

Understanding complexity in savannas: climate, biodiversity and people

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Savannas are the most extensive biome in the tropics. These extremely dynamic coupled socio-ecological ecosystems are shaped by a long history of interaction with humans, fire, climate and wildlife, particularly herbivores. Given the extensive spatial nature, and the many direct and indirect benefits savannas provide to surrounding human populations, savannas deserve a special place on the ecosystem management agenda. Increasing human population growth, climate change, atmospheric change and resource use impact on savanna composition, distribution and function bring a host of challenges. These impacts are compounded by political, land tenure and economic shifts — all factors that will bring more challenges. It is vital that knowledge gaps in ecological function, natural resource partitioning and predicted response of savannas to environmental change are filled; this will require truly inter-disciplinary and intra-disciplinary approaches. With this multi-dimension perspective it is imperative that our understanding on ecosystem socio-environmental interaction is considered to impart effective long-term management strategies and thus ensure a sustainable future for savanna ecosystems.

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Introduction

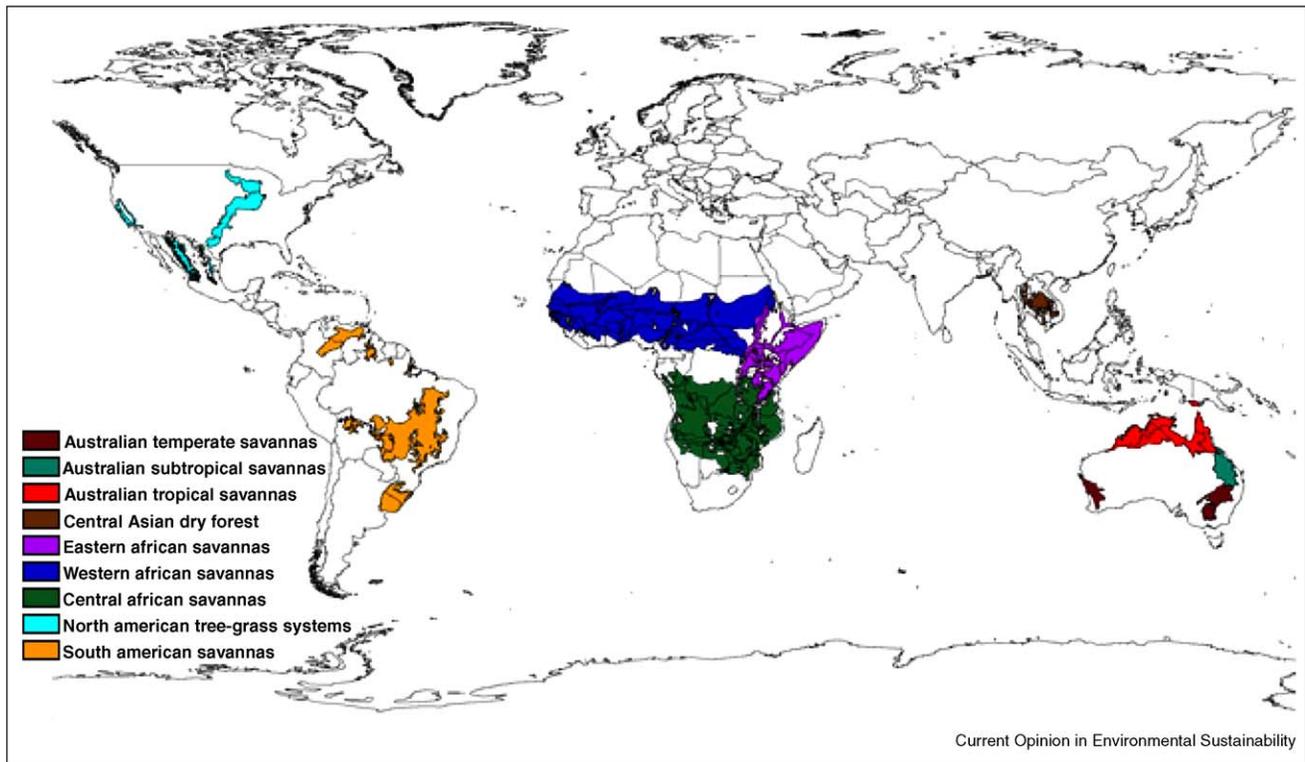
Savanna constitutes the most spatially extensive biome in the world (Figure 1). Originally derived from the native American term for prairie, ‘savanna’ has been ubiquitously applied to dry forest ecosystems — although the term is often disliked by botanists it benefits from being commonly understood and will be used through this paper. Savanna is a generic term comprising a catena of mixed grass–tree communities of varying structure and composition [1–3] that are inherently unstable through time and

across space [4]. Savannas are characterised by a continuous cover of perennial grasses, with an open canopy of drought, fire or browser-resistant trees (Plate 1), associated with tropical areas where there is at least one pronounced dry season. Savannas develop where seasonal forest would form but edaphic conditions or disturbance prevents the establishment of extensive tree cover. There are many different regional expressions of savanna with associated nomenclature: the common *Acacia*-dominated savannas are found through Africa, whereas the extensive Cerrado and Llanos found to the south and north of Amazonia respectively are dominated by *Brysonima* and *Curatella* species (Plate 1).

Savannas are effectively sub-climax ecosystems maintained due to edaphic, fire and/or herbivore influence (Plate 1). Edaphic savannas, for example, the grass savanna of the Serengeti, form on free-draining substrates that inhibit the growth of hydrophilous trees. The influence of fire, both from natural and human origins, creates ecosystems dominated by plants adapted to survive frequent and periodic burning. Humans have interacted with savannas for millennia contributing substantially to the contemporary composition and distribution [1,3,5]. The third main control on savannas is large mammals; particularly common in Africa, elephants maintain open woodlands by debarking and pushing over trees; opening the woodland to grass invasion and subsequently attracting a variety of grazing animals (Plate 1). Ungulate diversity is greatest within the savannas of Africa where numerous grazing and browsing species coexist by dividing resources spatially and temporally (Plate 1). Well-armed species of shrubs and trees establish themselves in clearings, leading to thorny thickets that exclude grazers.

The dynamic nature of savannas through time can be clearly demonstrated in the Sahara — the ‘greening’ and ultimate desiccation of the Sahara over the past 6000 years is one of the most extreme ecosystem responses to climatic fluctuation during the Holocene [6,7]. This dynamic continues today with northward extension of the Sahel and associated expansion and contraction of the cultivation frontier in response to climate and atmospheric change [8]. Hence, savanna composition, extent, structure and function arise from complex interactions with wildlife, livestock, humans, fires, climate and atmospheric CO₂ concentrations [2,9–11]. It is perhaps the complexity of the savanna ecosystem, or the spatially extensive nature of the biome, that has resulted in savannas being relatively neglected whilst other tropical

Figure 1



Global map showing the distribution of the major regional expressions of the savanna biome across the tropics, modified from [49].

forest ecosystems have attracted much scientific and public interest. Such neglect has to stop! This paper will focus on a number of thematic areas vital to understanding complexity in African savannas. There is a discussion on priorities for the conservation and sustainable development of savannas that build on the long history of human, animal, environmental and ecosystem interaction. The article culminates in emphasising the need to develop a management framework that combines ecological and social understanding of savanna ecosystems.

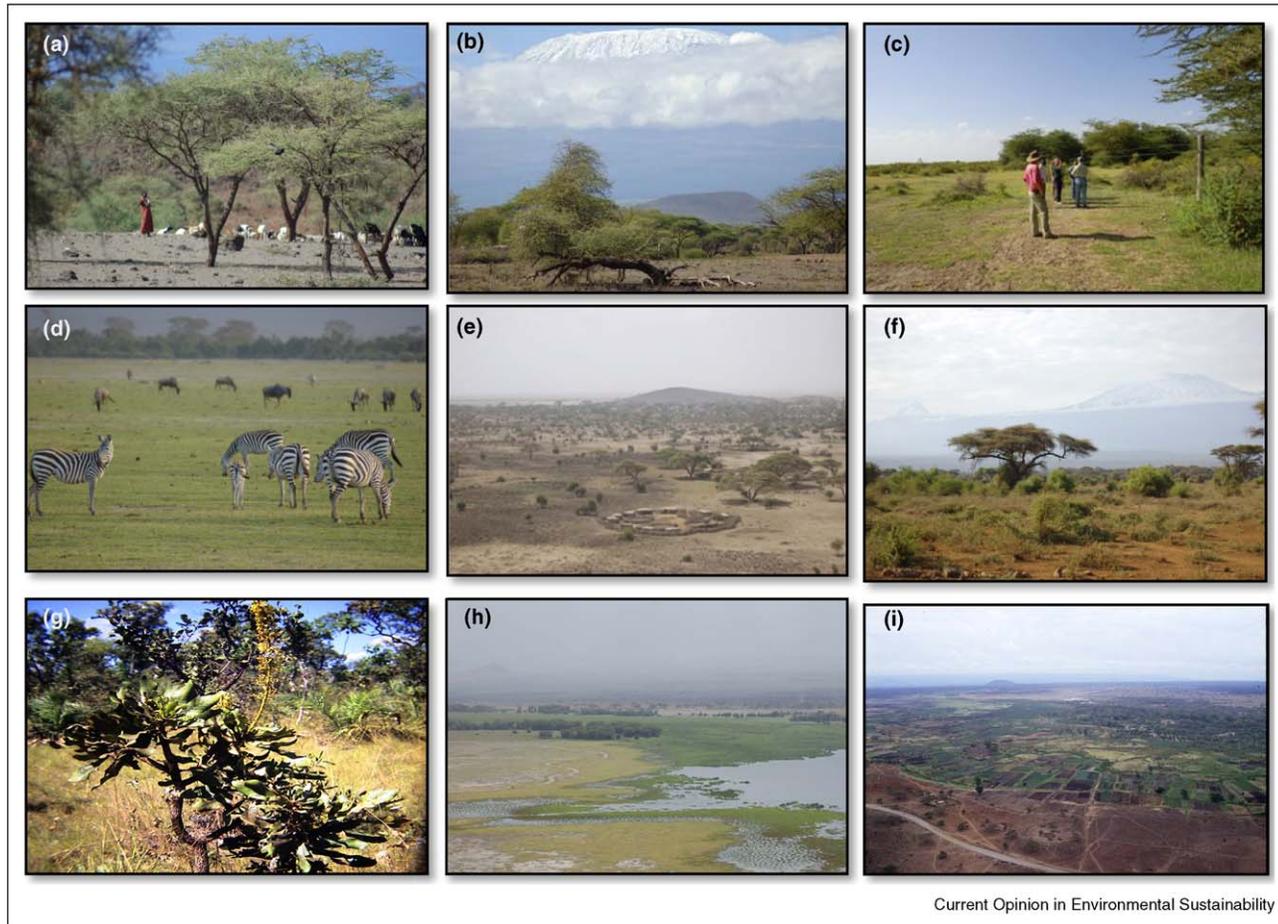
Socio-environment interactions in savannas

Humans have long distinguished themselves by using tools and technologies to shape savanna ecosystems [12]. To meet challenges of managing savannas in an increasingly populous world we need to fully understand the history of this interaction, particularly as the very nature of this long-term human–ecosystem interaction engenders sustainability. Human interactions with ecosystems are inherently dynamic and complex [13]; any categorisation of these is a gross oversimplification [14], particularly given the diversity of the savanna biome, and is not possible within the context of this paper. However, the history behind human–savanna interactions is vital to understand how these combine to form the productive savanna ecosystems of today [8]. Understanding savanna–

human interactions changes the narrative from one characterised by degradation, disturbance and impacts, to one of abundance with societies interwoven within the ecological fabric of the ecosystem. However, the nature of human–ecosystem interactions are changing—most extremely causing species extinctions [15] and current and predicted changes in environment not comparable in rate and character to those observed historically [16]. Understanding the close inter-linkages between societal and ecological processes that underpin livelihoods is essential to understand the nature of vulnerability under habitat transformation, fragmentation and human/animal conflicts [17].

Anthropogenically driven ecosystem change impacts strongly on current conservation initiatives that aim to sustain biological diversity for the future. In addition to savannas being a model of past human–ecosystem interaction they also experience a multitude of ongoing changes which are social and economic in character. Economic liberalisation, rising world food prices, public land reforms and increased demand for biofuels alter the boundaries and framework of human–ecosystem interaction. Economic liberalisation has, in the case of Mozambique, led to smallholders facing increased competition from commercial interests in accessing land and natural resources [18]. Land tenure changes

Plate 1



Current Opinion in Environmental Sustainability

(a) Goats are very important in maintaining an open savanna structure and preventing the herb layer and growing tree seedlings. (b) Elephants are also important in maintaining open savanna, in this case from Amboseli National Park. (c) The importance of excluding wildlife can be seen by these exclosure plots set up by the African Conservation Centre in the Amboseli National Park. (d) Wildlife maintains the open nature of savannas by resource sharing in space. (e) Savannas are a product of a long-term interaction with human inhabitation, in this case the Massai of the Kenya Tanzania borderland region. (f) The densities of trees, shrubs and herbs vary massively in space and are influenced by the surrounding topography, in this case Mount Kilimanjaro. (g) The Cerrado of Brazil is dominated by different species than the *Acacia*-dominated African savannas — in this case *Curatella* spp. (h), Groundwater-fed swamps are a vital drought refuge for animals and people alike, increasingly these areas are the focus of agricultural encroachment as pressure for land continues, for example (i) Namelok swamp southern Kenya. All photographs taken by Rob Marchant except plate i which was provided by courtesy of Jeff Worden, African Conservation Centre.

fundamentally affect social, economic and environmental components, in particular through the loss of political, economic and social rights of the population. Again a historical perspective to land tenure issues is crucial given that large areas covered by savanna were under former colonial administration. In numerous countries post-independence land reforms have not successfully addressed threats to social, economic and environmental sustainability created by colonial systems of land rights; in a number of countries land reform has even exacerbated the problems [19]. Tenure reform needs to be rooted in livelihood strategies of intended beneficiaries that emphasise justice, equity, clarity and security of land rights in addition to macro-economic goals [19].

Climate change: understanding the past to divine a modelled future

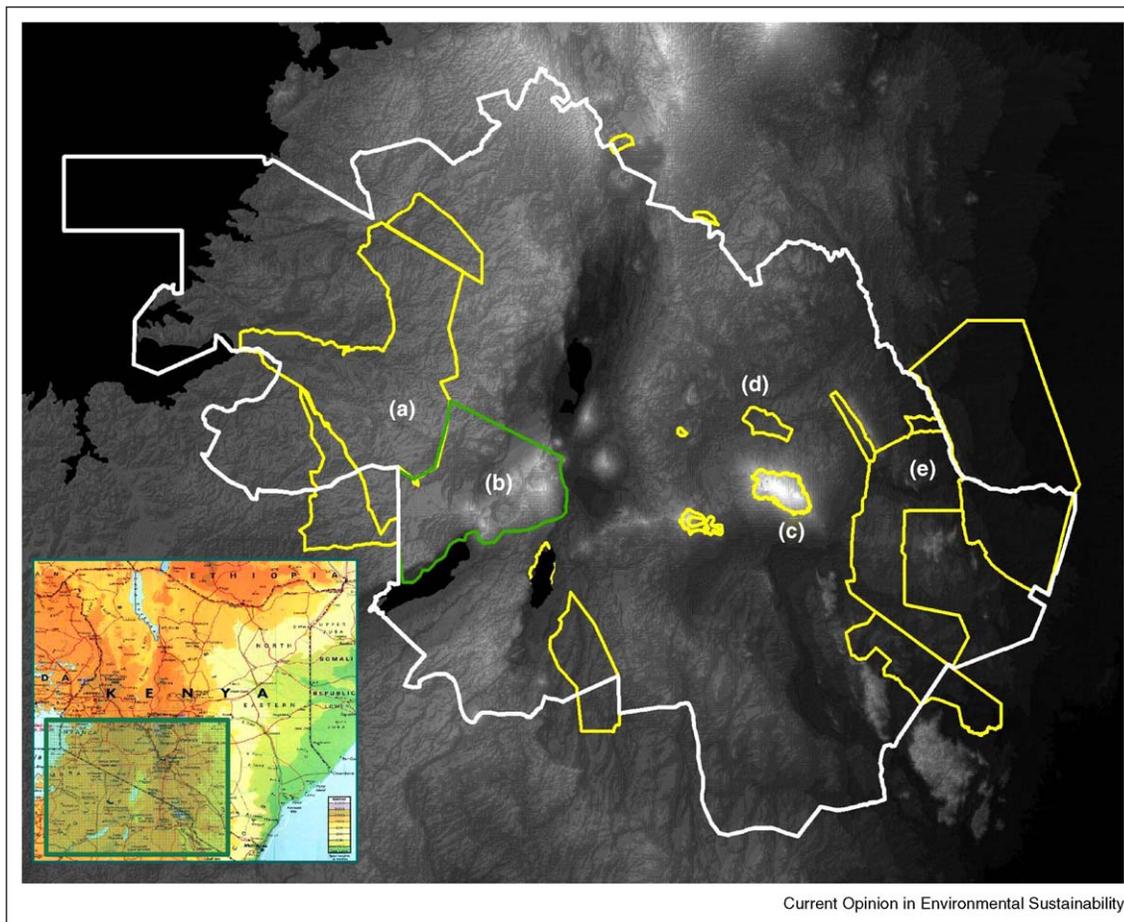
Climate change is not a new phenomenon; the only constant about climate throughout Earth's history is that it has changed! As more palaeoenvironmental data are produced from savanna areas a coherent perspective on the spatial and temporal character of climate shifts, and how these impact on ecosystems, emerges [20,21]. Understanding the range of natural variability, and ecosystem response to this, has a key (and hitherto largely ignored) role for the future management of savannas. The responsive nature of savanna ecosystems can be seen in the extensive 2009 drought that extended across the horn of Africa decimating herbivore (both domestic

and natural) populations and the livelihoods of people living within and adjacent to savanna areas, particularly those within more marginal areas. People and ecosystems have responded and adapted to such change during the past in a variety of ways. During droughts many savanna households resort to short-term survival activities such as casual employment or selling charcoal; often at the expense of long-term livelihood security [18]. Faunal and floral resources are the foundation of the livelihood system and can become rapidly marginal when there is a shift, be it in climate, policy or social structure. A diverse range of adaptation strategies can reduce vulnerability to climate change by making communities better able to adjust to climatic variability, moderating potential damages and helping them cope with adverse consequences. For example, pastoral communities maintain wealth and their environmental buffer in herds of cattle; during extreme periods of drought these 'stores' can be massively impacted on. Rather than enabling long-term security in the face of such shocks and changes, over reliance on faunal and floral resources can make for fragile

safety nets [17], with limited capacity to buffer against the most extreme impacts of climate change. A better understanding of how people within savanna areas perceive climate change, their ongoing adaptation measures, and the factors influencing the decision to adapt practices is needed to craft policies and programmes aimed at promoting successful adaptation — again salutary lessons can be learnt from a historical perspective [22].

Impacts of increasing water stress are predicted to become more acute in most southern African countries [16]. Even in East Africa, where most climate change models predict increased rainfall, recent research suggests that local circulation effects will actually result in decreased precipitation [23]. Anticipated climate changes pose great threats to food and water security, public health, natural resources and biodiversity [24]. A variety of models to investigate species responses to climate change are becoming available with multi-species and niche-based models commonly used to show species ranges, and investigate changes in these [25,26]. For

Figure 2



The Tanzanian Kenya borderlands areas highlighting the distribution of national parks and protected areas. Some of the more commonly known ones are labelled. (a) Serengeti, (b) Ngorogoro, (c) Kilimanjaro, (d) Amboseli and (e) Tsavo.

the last two decades it has been recognised that species will move into, and out of, protected areas as climates change [27] assessments have targeted the effects on species representation within protected areas [28] and the extinction risk associated with climate change [15]. With such tools to predict impacts of climate change, it is quite alarming that much of the high diversity in savanna ecosystems is found within a network of relatively static protected areas and game reserves. The robustness of the protected area network is not just a matter of conservation: there is great wealth stored in natural capital within savanna protected areas. For example, across the Tanzanian and Kenya Borderlands region (Figure 2) some 14 protected areas, including the world famous national parks like Amboseli, Masai Mara and Serengeti, attract millions of visitors per annum with billions of US\$ in associated tourist revenue vital to the national economies. Climate change is a dangerous and uncertain spectre for biodiversity, protected areas and the associated socio-economic benefits. For example, within the Amboseli National Park in southern Kenya the extensive drought experienced in 2009 has resulted in 90% reduction in the Wildebeest population with large coeval reductions in other ungulate populations (David Western, unpublished data). Although the carnivore populations did particularly well during the drought, the present-day lack of prey species is leading to serious human–wildlife conflict as the carnivores turn to domesticated stock. To deal with this situation the Kenyan wildlife service are buying in 150 zebra from a private game reserve in Kenya at the cost of US\$ 1 000 000.

Although the degree to which ecosystem readjustments can be compensated for by the occupation of newly suitable ranges is highly uncertain [29], the present degree of protection that many species enjoy within protected areas is likely to erode as a result of predicted climate change. Current and future modelled ranges can be used to calculate the area of a species' range under protection, although it is important to keep in mind that a species' modelled potential range does not always precisely match its actual range [30]. Ecology, ecosystem modelling, archaeology and palaeoclimate research strands need to be woven together in a cross-disciplinary effort to assess the range of natural environmental variability and associated response of savanna ecosystems to environmental shifts in the past, at the present and into the future. Whilst conservation initiatives are still motivated by a desire to conserve 'pristine nature' in protected areas, there is growing recognition of the long-term human involvement in driving savanna dynamics, and of the importance of conservation outside protected areas. O'Brien *et al.* [31] stress that external interventions should be carried out in such a way as to enhance people's ability to respond to change by focusing on interacting, sometimes hidden and geographically linked, coping strategies so that vulnerability may be buffered. Thoughtful con-

sideration must be given to how societies might have perceived, been impacted by, and adapted to changing climate conditions in the past; such an understanding can only be achieved by combining such disciplines that are currently too separate. Much basic ecological knowledge for predicting the likely impacts of global change, although often lacking, is a requirement to develop future policies that take into account the dynamic nature of ecosystem response to environmental scenarios [32].

Fire, grazers, CO₂ and tree growth: changing interactions

Fire is an under-appreciated control on savanna composition, distribution and structure [33]. Savannas have been influenced by fire for millennia with the reduction of tree cover by burning resulting in the evolution of highly biodiverse ecosystems, and facilitating the rise of C₄ grass-dominated floras and associated faunas [33]. Fire, not surprisingly, limits tree growth, as clearly shown by fire exclusion experiments [34,35]. Increased anthropogenic use of fire as a tool for clearing savannas has a profound influence on the amount of burned biomass [35,36]. To understand the changing nature of the impact of fire there is a need for better information on the temporal and spatial character of fire activity and land cover impacts at the landscape level [37]. For example, there has been growing interest in the effects of changing atmospheric CO₂ as an additional and interacting factor with fire and grazing activity that influences vegetation composition and structure [38].

Atmospheric CO₂ concentration influences plants by altering water use efficiency, photosynthetic rates, light-use and nutrient-use efficiency [33]. Recently, it has become possible to disentangle correlation from causality using Dynamic Global Vegetation models (DGVMs) designed to simulate vegetation responses to changing environments [39]. For example, application of DGVMs has allowed integrated assessment on the extent of fire-dependent ecosystems and an evaluation of the mismatch between climatic potential and actual world distribution [33]. Biome-type vegetation models have also demonstrated important interactions by increasing CO₂ in African ecosystems [40]. Increased tree growth and woody thickening allows trees to grow above a threshold where fire will maintain an open structure [41]. The resulting more densely forested landscape, whilst beneficial for biomass and carbon storage, is deleterious to wildlife and tourism — preventing the open savanna structure ideal for game viewing. Ecosystem modelling is a crucial tool for evaluating such impacts and enabling people to predict and hence manage such change. Although there are a variety of approaches that can be applied, each of these has its own drawbacks, and users who favour one approach over another. Whilst it is clear that future ecosystem composition, structure and functioning will be dramatically different, it is imperative to understand

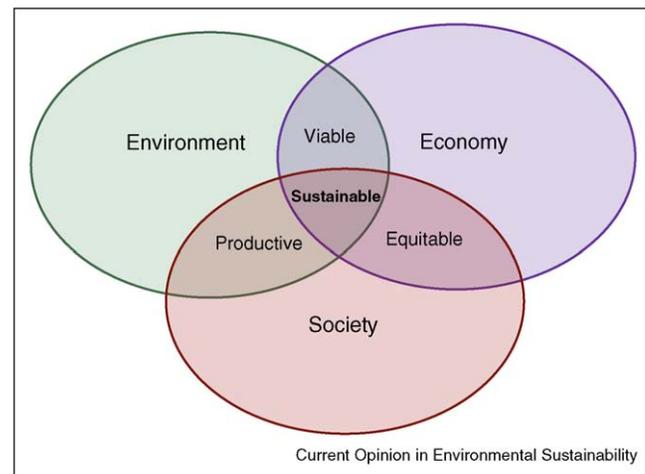
the full range of environmental variability, and how this will impact ecosystems. Such an understanding may be considered by conservation biologists to impart effective long-term management strategies that promote research capacity and the ability for communities to contribute to, and benefit from, their conservation [42].

Savanna ecosystem services: sustainable policies for natural capital

Savanna ecosystems deliver goods and services to humankind such as food, materials, pollinators and less tangible commodities such as carbon storage, and regulation of the carbon cycle and the moderating flows of energy and water. Hence, they can influence local weather and moderate atmospheric composition. Maintaining the flow of these goods and services requires healthy ecosystems — a challenge in the face of increasing human-induced global environmental changes [5,43]. Changes in the biophysical environment, and the social and economic processes with which they interact, must form a key focus of any savanna management policy. Herbaceous and woody layers are an interacting entity with the various grass–tree communities being an integral part of a catena. Policies that target individual sectors and aspects of the savanna environment, in the absence of a coherent understanding of the whole, undermine savanna ecosystem functioning and fail to address the critical threats to (or realise the potential opportunities of) the economic, social and environmental benefits of savannas. Sustainable ecosystem management must therefore be directed towards developing and maintaining beneficial interactions between managed and natural systems — avoiding these interactions is not a practical option [1,3,44]. The dynamic social, economic and biophysical environment of savannas must continue to be a focus of any savanna policy if sustainable use is to be achieved [17].

As understanding grows about the close linkages of hitherto separate urban, regional and global processes, such as an increase in demand for biofuels, the invasion of alien species and the increase in game farming [17], it is clear that human–savanna interactions are more diverse than simple degradation and livelihood narratives. The nature and rate of these interactions, and how local changes link to global processes, makes it paramount to identify what may constitute threats under what particular set of conditions, and what interventions may ensure that ongoing processes of change can be turned into potential for enhanced sustainability [17]. Structural analysis can be used to examine the multitude of different interactions between social, economic and environmental processes to identify key drivers of sustainability, in particular the central role of the biophysical environment, both in driving and being dependent on other processes [17]. The importance of a holistic approach is clearly demonstrated by vulnerability interventions that focus on single stressors alone; these often have unintended

Figure 3



The three pillars of environment, economy and society and how these interact to lead to sustainable development.

results, particularly for vulnerable groups, as outcomes are influenced by multiple processes [31]. This spatially wide interaction stresses the need for researchers and policy-makers alike to, in addition to measuring the extent and rate of isolated processes and their effects on singular elements of the savanna system, consider the savanna dynamism in terms of process interactions [17]. Economic and political empowerment of localised savanna communities needs to be an ingredient in any effort aiming to address social sustainability and vulnerability. This process of empowering should allow social sustainability to affect ecosystem sustainability and *vice versa*. As some of the key driving factors are generated externally to the savanna system, such policies clearly also need to take the multi-sectoral nature of savanna economies into account to effectively manage this diversity [17]. Actions by other formal and informal institutions and the development of new governance structures in natural resource management may also be important [45,46] if the three pillars of sustainability (Figure 3) are to be reinforced.

Future savannas

The future character of savannas, given their dynamic ecology, complexity of human–ecosystem interaction, and response to atmospheric, climatic and land use change is uncertain. The world’s environment is changing more rapidly than at any time in human history; these changes, as throughout history, are intimately connected to form coupled human–ecosystem which maintain life. The fate of humanity is inseparable from the fate of our ecosystems, of which savannas are one of the most important, and, possibly because of their great spatial extent, also one of the most overlooked and undervalued ecosystems. There are initiatives to try and limit impacts of global climate change — a huge

task with huge benefits. Predicting and clarifying impacts of global change on biodiversity, ecosystem services, human livelihoods and land use change (degradation, fragmentation, biotic invasion and overuse) presents considerable challenges. To meet this challenge we need to apply skills, analytical methods, data and intellect from a diverse range of actors from international institutions to households must develop a strategic blend of disciplines, tools and understanding. One crucial area in need of development is more realistic coupled ecosystem–climate change modelling approaches that can be used to incorporate impacts of climate change on the protected area network under future socio-economic and climate scenarios. Although the current protected area network provides an important conservation apparatus, further expansion of this network is limited by competing demands for other land use. Therefore, conservationists need also to look beyond reserves and consider the importance of the surrounding landscape matrix by integrating traditional knowledge on land management with contemporary science. Such work on savanna dynamics must be embedded within field-based monitoring programmes, particularly in vulnerable areas. Such monitoring needs a range of skilled researchers from botanists to social scientists who are able to communicate their findings across disciplines. There is an urgent need to conduct a gap-analysis of *in situ* and *ex situ* conservation actions for species and livelihoods threatened by climate change. To implement urgent conservation actions for taxa and communities such an approach must be able to identify geographical priority areas that account for plant life history strategies and capacity for adaptation, keystone species (including those currently ‘taken for granted’) and must be interconnected between people and ecosystems.

There need to be incentives in place to encourage sustainable management of savanna ecosystems through post-Copenhagen mechanisms such as International Emissions Trading, the Clean Development Mechanism and/or offsets mechanisms such as REDD. Such a targeted approach has to ensure it is ecologically and bioclimatically suitable, and not at the expense of other ecosystem functions, builds on solid ecological science and maintain ecosystem function for the benefit of society, locally regionally and globally. For tangible progress to be made towards a sustainable coupled social savanna, natural and social scientist must overcome language barriers to ensure conservation of biodiversity [47]. However, this is much more than just semantics; there must be closer intervals between researcher, conservation and development of NGOs and Government agencies that actually develop, implement and enforce policy [48]. Such a shift in focus will only be successful if it is embedded within the concept that savanna ecosystems are a product of a long history of human–environmental interaction and that sustainable human use of

savannas is something to be celebrated rather than discouraged.

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References

- Mistry J: *World Savannas – Ecology and Human Use*. Harlow: Prentice Hall; 2000.
- Scholes RJ: **Woodlands of South Africa**. In *Indigenous Forests and Woodlands in South Africa: Policy, People and Practice*. Edited by Lawes MJ, Eeley HAC, Shackleton CM, Geach BGS. Pietermaritzburg: University of KwaZulu-Natal Press; 2004:3-29.
- Scholes RJ, Walker BH: *An African Savanna: Synthesis of the Nylsvley Study* Cambridge: Cambridge University Press; 1993.
- Gillson L: **Evidence of hierarchical patch dynamics in an East African savanna?** *Landscape Ecol* 2004, **19**:883-894.
- Bassett TJ, Crummey D: **Contested images contested realities: environment and society in African savannas**. In *African Savannas: Global Narratives and Local Knowledge of Environmental Change*. Edited by Bassett TJ, Crummey D. Oxford: James Currey; 2003:1-30.
- de Noblet-Ducoudré N, Claussen M, Prentice C: **Mid-Holocene greening of the Sahara: first results of the GAIM 6000 year BP experiment with two asynchronously coupled atmosphere/biome models**. *Clim Dynam* 2000, **16**:643-659.
- Schulz E: **Holocene environments in the central Sahara**. *Hydrobiologia* 1999, **214**:359-365.
- Reenberg A: **Getting the climate impacts right – the complex dynamics of the agricultural frontier in the Sahel**. *IOP Conf Series: Earth Environ Sci* 2009, **6**:342037.
- House JI, Archer S, Breshears DD, Scholes RJ: **Conundrums in mixed woody-herbaceous plant systems**. *J Biogeogr* 2003, **30**:1763-1777.
- Scholes RJ, Archer SR: **Tree–grass interactions in savannas**. *Annu Rev Ecol Syst* 1997, **28**:517-544.
- Watson HK: **The sustainability of southern Africa’s savanna resources**. In *A Rebirth of Science in Africa: A Vision for Life and Environmental Sciences*. Edited by Baijnath H, Singh Y. Pretoria: UMDAS Press; 2002:160-174.
- Sereno PC, Garcea EAA, Jousse H, Stojanowski CM, Saliège J-F, Maga A, Ide OA, Knudson KJ, Mercuri AM, Stafford TA Jr et al.: **Lakeside Cemeteries in the Sahara: 5000 years of Holocene population and environmental change**. *PLoS ONE* 2008, **3**:2995.
- DeFries RS, Foley JA, Asner GP: **Land-use choices: balancing human needs and ecosystem function**. *Front Ecol Environ* 2004, **2**:249-257.
- Ellis LE, Ramankutty N: **Putting people in the map: anthropogenic biomes of the world**. *Front Ecol Environ* 2008, **6**:439-447.
- Thomas CD, Cameron A, Green RE, Bakkenes M, Beaumont LJ, Collingham YC, Erasmus BFN, de Siqueira MF, Grainger A, Hannah L et al.: **Extinction risk from climate change**. *Nature* 2004, **427**:145-148.
- IPCC: *Climate change 2007: Synthesis Report* Cambridge: Cambridge University Press; 2007.
- Eriksen S, Watson H: **The dynamic context of southern African savannas: investigating emerging threats and opportunities to sustainability**. *Environ Sci Policy* 2009, **12**:5-22.

18. Eriksen S, Silva S: **The vulnerability context of a savanna area of Mozambique: household drought coping strategies and responses to economic change.** *Environ Sci Policy* 2009, **12**:33-52.
19. Clover J, Eriksen S: **The effects of land tenure change on sustainability: human security and environmental change in southern African savannas.** *Environ Sci Policy* 2009, **12**:53-70.
20. Rucina S, Downton L, Muiruri VM, Marchant R: *Late Holocene Savanna Dynamics in the Amboseli Basin.* Kenya: The Holocene; 2009.
21. Ryner MA, Bonnefille R, Holmgren K, Muzuka A: **Vegetation changes in Empakaai Crater, Northern Tanzania, at 14,800–9300 cal yr BP.** *Rev Palaeobot Palynol* 2006, **140**:163-174.
22. Bryan E, Deressa TT, Gbetibouo GA, Ringler G: **Adaptation to climate change in Ethiopia and South Africa: options and constraints.** *Environ Sci Policy* 2009, **12**:5-22.
23. Funk C, Dettinger MD, Michaelsen JC, Verdin JP, Brown ME, Barlow M, Hoell A: **Warming of the Indian Ocean threatens Eastern and Southern African food security but could be mitigated by agricultural development.** *Proc Natl Acad Sci U S A* 2008, **105**:11081-11086.
24. McCarthy J, Canziani OF, Leary NA, Dokken DJ, White C: **Climate change 2001: impacts, adaptation, and vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change.** Cambridge: Cambridge University Press; 2001.
25. Erasmus BFN, Van Jaarsveld AS, Chown SL, Kshatriya M, Wessels KJ: **Vulnerability of South African animal taxa to climate change.** *Global Change Biol* 2002, **8**:679-693.
26. Platts P, McClean C, Lovett J, Marchant R: **Predicting tree distributions in an East African biodiversity hotspot: model selection, weights and space.** *Ecol Modell* 2008, **218**:121-134.
27. Peters RL, Darling JD: **The greenhouse effect and nature reserves.** *BioScience* 1985, **35**:707-717.
28. Araujo MB, Cabeza M, Thuiller W: **Would climate change drive species out of reserves? An assessment of existing reserve-selection methods.** *Global Change Biol* 2004, **10**:1618-1626.
29. Hannah L, Midgley G, Hughes G, Bomhard B: **The view from the Cape: extinction risk. Protected areas, and climate change.** *BioScience* 2005, **55**:231-242.
30. Pearson RG, Dawson TP: **Predicting the impacts of climate change on the distribution of species: are bioclimate envelope models useful?** *Global Ecol Biogeogr* 2003, **12**:361-371.
31. O'Brien K, Quinlan T, Ziervogel G: **Vulnerability interventions in the context of multiple stressors: lessons from the Southern Africa Vulnerability Initiative (SAVI).** *Environ Sci Policy* 2009, **12**:23-32.
32. Thuiller W, Broennimann O, Hughes G, Alkemade RM, Midgley GF, Corse F: **Vulnerability of African mammals to anthropogenic climate change under conservative land transformation assumptions.** *Global Change Biol* 2006, **12**:424-440.
33. Bond W, Woodwood I, Midgley G: **The global distribution of ecosystems in a world without fire.** *New Phytol* 2005, **165**:525-538.
34. Bowman DMJS: **Understanding a flammable planet — climate, fire and global vegetation patterns.** *New Phytol* 2005, **165**:341-345.
35. Bowman DMJS, Dingle JK, Johnston FH, Parry D, Foley M: **Seasonal patterns in biomass smoke pollution and the mid 20th-century transition from Aboriginal to European fire management in northern Australia.** *Global Ecol Biogeogr* 2007, **16**:246-256.
36. Allen TG: **Land clearing in African savannas.** In *Land Clearing and Development in the Tropics.* Edited by Lal R, Sanchez PA, Cummings RW. Rotterdam: A.A. Balkema; 1986:69-80.
37. Eva H, Lambin EF: **Fires and land-cover change in the tropics: a remote sensing analysis at the landscape scale.** *J Biogeogr* 2000, **27**:765-776.
38. Ehleringer JR, Cerling TE, Helliker BR: **C₄ photosynthesis, atmospheric CO₂ and climate.** *Oecologica* 1997, **112**:285-299.
39. Sitch S, Smith B, Prentice I: **Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ Dynamic Global Vegetation model.** *Global Change Biol* 2003, **9**:161-185.
40. Jolly D, Haxeltine A: **Effect of low glacial atmospheric CO₂ on tropical African montane vegetation.** *Science* 1997, **276**:786-788.
41. Rohde RF, Moleele NM, Mphale M, Allsopp N, Chanda R, Hoffmann MT, Magole L, Young E: **Dynamics of grazing policy and practice: environmental and social impacts in three communal areas of southern Africa.** *Environ Sci Policy* 2006, **9**:302-316.
42. Burgess N, Mwakalila S, Madoffe S, Ricketts T, Olwero N, Swetnam R, Mbilinyi B, Marchant R, Mitalo F, White S *et al.*: **Valuing the Arc – a Programme to Map and Value Ecosystem Services in Tanzania.** *Mountain Research Initiative Newsletter* 2009, **18(3)**:18-21.
43. Sporton D, Thomas D: *Sustainable Livelihoods in Kalahari Environments: Contributions to Global Debates* Oxford: Oxford University Press; 2002.
44. Foley JA, DeFries R, Asner GP, Barford C, Bonan G, Carpenter SR, Chapin FS, Coe MT, Daily GC, Gibbs HK *et al.*: **Global consequences of land use.** *Science* 2005, **309**:570-574.
45. Ostrom E: In *Understanding Institutional Diversity.* Edited by Ewing NJ. Princeton University Press; 2005.
46. Ostrom E: **A general framework for analyzing sustainability of social-ecological systems.** *Science* 2005, **325**:419-422.
47. Ewers RM, Rodrigues ASL: **Speaking different languages on biodiversity.** *Nature* 2006, **443**:506.
48. Smith RJ, Verissimo D, Leader-Williams N: **Let the locals lead.** *Nature* 2009, **462**:280-281.
49. Olson DM, Dinerstein E, Wikramanayake P, Burgess ND, Powell GVN, Underwood EC, D'Amico JA, Itoua I, Strand HE, Morrison JC *et al.*: **Ecoregions of the world.** *BioScience* 2001, **51**:933-938.