2018).

64. Eastwood R. & Lipton, M. Demographic transition in sub-Saharan Africa: How big will the economic dividend be? *Population Studies* **65**, 9-35 (2011).

65. Cabral A.I.R., Vasconcelos, M.J., Oom, D., & Sardinha, R. Spatial dynamics and quantification of deforestation in the central-plateau woodlands of Angola (1990-2009). *Applied Geography* **31**, 1185-1193 (2011).

66. Dewees, P., Campbell, B., Katerere, Y., Sitoe, A., Cunningham, A., Angelsen, A., & Wunder, S. *Managing the Miombo Woodlands of Southern Africa: Policies, Incentives and Options for Rural Poor*. Program on Forests (PROFOR), Washington, DC. (2010).

67. VCS. VM0029 methodology for avoided forest degradation through fire management (2015a).

68. Emissions Reduction Fund. http://www.cleanenergyregulator.gov.au/ERF/Auctions-results/july-2019). (2019).

69. Commonwealth of Australia. Participating in the Emissions Reduction Fund: A guide to the savanna fire management method 2015. (2015).

70. Stolton, S. & Dudley, N. *The New Lion Economy. Unlocking the Value of Lions and Their Landscapes*, (Equilibrium Research, Bristol, UK, 2019).

71. Maquia I., Ribeiro N.S., Silva V., Bessa F., Goulao L.F., & Ribeiro A.I. Genetic diversity of *Brachystegia boehmii* Taub. and *Burkea africana Hook*. f. across a fire gradient in Niassa National Reserve, northern Mozambique. *Bioch. Syst. and Ecol.* **48**, 238–247 (2013).

72. Burgess, N.D., D'Amico Hales, J.A., Underwood, E., Dinerstein, E., Olson, D., Schipper, J., Ricketts, T., Itoua, I., & Newman, K. *Terrestrial Ecoregions of Africa and its Islands: A Conservation Assessment*. World Wildlife Fund. Island Press, Washington D.C., USA. (2004).

73. Tear, T.H., Stratton, B.N., Game, E.T., Brown, M.A., Apse, C.D., & Shirer R. A return-on-investment framework to identify conservation priorities in Africa. *Biological Conservation* **173**,42-52. (2014).

74. Ribeiro N. S., Cangela A., Chauque A., Bandeira R. R., & Ribeiro-Barros A. I. Characterisation of spatial and temporal distribution of the fire regime in Niassa National Reserve, northern Mozambique. *Int. J. of Wildland Fire* **26**,1021-1029 (2017).

75. Ribeiro N.S., Shugart H.H., & Washington-Allen R. The effects of fire and elephants on species composition and structure of the Niassa Reserve, northern Mozambique. *Forest Ecol. and Manage.* **255**, 1626–1636 (2008).

76. IPCC. Guidelines for National Greenhouse Gas Inventories. Agriculture, Forestry and Other Land Use. Volume 4 (2006).

77. Cook et al. in Carbon Accounting and Savanna Fire Management (eds Murphy, B., Edwards, A., Meyer, M. & Russell-Smith, J.) pages 321–328 (CSIRO Publishing Commonwealth of Australia: Melbourne, 2015).

78. Nolan, R. H., Sinclair, J., Eldridge, D. J. & Ramp, D. Biophysical risks to carbon sequestration and storage in Australian drylands. *J. Environ. Manag*. **208**, 102–111 (2018).

79. WCI. https://ww3.arb.ca.gov/cc/capandtrade/wcicarbonallowanceprices.pdf (2019). Accessed 8 April 2020.

80. Dass, P., Houlton, B.Z., Wang, Y. & Warlind, D. Grasslands may be more reliable carbon sinks than forests in California. *Environ. Res. Lett.* **13**, 074027 (2018).

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.

Competing interests

The authors declare no competing interests.

Additional Information

Supplementary information is available for this paper (two tables submitted separately).

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Figures

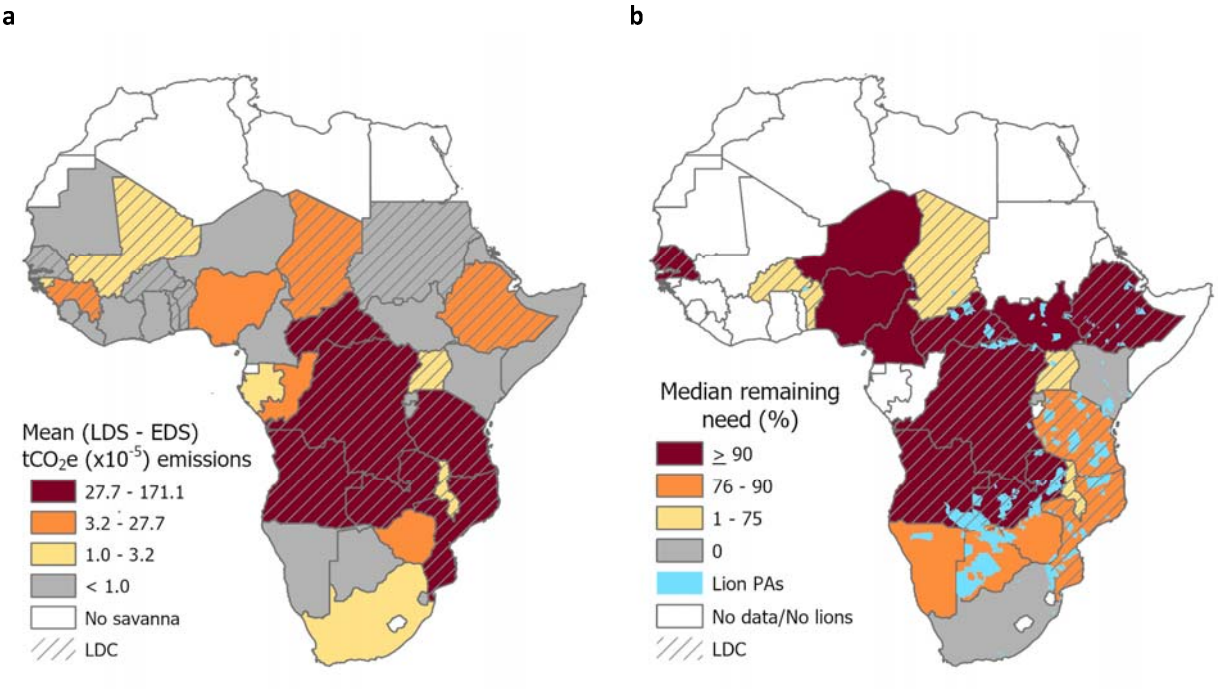

Figure 1. The country-level relationship between a) carbon emission reductions resulting from instituting a fire management plan that shifts fires from the late dry season (LDS) to the early dry season (EDS) compared to b) countries with lions and the financial need estimated for effective protected 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.[31]).

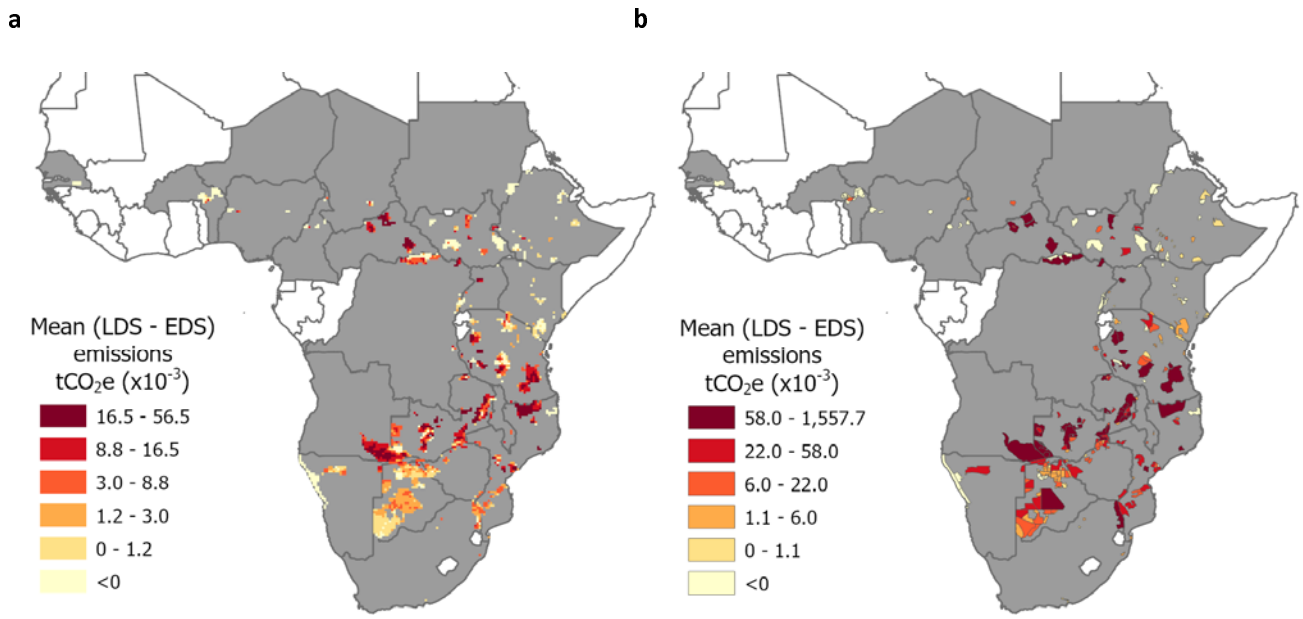

Figure 2. Mean annual emissions abatement potential (LDS-EDS) for 256 protected areas (PA) with lions by a) pixels within lion PAs, and b) summed for the entire lion PA. Classes were based on quintiles (for all values >0). Twenty-three countries (gray) contain at least 1 of the 256 PAs.

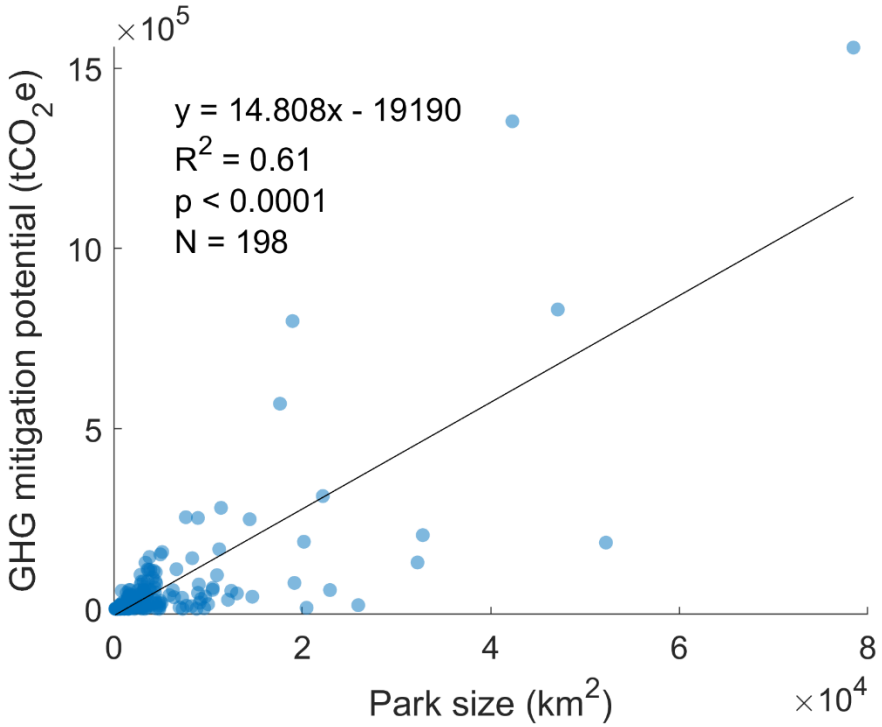

Figure 3. Linear regression showing the significant relationship between protected area size and greenhouse gas emissions reduction potential (>0 tCO_2-e) from EDS fire management.

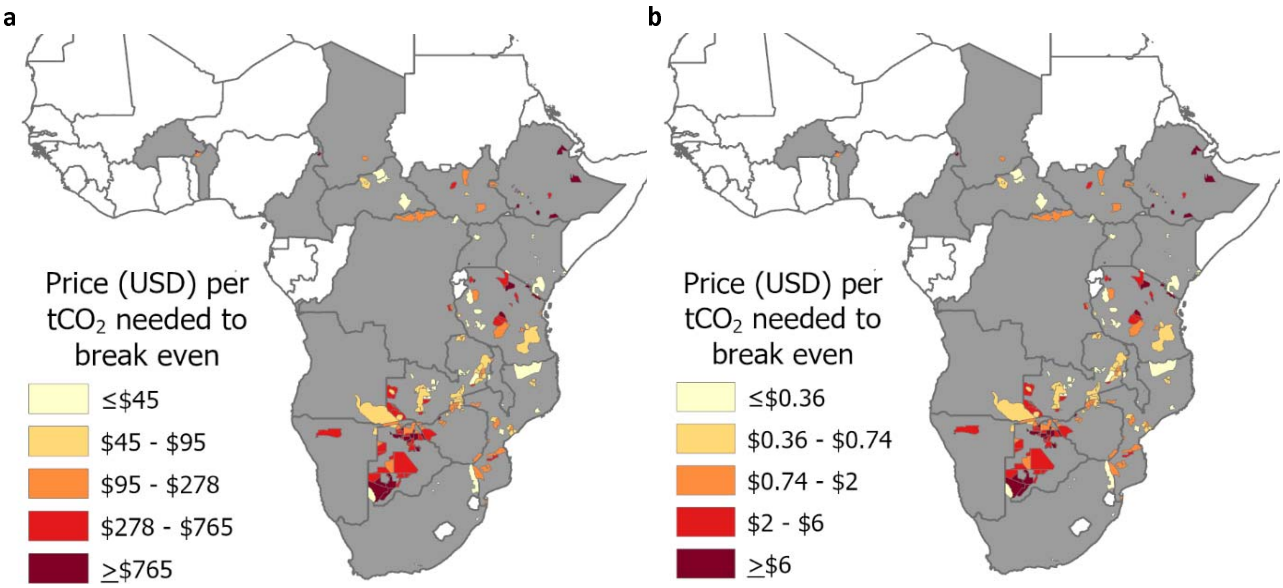

Figure 4. The market price needed to cover the estimated funding gap in each of 198 protected areas (based on Lindsey et al.[12]) with >0 GHG abatement potential if the revenue were generated by carbon projects. The estimates show the difference between selling carbon credits from a) emissions reduction alone (e.g., Lipsett-Moore et al.[31]), and b) multiple methods that combine possible credits from four existing fire-driven carbon methodologies that would add carbon sequestration with emissions reductions. Nineteen countries (gray) contain at least 1 of the 198 PAs.

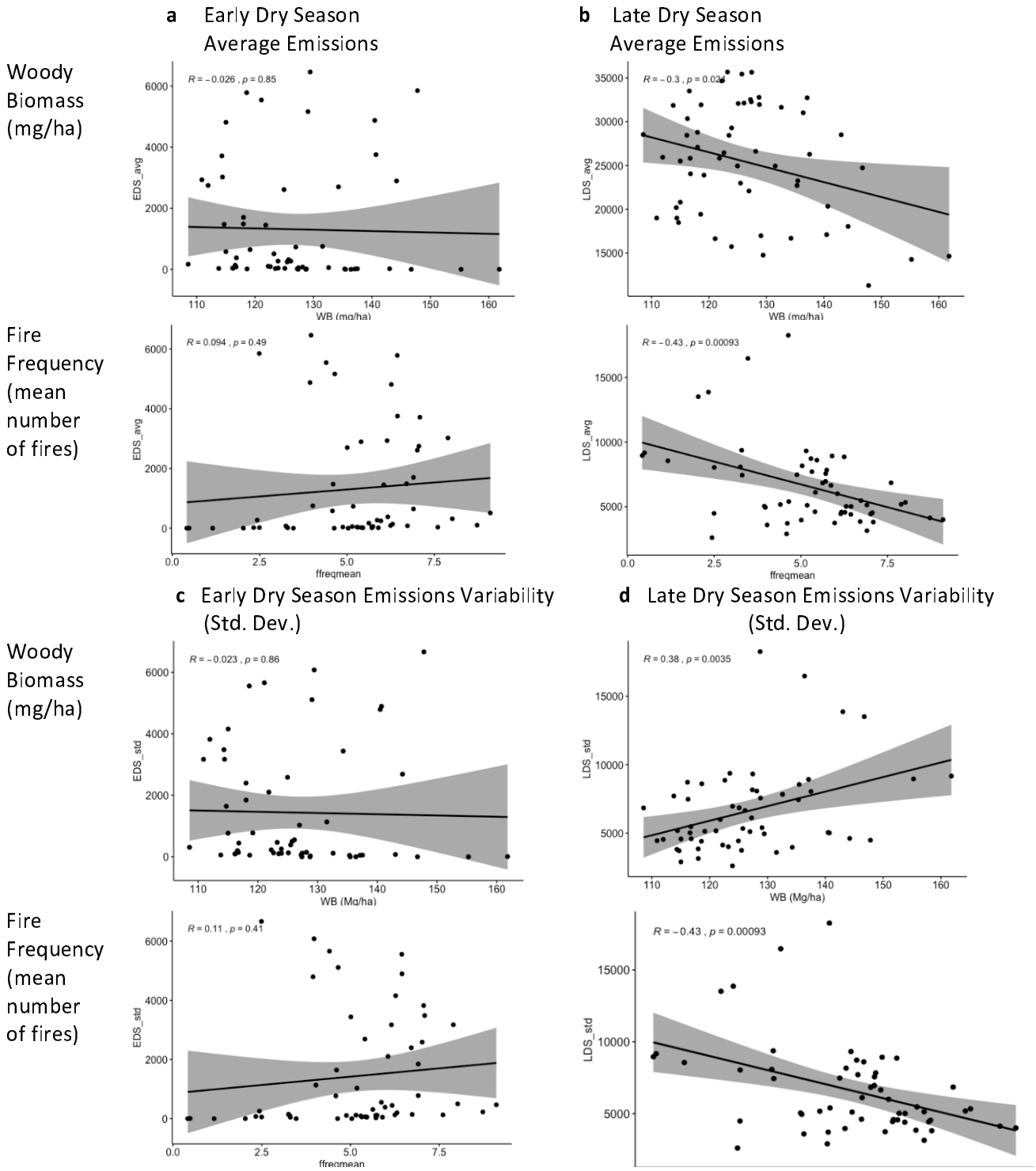

Figure 5. Linear regression relationships in Niassa National Reserve on a per-pixel basis for a) early (EDS) emissions, b) late (LDS) emissions, c) EDS variability and d) LDS variability in relation to mean fire frequency (number of fires) and mean woody biomass (mg/ha).

Tables

Table 1: African Lion range states and the potential for EDS fire management programs to generate carbon revenue in relation to protected area (PA) finance gaps for all PAs (with >0 greenhouse gas (GHG) reduction potential). The rate of USD $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[12].

Africa Lion Range-state Country	Number of PAs with Lions		GHG emission reduction potential (USD $)	Soil carbon sequestration potential (USD $)	Live woody biomass carbon sequestration potential (USD $)	Non-living woody biomass carbon sequestration potential (USD $)	Multiple carbon methods combined (USD $)	% 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	4		1,864,276	5,592,828	6,524,966	6,524,966	20,507,037	5.1	56.0

Republic of the Congo								
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		

Table 2: African Lion range states and the potential for EDS fire management programs to generate carbon revenue in relation to protected area (PA) finance gaps for all PAs (with >0 greenhouse gas (GHG) reduction potential). The rate of USD $13/ton was applied as an upper estimate based on an average of Western Climate Initiative Carbon Auction Settlement prices[79]. 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.[12].

Africa Lion Range-state Country	Number of protected areas with Lions		GHG emission reduction potential (USD $)	Soil carbon sequestration potential (USD $)	Live woody biomass carbon sequestration potential (USD $)	Non-living woody biomass carbon sequestration potential (USD $)	Multiple carbon methods combined (USD $)	% 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		

Table 3: Top twenty lion protected areas in Africa estimated to gain the most carbon revenue generated from a fire management program. The low estimate of potential carbon revenue (PCR) was based on emissions reduction (Lipsett-Moore et al. 2018[32]), 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 (2009[46]).

Rank	Africa Lion Range-state Country	Africa Lion Protected Area	Low PCR/yr $USD	Middle PCR/yr $USD	High PCR/yr $USD	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	918,503	10,103,529	26,269,176	1,616

14	Central African Republic	Kalahari 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

Table 4: Top twenty protected areas in Africa with the largest estimated lion populations, and the amount of potential carbon revenue generated from a fire management program. The low estimate of potential carbon revenue (PCR) was based on emissions reduction (Lipsett-Moore et al. 2018[32]), 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 (2009[46]).

Rank	Africa Lion Range-state Country	Africa Lion Protected Area	Low PCR/yr $USD	Middle PCR/yr $USD	High PCR/yr $USD	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

Table 5. Highest combined priority ranking of lion protected areas (PA) for both potential carbon revenue (PCR) generation and predicted lion population size (i.e., carrying capacity).

Combined Rank	Combined score	Africa Lion PA	Country	Predicted Lion Population Size	Low PCR Estimate (USD $/yr)	High PCR Estimate (USD $/yr)
1	2	Luengue-Luiana	Angola	5,633	7,788,312	22,745,714
3	5	Niassa	Mozambique	1,881	6,765,565	193,495,153
3	5	Selous	Tanzania	2,157	4,153,721	118,796,419
4	12	Kafue	Zambia	1,714	1,564,726	44,751,166
5	13	Manovo-Gounda-Saint Floris	Central Africa Republic	1,457	3,993,089	114,202,353
6	18	Musalangu	Zambia	1,594	1,242,875	35,546,217
7	20	Central Kalahari	Botswana	1,616	918,503	26,269,243
8	22	South Luangwa	Zambia	1,104	1,260,615	36,053,589
9	30	West Zambezi	Zambia	1,254	642,915	18,387,369
10	36	Luano	Zambia	800	702,844	20,101,341
Median				1,605	1,412,671	35,799,903
Total				19,210	29,033,165	630,348,564