THE FUTURE OF SUB-SAHARAN AFRICA'S BIODIVERSITY IN THE FACE OF CLIMATE AND SOCIETAL CHANGE

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IDRC GRANT / SUBVENTION DU CRDI : - CANADA-SOUTH AFRICA TRILATERAL RESEARCH CHAIR IN CLIMATE CHANGE AND HUMAN-WILDLIFE INTERACTIONS

frontiers | Frontiers in Ecology and Evolution

TYPE Review
PUBLISHED 02 August 2022
DOI 10.3389/fevo.2022.790552

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OPEN ACCESS

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SPECIALTY SECTION
This article was submitted to
Conservation and Restoration Ecology,
a section of the journal
Frontiers in Ecology and Evolution

RECEIVED 06 October 2021
ACCEPTED 14 July 2022
PUBLISHED 02 August 2022

CITATION
Chapman CA, Abernathy K,
Chapman LJ, Downs C, Effiom EO,
Gogarten JF, Golooba M, Kalbitzer U,
Lawes MJ, Mekonnen A, Omeja P,
Razafindratsima O, Sheil D, Tabor GM,
Tumwesigye C and Sarkar D (2022)
The future of sub-Saharan Africa's
biodiversity in the face of climate
and societal change.
Front. Ecol. Evol. 10:790552.
doi: 10.3389/fevo.2022.790552

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The future of sub-Saharan Africa's biodiversity in the face of climate and societal change

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Many of the world's most biodiverse regions are found in the poorest and second most populous continent of Africa; a continent facing exceptional challenges. Africa is projected to quadruple its population by 2100 and experience increasingly severe climate change and environmental conflict—all of which will ravage biodiversity. Here we assess conservation threats facing Africa and consider how these threats will be affected by human population growth, economic expansion, and climate change. We then evaluate the current capacity and infrastructure available to conserve the continent's biodiversity. We consider four key questions essential for the future of African conservation: (1) how to build societal support for conservation efforts within Africa; (2) how to build Africa's education, research, and management capacity; (3) how to finance conservation efforts; and (4) is conservation through development the appropriate approach for Africa? While the challenges are great, ways forward are clear, and we present ideas on how progress can be made. Given Africa's current modest capacity to address its biodiversity crisis, additional international funding is required, but estimates of the cost of conserving Africa's biodiversity are within reach.

The will to act must build on the sympathy for conservation that is evident in Africa, but this will require building the education capacity within the continent. Considering Africa's rapidly growing population and the associated huge economic needs, options other than conservation through development need to be more effectively explored. Despite the gravity of the situation, we believe that concerted effort in the coming decades can successfully curb the loss of biodiversity in Africa.

KEYWORDS

climate change, human population growth, economic development, sustainable development, biodiversity, tropical forests

Introduction

Humanity faces unprecedented environmental challenges. Nowhere are these challenges greater than in Africa, the poorest and second most populous continent (UN, 2015). Twenty percent of Africa's land surface (6.6 million km^2) is degraded, an area twice the size of India (Archer et al., 2018), while Africa's population is projected to quadruple by 2100 (UN, 2015), the effects of climate change will be severe (Niang et al., 2014), and environmental conflict is projected to rise sharply (Laurance et al., 2014). These changes will not only severely impact biodiversity but also the life and livelihoods of Africans. For example, by 2100, more than half of Africa's bird and mammal species could be lost and the productivity of Africa's lakes could decline by 20–30% (Archer et al., 2018).

Grappling with these challenges requires new approaches to conservation, a scaling up of effort, enhanced integration of fields of inquiry, and, most importantly, the popular will to enact meaningful change. Conservation scientists and managers are moving away from project-based schemes, centered on specific protected areas or endangered species. They are adopting more integrated strategies that couple social and ecological dynamics (Gardner et al., 2009; Sayer et al., 2013). Researchers now appreciate the magnitude of effects on conservation outcomes that are imposed by increasing human populations, foreign investment strategies, and changing patterns of extractive development. Such factors are now included in integrated management schemes (e.g., landscape approaches) to conserve biodiversity and ensure human wellbeing. Nonetheless, the complexity of integrated and adaptive conservation and management strategies, and the need to reconcile maintenance of biodiversity and ecosystem services with economic development and human health is daunting and likely beyond the reach of economically impoverished countries.

Here we assess the conservation challenges facing Africa, focusing on the forest landscapes of sub-Saharan Africa. We synthesize the scientific insights that guide our understanding of biodiversity conservation in human-modified and protected landscapes. We examine the most pressing problems and challenges affecting the continent's biodiversity. Our review includes four lines of inquiry. **First**, we present a conceptual framework that integrates the range of driving factors that define and contextualize our understanding of the future of tropical biodiversity in sub-Saharan Africa. **Second**, we assess the state of sub-Saharan African biodiversity, the current threats, and consider how these will change under projected patterns of human population growth and movement, economic expansion, and climate change. **Third**, we consider the current capacity and institutional infrastructure available to conserving the continent's biodiversity. **Finally**, we draw upon the first three lines of inquiry to discuss pathways of maintaining as much of Africa's biodiversity as possible.

Conceptual framework

Our conceptual framework examines the societal factors that affect biodiversity as well as those that must be considered to develop optimal conservation outcomes for Africa's biodiversity (**Figure 1**). Our framework identifies the complex, inter-related socio-economic factors, at local, national, and international levels, which largely determine the pressures on biodiversity. Ignoring these factors and how they will change will cause conservation efforts to fail in the long-term. On the other hand, the ability to respond to threats to biodiversity is determined by institutional capacity operating at local, national, and international levels. The best designed conservation plans will fail if, for example, appropriately trained personnel and funds are not available. The type and extent of influence of societal and institutional factors are context-dependent and vary among environments, economies, cultures, and thus countries. While the strength of the interactions among factors will change and the significance of different factors will vary within and among countries, the framework's overall structure and integration of coupled social and ecological dynamics are generalizable.

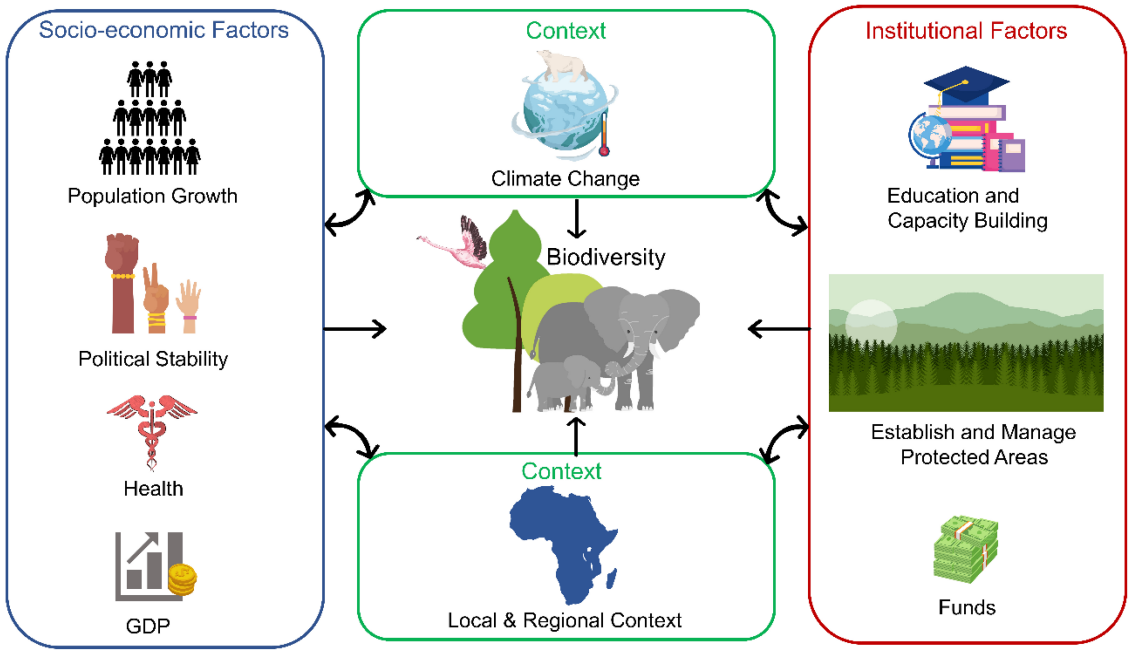

FIGURE 1
A conceptual framework that integrates threats, context, and the factors that must be considered if Africa's biodiversity is to persist and be effectively protected/maintained.

While recognizing their need, we go beyond traditional, project-based methods that are focused on specific protected areas or endangered species and shift the emphasis to large-scale programs that couple social and ecological issues of concern to conservation management. We emphasize what actions are most needed to make progress, how academic researchers can best contribute to these efforts, and what policy transformations are needed to protect Africa's biodiversity.

The sub-Saharan African context

Biodiversity

Africa is extraordinarily biodiverse, with an estimated 50,000–73,000 plants, 1,100 mammals, including 194 species of primate and 91 species of antelope, 2,500 birds, 3,000–5,500 freshwater fish, 950 amphibians, and 1,600–2,100 reptile species (Cormier-Salem et al., 2018; O'Connell et al., 2019). This is approximately one-quarter of the world's mammal and bird species. These animals occur in a great diversity of habitats, from deserts to rainforests, from the glaciers on tops of mountains to Lake Assal, 156 m below sea level. Africa hosts eight of the world's 36 recognized biodiversity hotspots (Archer et al., 2018), 373 Ramsar sites and >1,250 Important Bird and Biodiversity Areas (Mittermeier et al., 2011; Ajagbe, 2013). It is home to some of the world's most iconic species that often serve as flagship species for conservation, including gorillas (*Gorilla* spp.), chimpanzees (*Pan troglodytes*) and the "Big Five" (lion—*Panthera leo*, leopard—*Panthera pardus*, rhino—*Diceros bicornis* and *Ceratotherium simum*, elephant—*Loxodonta africana and L. cyclotis,* African buffalo—*Syncerus caffer*).

Most of these species have populations within the 7,800 terrestrial protected areas that cover 5.3 million km^2, approximately 17% of the continent's land area (UNEP-WCMC, 2019; Lindsey et al., 2020). In some countries, particularly in East and Southern Africa, the proportion of land protected far exceeds the global average. However, only 13% of Africa's landmass is covered by rainforest (20% of the total global tropical rainforest area). These rainforests support the largest proportion of the continent's biodiversity, 90% of its stored carbon as defined by above- ground biomass (Mayaux et al., 2013), and are estimated to directly or indirectly support 100 million people by providing food, medicines, wood, and non-timber forest products (Mayaux et al., 2013).

Human populations and extraction

The extraordinary natural capital of Africa faces enormous challenges as Africa is the world's poorest continent and it has a large and rapidly growing human population. As of March 2022, the average monthly pay in Africa is around $758 USD (Mushayi, 2022). Africa's human population is 1.1 billion, and

it is projected to increase to at least 2.4 billion by 2050 and 4.2 billion by the end of the century (Gerland et al., 2014). Africa has the highest human population growth rate of any continent (**Figure 2A**), and all 10 nations with the highest fertility rates are in sub-Saharan Africa. The age structure on the continent is relatively young with 43% of its population being less than 15 years and 60% less than 24 years (He et al., 2016; Juju et al., 2020). Fertility rates in Africa were projected to decline over the last two decades (UN, 2015); however, the actual decline was only a quarter the projection, and in some African countries, the decline stalled altogether (Gerland et al., 2014). This is partially attributed to the unmet need for contraception—the difference between demand and availability is approximately 25%, and this difference has not declined over the last 20 years (Gerland et al., 2014; Kirumira et al., 2019). This contrast has arisen, in part, from international funders withdrawing funding from family planning (Brooks et al., 2019). The inevitable outcome of this high rate of human population growth is continued conversion of wildlands to agriculture that is exacerbated by poor agricultural practices (Salerno et al., 2018).

The environmental impacts of human population growth will be strongly influenced by urbanization (**Figure 2B**). Each year, an estimated 22 million more people are added to Africa's cities (Cartwright, 2015). The urban population is projected to triple between 2011 and 2050, with more than half the continent's inhabitants residing in cities by 2035 and 1.34 billion people living in cities in 2050 (Cartwright, 2015). In general, urban dwellers have higher consumption levels than rural inhabitants in tropical regions where agricultural expansion takes place (Lambin and Meyfroidt, 2011). In some areas of the world, particularly where birth rates are low, urbanization has resulted in conservation gains (Jacob et al., 2008); however, urbanization is likely to increase demand for production land in Africa. This is because urban migrations can accelerate deforestation and agricultural expansion due to a concentrated demand for food and charcoal, which results in peri-urban haloes of unsustainable extraction that can be hundreds of kilometers wide (Ahrends et al., 2010; Rudel, 2013; Abernethy et al., 2016). The effect of urbanization in Africa differs from South-Central America and Asia because African farmers have little access to fertilizers (Salerno et al., 2018); people/countries do not have the capital to import food as crop production in the country declines; agriculture remains one of the few options for advancing personal wealth as alternative reliable employment options are few; and, unlike city-dwellers in Asia and South-Central America, many urban dwellers in Africa still rely heavily on fuelwood or charcoal for cooking (Bonilla Cedrez et al., 2020).

In general, wood supplies 80% or more of domestic energy needs across Africa. In the Democratic Republic of Congo (DRC), fuelwood contributes 95% of energy needs, which amounts to an estimated 70 million m^3 of wood each year (Mayaux et al., 2013). Two trees that are 15–20 m tall and 60 cm in diameter yield 10 m^3 of wood, thus 70 million m^3 harvested is equivalent to the cutting of approximately 14 million trees every year. The consumption of charcoal in Kinshasa alone is estimated at 4.8 million m^3 and affects forests up to 300 km from the city (Mayaux et al., 2013). This urban demand intensifies deforestation along road corridors as wood/charcoal needs to be transported to urban centers. Thus, as national governments, foreign investors, and aid agencies facilitate development of road networks, deforestation increases. For example, in the Republic of Congo, road construction increased from 156 km per year between 1976 and 1990 to more than 600 km per year after 2000, and in north-central parts of the DRC road construction increased from 336 km per year between 1986 and 1990 to 456 km per year between 2000 and 2002 (Laporte et al., 2007). On 21 June 2021, Uganda and DRC announced a $330 million USD road project, which is expected to double trade between the two countries.[1] Finally, cities occupy huge areas. In 2000, African cities covered 33,025 km^2, and over the next three decades, this area is predicted to increase by 590%, the highest rate of increase in urban land cover in the world (Seto et al., 2012). Thus, by the year 2050, the land covered by cities in Africa will be about half the size of Zimbabwe.

The demand for housing, infrastructure, and services associated with urbanization is often met through private sector development and has led to entirely new cities being built from scratch (e.g., Kankugulu, Uganda). These new cities are promoted by real estate investors as eco-friendly, smart, and satellite cities, and are often large-scale gated communities (van Noorloos and Kloosterboer, 2017). Such new developments are a response to the growth of the middle class in Africa; however, while the middle class is growing rapidly and has significant economic influence, they are not influencing political stability, nor growing as fast as lower income classes (Kodila-Tedika et al., 2016). Thus, these cities will not solve Africa's urbanization problems and will lead to increasing expulsion, enclosure, and marginalization of the poor.

The growing human population and investment in infrastructure development will affect Africa's biodiversity, especially its forests, as wood is needed for building material and fuelwood. Globally, ∼60 million ha of tropical primary forest were lost from 2002 to 2019 (Weisse and Gladman, 2020) with 21% of this loss occurring in Africa (Estrada et al., 2020). The rainforest of the Congo Basin covers 200 million ha, but it lost 16 million ha between 2000 and 2014, mostly to small scale agriculture (Reiche et al., 2021). As infrastructure improves in the DRC and the Republic of Congo, forest loss in Africa is expected to increase dramatically. In contrast to Southeast Asia and South America, where deforestation is primarily driven by clearing for plantations (Vijay et al., 2016; Meijaard et al., 2018),

1 https://www.globalconstructionreview.com/news/uganda-and-drc-begin-work-tremendous-road-building/

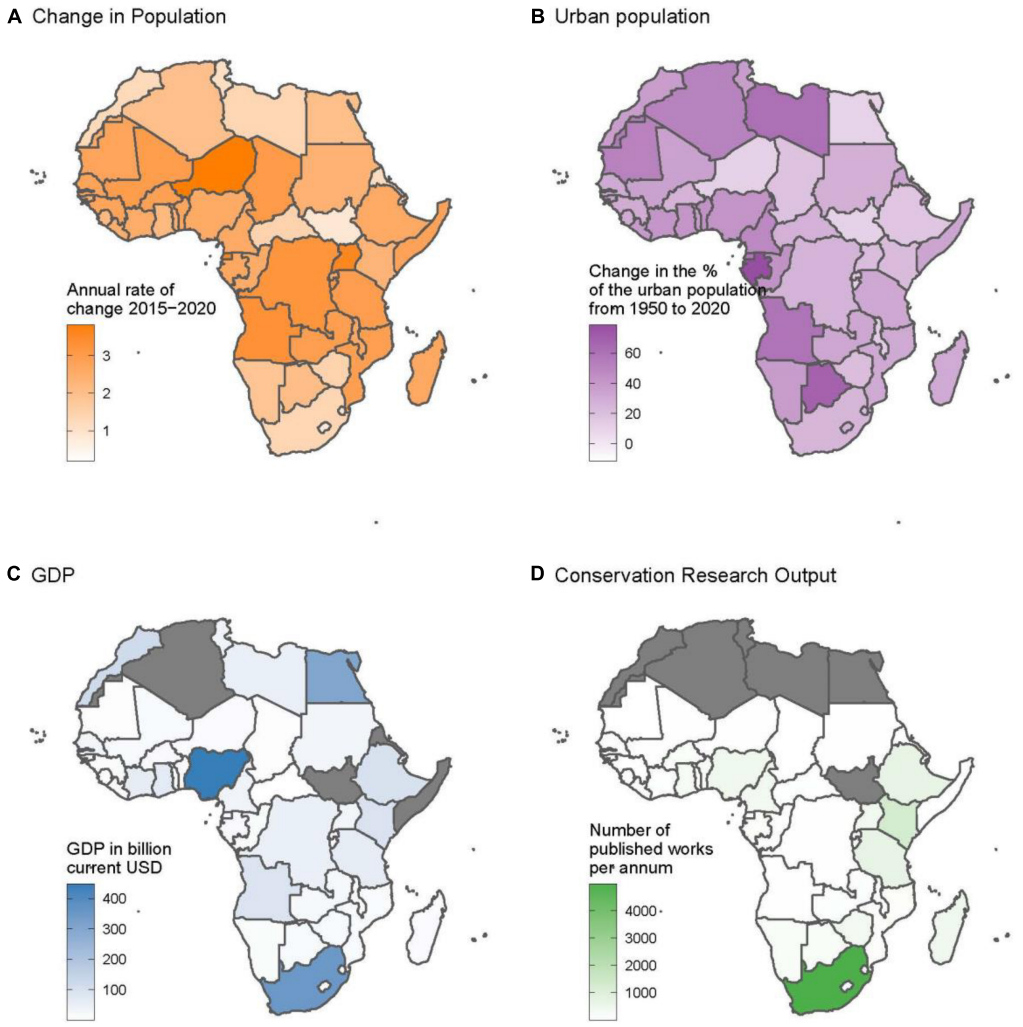

FIGURE 2
Variation among African countries in factors that influence the conservation of biodiversity: **(A)** The percentage with which the population of African countries grows each year, **(B)** urbanization, **(C)** GDP, and **(D)** conservation research output [number of published works per annum based on the Scopus database—a relationship between research output and conservation success has been demonstrated (Hu et al., 2019)]. Data from population.un.org, data.worldbank.org, and Lan et al. (2014) and Makaya (2017). Data were not available for countries in gray.

deforestation in Africa is primarily driven by the expansion of smallholder/subsistence agriculture and fuelwood and charcoal extraction for domestic use (Fisher, 2010). However, with the expansion of global markets, the adverse environmental effects in Africa that have historically come from smallholder agriculture are increasingly being overtaken by large-scale commercial development.

Many African countries are selling large amounts of land to businesses from countries that are capital-rich but lack sufficient agricultural land (Friis and Reenberg, 2010). For example, >50 million ha of farmland in Africa, roughly the area of France, was appropriated by oil- or capital-rich, but food-poor, Middle-Eastern or Asian countries in 2009, with the products destined for export (Lambin and Meyfroidt, 2011). In many cases, the area of land used in this way comprises a large proportion of the available agricultural land, for example in Uganda ∼ 14% of the country area, in Mozambique ∼ 21%, and in DRC ∼ 48% (Friis and Reenberg, 2010). Some of these land transactions are facilitated by the corruption that exists in the political system (Chiweshe, 2021), and thus will not slow down until there is government reform. These acquisitions secure food and domestic animal feed supplies for countries in the Gulf States, China, South Korea, and India. This trend is partially driven by the increasing wealth of countries like China and India and an associated increased preference for animal-based diets (Shimokawa, 2015). The consumption of animal products requires significantly more land than vegetarian diets, and in general, wealthier people consume more food than poor people (Dickson-Hoyle and Reenberg, 2009). Since the food grown on these foreign-owned lands is likely to be exported,

African nations must assign more land, often forested land in high rainfall areas, to domestic agricultural production for their growing human populations. When Africa experiences an environmental crisis, such as drought, the foods produced by internationally owned agriculture are not available for domestic consumption. Such environmental events are set to increase in frequency and intensity with climate change (IPCC, 2019), and the attendant humanitarian crises are likely to be extreme.

Many of these international land sales involve planting cash-crops such as tea, sugarcane, cocoa, and palm oil (Kroeger et al., 2017). The forests of central Africa represent the last remaining unprotected block of rainforest in Africa, but they are threatened. More than 600,000 km^2 of forest (30%; an area roughly the size of France) in Central Africa are under logging concessions, whereas just 12% are protected (Laporte et al., 2007). Between 1960 and 2010, annual industrial round-wood production increased from 23 to 71 million m^3 in sub-Saharan Africa (Estrada, 2013). The conversion of forest for cacao production deserves special attention, as most of the world's cocoa for chocolate is grown in West Africa. Globally, cacao production resulted in the conversion of 30 million ha of land between 1988 and 2008 (Kroeger et al., 2017). In the forest region in Ivory Coast, Ghana, Nigeria, and Cameroon smallholders increased their cultivated area by 3.3% annually between 1988 and 2007, causing 2.3 million ha of forest loss (Kroeger et al., 2017). The conversion of forest for cocoa production was a main driver of forest conversion in the Ivory Coast (**Figure 3**). Chocolate is big business; in 2015 the global chocolate market was ∼ $100 billion, and every year nearly 3 million metric tons of chocolate and other cocoa products are consumed globally. Palm oil production in Africa is also increasing, mostly through foreign investment. Although an estimated 93% of plantations have been established on previously cleared land (Vijay et al., 2016), this has led to a loss of agricultural production. Presently, ∼1.5 million km^2 of Africa are vulnerable to conversion to palm oil production, approximately twice the area of Zambia (Vijay et al., 2016).

With respect to biodiversity loss, hunting and bushmeat harvesting have severely reduced wildlife populations in Africa. For example, since 2007, illegal trade in ivory has doubled (Bennett, 2015) and forest elephant populations declined by 62% between 2002 and 2011 (Maisels et al., 2013). Illegal wildlife trading has become the fourth biggest international organized crime (Wasser et al., 2015). It is estimated that between 1.6 and 4.6 million tons of bushmeat are extracted each year from Central Africa alone (Ingram, 2018; Ingram et al., 2021) (for context, the upper estimate is equivalent to ∼5.7 million cattle, which would make 6.8 billion hamburgers—an equivalent amount is consumed in the United States in just 50 days, as per capita consumption in the United States = 0.388 hamburgers per person per day). Hunting occurs even in many of the national parks that are intended as safe havens (Laurance et al., 2012). This is poignantly illustrated by a study in Taï National Park, Ivory Coast. A park-wide survey of primates found that regardless of species, density was 100 times higher near the protected research station and tourism site than in the remainder of the park, where hunting pressure was severe (N'Goran et al., 2012).

Deforestation, bushmeat hunting, and agricultural expansion are all connected to development and foreign investments. While the EU and US's investment in Africa still dwarfs China's, China's investment is growing rapidly. China invested ∼ $US362 billion in Africa between 2005 and July 2019 (Kalu and Aniche, 2020). Total trade between China and Africa increased from USD 9 billion in 2000 to USD 175 billion in 2015, making China Africa's largest trade partner (Kalu and Aniche, 2020). China imports mostly raw materials from Africa, particularly oil and food products and exports low-cost manufactured goods. The rise in China's investment has caught the attention of conservationists because of its focus on natural resources and frequent disregard for good governance and environmental safeguards (Kalu and Aniche, 2020). In some sectors, there are reasons for concern. For example, China's trade in the forestry sector has increased exponentially in the last two decades, and China is the largest importer of Central African timber (70% in 2015) (De Wasseige et al., 2014; OFAC, 2020). The Chinese market has decreased timber selectivity and resulted in the harvest of a greater number of species. This results in higher extraction densities and the re-harvesting of previously logged concessions, as seen in other areas of the world (Felton et al., 2013). Thus, in the future it will be important to actively engage China in the conservation and management of Africa's biodiversity. Two avenues of engagement are readily evident. First, since 1996, China's involvement in training African university students has grown exponential and as of 2015, 50,000 African students were being trained at Chinese Universities (Li, 2022). If more of this training could be focus on building the continents capacity to engage in conservation, advances would be significant. Secondly, China is funding many development projects in African, including road and oil infrastructure, and if these developments projects can be done following the highest environmental standard, the loss of habitat and biodiversity can be minimized.

A mining boom is underway in Africa. The continent contains approximately 30% of the world's minerals—including the largest known reserves of a wide range of strategically important minerals, including lithium that will be needed for batteries in the very rapidly growing electric car market (Edwards et al., 2014; Goodenough et al., 2021). This represents a huge, largely untapped, opportunity for development. For example, the DRC is estimated to have $24 trillion US dollars' worth of untapped mineral reserves (Stimpson, 2020). This development opportunity is attracting a stampede of foreign investment, from countries like Canada, Australia, and China. Between 2000 and 2009, China's investment in African mining

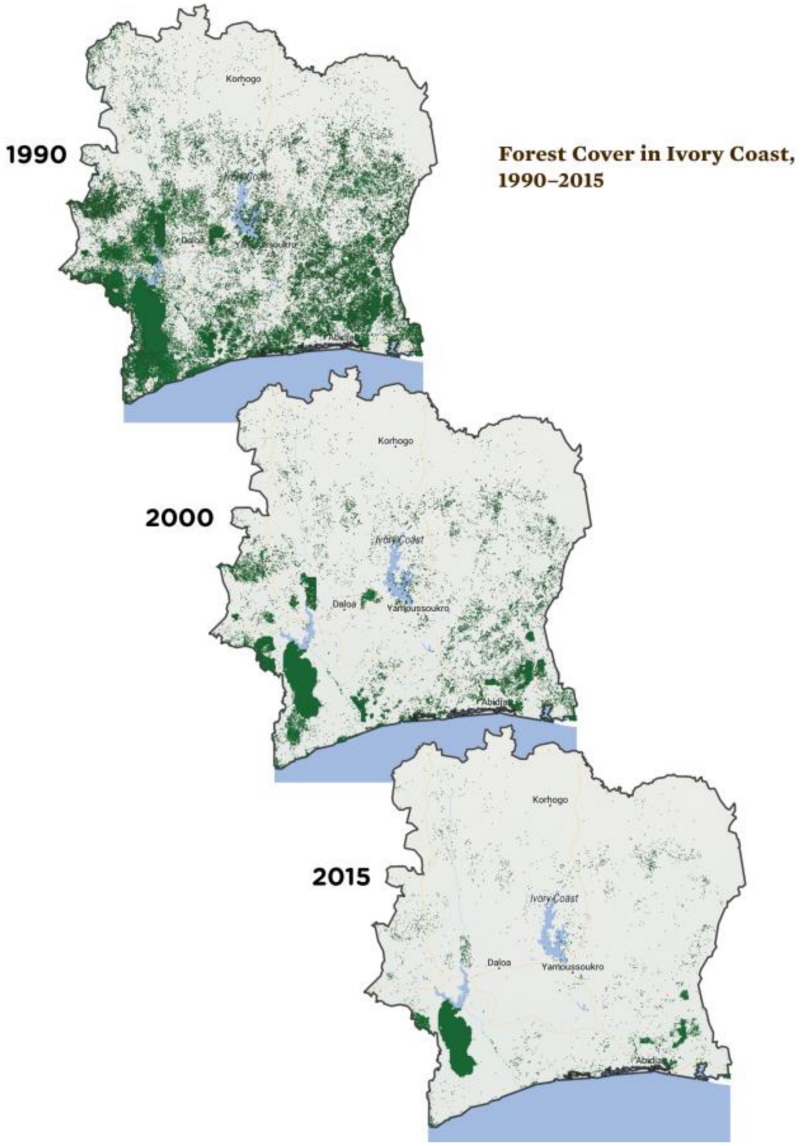

FIGURE 3
Forest cover (depicted in green) in the Ivory Coast in 1990, 2000, and 2015 (figure adapted with permission from Higonnet et al., 2017). In 2015 the remaining forest in the Ivory Coast was primarily in protected areas, but much of the wildlife in these areas has been dramatically reduced by bushmeat hunting (N'Goran et al., 2012).

increased from US$25.7 billion to US$103.4 billion per year (Edwards et al., 2014). Canada has a huge interest in the success of mining in Africa, because more than 80% of the global mining industry's financing is raised on the Toronto Stock exchange (Abadie, 2011). Between 2000 and 2018 there were 260 new mines created and a major expansion of many old mines in sub-Saharan Africa, with key areas of expansion occurring in DRC, Zambia, Ghana, and Nigeria (Ahmed et al., 2021). While the direct effects of mining operations tend to be small, with most mining operations directly impacting less than 10 km^2 (the total new area affected by mining between 2008 and 2018 was 1892 km^2) (Ahmed et al., 2021), indirect impacts of mining on biodiversity are significant. For example, the building of roads and railways open up forested regions for agricultural expansion and bushmeat hunting (Laurance et al., 2014).

Climate change

Protecting Africa's biodiversity is further complicated by the uncertainties of climate change. The earth's climate has warmed by 1.2°C since industrialization, and by the end of the twenty-first century the earth's mean surface temperature is set to increase by at least 1.5°C (IPCC, 2021). For Africa, climate

change projections indicate more extreme change for rainforest regions and estimate a 3–4°C increase in temperature by 2100 (Zelazowski et al., 2011; Malhi et al., 2013) (**Figure 4A**). These projections are supported by meteorological data (Bush et al., 2020a). For example, the Congo Basin and Guinea Conakry regions are clearly warming, with cold extremes decreasing and warm extremes increasing, while total precipitation is decreasing (Aguilar et al., 2009; De Wasseige et al., 2014). In the highlands of Uganda, the maximum monthly temperature has risen by 1.05°C over the last 50 years (Chapman et al., 2021). The effect of this temperature change on forest cover and biodiversity needs to be investigated.

The effect of rising temperature on air circulation and rainfall patterns is very complex and influenced by regional factors, including forest cover (Graham et al., 2016; Sheil, 2018, 2019). Climate models for West Africa and the Congo Basin produce conflicting results; some suggest more rain, while others suggest less (Zelazowski et al., 2011). East African forests will become wetter (**Figure 4B**). However, in general data show that forest loss in Africa tends to lead to reduced rainfall (Duku and Hein, 2021). Various theories and models suggest that, as proposed for Amazonia, this could lead to a transition of the Congo region from wet to arid conditions (Sheil, 2018).

Short-term extremes such as droughts and floods will affect plants, animals, and human populations, and such events will come more frequently and be more intense with climate change. In fact, droughts have already increased in frequency and intensity since the 1970s (Cai et al., 2021). The variation in rainfall events is likely to increase over most of the continent (**Figures 4C,D**), with events becoming fewer but more intense (Archer et al., 2018).

Climate change will affect ecosystem services critical to human wellbeing. For example, agriculture in much of Africa is dependent on rainwater and lacks drought resilience. During times of drought and food shortages, people often turn to harvesting resources from forest systems, including those in protected areas. It is estimated that the continent's population growth will result in an additional 36 million Africans being affected by drought-related famine by 2050 (O'Connell et al., 2019). This will be particularly acute in East Africa and the Horn of Africa in association with the El Niño-Southern Oscillation (ENSO) and positive Indian Ocean Dipole events (Cai et al., 2021).

Climate change will directly impact animal populations as forests disappear and food resources are affected. For example, long-term tree phenology data revealed a 81% decline in fruiting over 32 years in Lope National Park, Gabon that corresponded to an 11% decline in body condition of fruit-dependent forest elephants in the last decade (Bush et al., 2020b). Climate change may result in a decline in the nutritional quality of food (Rothman et al., 2015), thus not only will animals have less to eat, but what is available will be less nutritious.

There is mounting evidence that climate change in sub-Saharan Africa will lead to political conflict and potentially war over access to water (Acemoglu et al., 2017; Witmer et al., 2017; Mack et al., 2021). Aside from the considerable hardships and terrible human costs these events cause, wars are often associated with challenges to wildlife management (Hanson et al., 2009). Conflict in Africa will be more likely in the future, because when populations are dense, young, and growing rapidly, the conditions are ripe for conflict (Bradshaw et al., 2021). In fact, globally, countries with higher population growth rates experience greater levels of social conflict; for countries already in conflict, a doubling of a country's population has been demonstrated to be associated with 4 additional years of full-blown civil war or low-intensity conflict (Acemoglu et al., 2017). Conflicts that may result in the loss of biodiversity may occur in association with dramatic climatic events or anomalies. For example, in March 2019, the southeast coast of Mozambique was devastated by Tropical Cyclone Idai, 1.85 million people needed assistance, and 146,000 people were internally displaced. The cyclone and its associated flooding damaged approximately 100,000 homes, ruined 400,000 ha of crops, and destroyed $1 billion worth of infrastructure (Podesta, 2019). This cyclone was followed by another a month later, and Islamist Militant groups took advantage of the natural disasters to increase attacks in the areas made inaccessible to government forces (Mukwakwa, 2020). Historically, war has often led to losses of wildlife and natural areas, often in biodiversity hotspots. In fact, globally, between 1950 and 2000, 80% of the major armed conflicts took place directly within hotspot areas (Hanson et al., 2009). Africa has had more than 30 wars since 1970 (Shambaugh et al., 2001). During the 1996–1997 war in the DRC, wildlife in Garamba National Park was heavily exploited for meat, and the elephant population was reduced by half, buffalo by two-thirds, and hippo by three-quarters (Hanson et al., 2009).

The World Bank estimates that by 2050 there will be 86 million internally displaced climate migrants in sub-Saharan Africa (Rigaud et al., 2018). In East Africa alone, there will be an estimated 10.1 million climate migrants by 2050, and the number will increase each year by a quarter of a million people. The sudden migration of large numbers of people to a region creates substantial environmental stress if not very carefully managed.

Current conservation capacity

Funding conservation in Africa

Africa is currently making choices about how and where to develop. African leaders, and those who elect them, must ask what areas should be protected and why, and which ones will be given over to development. The role of wildlife and wildlands in Africa's development must be valued to the region's economy

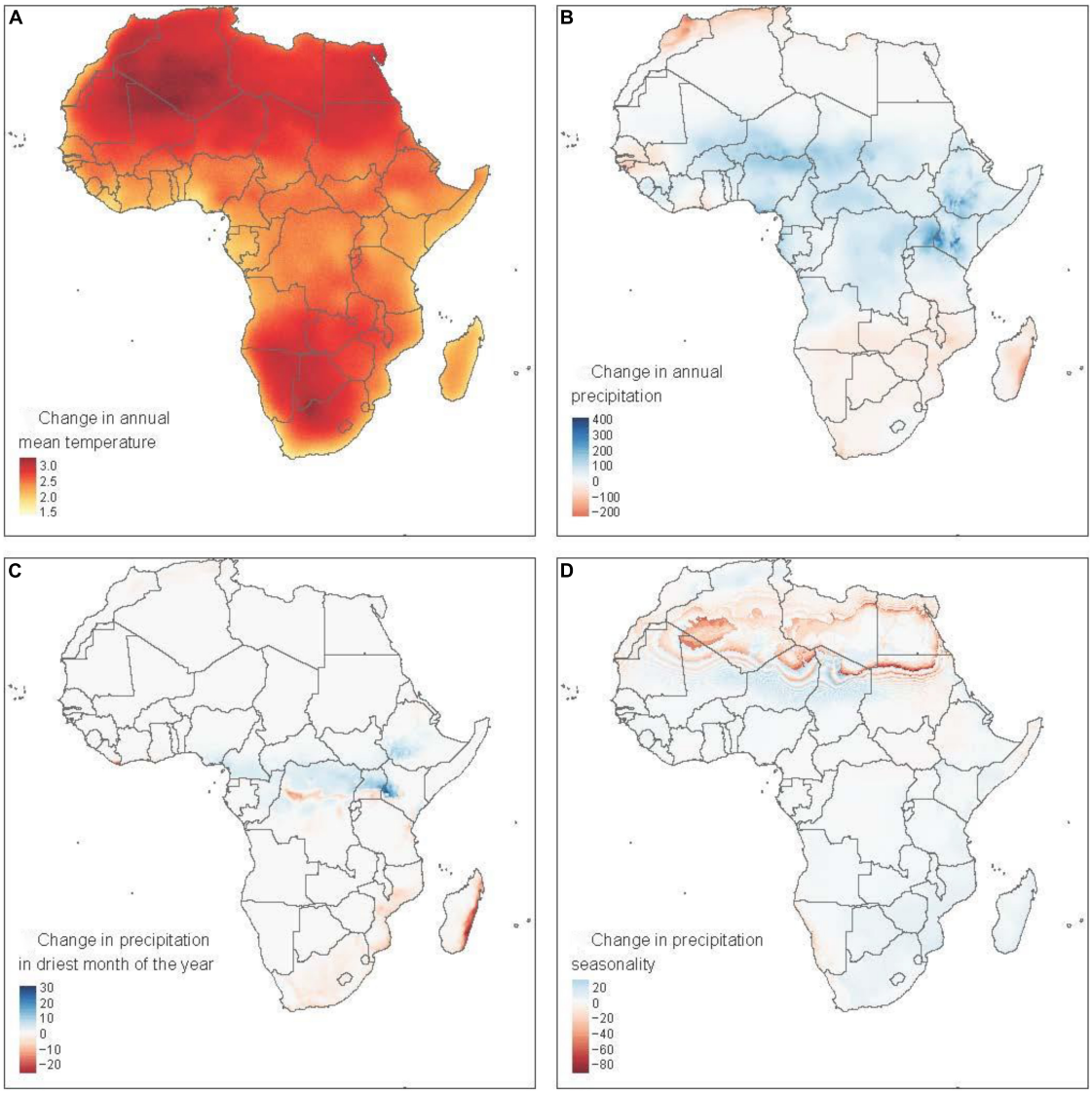

FIGURE 4
Predicted patterns of changes between the reference period 1966–1990 and the CMIP5 predictions for the period 2060–2079 in annual mean temperature **(A)**, annual precipitation **(B)**, precipitation in the driest month of the year **(C)**, and seasonality of precipitation as assessed by the coefficient of variation of monthly values **(D)** across the African continents (all data from worldclim.org). Note there are many uncertainties with these estimates as they do not account for the land-cover effects, which are increasingly recognized as important (Sheil, 2019).

and against human wellbeing. We believe this development and the conservation trade-offs that will be made must ultimately be decided within the continent. This perspective is nicely portrayed as a guiding principle of the strategic plan of the African Wildlife Foundation that states that "Ownership of conservation must rest with the people who ultimately bear the costs and/or reap the benefits of conservation—stakeholders include communities (mostly youth), protected area authorities, national governments, and others who hold rights over the natural resource base. . ." (AWF, 2020b). This ownership of conservation needs to rely on the co-production of information, the use of indigenous knowledge, and requires that funds be provided in a flexible manner not coming with a series of strings attached.

Strategic conservation policies and their implementation requires Africa to build capacity in several ways. Throughout sub-Saharan Africa, inadequate funding is a major impediment to effective park management. Currently, funding to protected areas cannot manage the growing threats, particularly in the face of declining tourist revenue due to the COVID-19 pandemic (Wilkie et al., 2001; Waldron et al., 2013, 2020; Lindsey et al., 2020; Seidl et al., 2021). The global value of wildlife tourism, including the multiplier effect in 2019 was USD $346 billion and it generated 21.8 million jobs worldwide (Hockings et al., 2020).

The pandemic almost stopped this income stream in Africa. For example, a survey of African safari tour operators documented that 90% of them experienced declines in revenue of greater than 75% (Katongole, 2020). In Uganda, the pandemic resulted in a US $1.6 billion loss in tourist revenue, and the government anticipates a $5 billion loss through 2025 (Katongole, 2020). By comparison, Ugandan parks (Uganda Wildlife Authority) have an annual operating budget of US $14 million. Considering just hotel staff in Uganda, 8,636 people have been laid off. These workers' earnings total $ 29.3 million annually and represent the only income for many households (financial data from documents obtained by CAC from the Uganda Wildlife Authority and Ministry of Finance and are available upon request). However, tourism is expected to recover and funding the capacity associated with environmental tourism is a priority.

In Africa, there are 7,800 terrestrial protected areas that cover 5.3 million km^2 (UNEP-WCMC, 2019; Lindsey et al., 2020) that require financial support to cover administration, infrastructure acquisition and maintenance, ranger salaries, and outreach and community development activities. Funds typically come from government sources (including tourist revenue and contributions from international aid agencies), but non-government organizations (NGOs) also provide financial input. During the last two decades, international government aid agencies have invested ∼$150 million a year to protect biodiversity in Africa's parks and reserves. This amounts to spending $28.2/km^2 (Bare et al., 2015). It is difficult to obtain accurate information on NGO spending; however, in 2006, NGOs are reported to have spent $143 million on conservation projects in protected areas, amounting to $27.0/km^2 (Brockington and Scholfield, 2010). Brockington and Scholfield (2010) suggest that the shortfall between what African governments spend on protected areas and the actual needs is approximately $650 million a year (value averaged among years) or $122.6 more per km^2 than is available. Given the funding provided by aid agencies and NGOs, the shortfall is ∼$357 million a year. This does not consider that park services need to grow substantially to meet the challenges they will be facing in the coming decades. Nor does this include the costs incurred by local people associated with protected areas, such as the destruction of crops caused by the park's animals. However, this amount is less than 0.001% of the GDP of sub-Saharan African countries' (GDP values from WorldBank, 2021) and tiny compared to the 2020 military spending of the United States which was $714 billion (Office, 2020) (**Figure 2C**). While these estimates are crude, at face value, this shortfall is not a large sum; however, these countries have many competing demands. In general, after controlling for GDP, wealthier countries invest proportionately less in conservation than poorer countries (Seidl et al., 2021).

This raises an important ethical question; who should pay to protect Africa's biodiversity? In answering this question, it is important to consider the distribution of biodiversity and biomes that are critical to global climate change and health (**Figure 2D**). The forests of Africa are storehouses of carbon that slow climate change (Hubau et al., 2020), yet the countries that are custodians of Africa's rainforest have limited financial resources, are largely unable to conserve these forests in the face of urgently required economic development and unethical foreign investments that promote environmental degradation as a pathway to such development. Often calls to protect biodiversity come from wealthy nations with substantially higher living standards. Thus, it is clear that at least in the short-term it will be necessary for these wealthy nations to make up the funding shortfall needed to conserve Africa's protected areas. This is a realistic option, especially given the global costs of not protecting vital ecosystem services provided by these vital biomes and, relatively speaking, the wealthy nations have the finances to contribute. For example in 2015, the GDP of the United States alone was 14 times the GDP of the whole of sub-Saharan Africa (Seidl et al., 2021). New policy perspectives that consider the global consequences of not protecting biodiversity, and that transcend national interests and capacity are needed.

Research and education capacity

Surmounting Africa's environmental challenges will require significant improvements in education, research capacity, and the ability to implement research (Yusuf et al., 2009; Wickstead and Hickson, 2010; USAID, 2014). Investing in education to protect biodiversity requires an understanding of Africa's current environmental research capacity. Presently, research output from sub-Saharan Africa is less than 0.7% of the global total, despite having 12% of world's population (Lan et al., 2014; Makaya, 2017), and citations to sub-Saharan African articles comprise only 0.2% of global citations (Lan et al., 2014). Efforts to improve research capacity must come primarily from within Africa's higher education systems (Yusuf et al., 2009), with the assistance of the international scientific community (Confraria and Godinho, 2015; Atickem et al., 2019).

Recognizing that to advance economically, Africa's education capacity has to improve, national governments and international donors have encouraged a rapid expansion of higher education over the last 20 years (Benneh, 2002; Yusuf et al., 2009). As a result, between 2000 and 2013, enrollment in higher education increased from 6.1 to 12.2 million (UNESCO, 2018b), and the number of universities increased almost tenfold. However, capacity (i.e., teacher numbers and salaries, research funding) did not grow in step (Atickem et al., 2019). As a result, the quality of education and research capacity has suffered. This is illustrated by the fact that only seven universities in Africa (five in South Africa, one in Nigeria, and one in Uganda) appear in the top 500 universities in the *Times Higher Education*'s world rankings in 2021.

Despite Africa's recent economic growth, funding for tertiary education remains exceedingly low: sub-Saharan Africa invests only 0.4% of its GDP in research and development, compared with 2.4% in North America and Western Europe (UNESCO, 2018a). However, there are positive developments, such as Kenya and Ghana committing 2 and 1% of their GDP to research (Karikari and Amoateng, 2018). As enrollment in universities continues to grow unabated, the underfunded higher education system is being stretched to its breaking point (Yusuf et al., 2009). Poorly-paid faculty now teach more classes to greater numbers of students, leaving little time for research, and they often take on additional paid work to make ends meet (Arvanitis and Mouton, 2019; Atickem et al., 2019). To make matters worse, many of the professors in Africa have limited research training (Watkins and Ehst, 2008; Confraria and Godinho, 2015). In Ethiopia, for example, though graduate degree holders are on the rise, less than 20% of university instructors have advanced degrees (Reisberg and Rumbley, 2010). Nigeria is the largest economy in Sub-Saharan Africa, yet less than half of the more than 10,000 academic staff at public universities hold a PhD (Makaya, 2017). Even in South Africa, only 39% of academic staff have PhDs (Cloete et al., 2015; Atickem et al., 2019). The lack of PhD holders is partially because of poor working conditions at many universities in Africa (UNESCO, 2010). The monthly salary for a starting professor in Uganda is $2,300, in South Africa it is $2,176, in Nigeria it is $890, in Madagascar it is $531 and in Ethiopia it is only $365, whereas in Europe or the US it would be around $3,500–$8,000 (Mekonnen et al., 2021). An estimated 30,000 PhD holders of African descent are living and working outside their home countries; a number exceeding the total number of African-born scientists with PhDs working in Africa (Hassan, 2001).

There are signs research and education systems are improving in Africa. Between 2003 and 2012 research output in Sub-Saharan Africa more than doubled; its share of global research has increased from 0.44 to 0.72%, and its share of citations grew from an average of 0.12–0.20% (Lan et al., 2014). With respect to the conservation sector, Pototsky and Cresswell (2020) conducted a bibliometric analysis of journal papers published by authors of 41 sub-Saharan countries between 1987 and 2017. They found that while conservation research output increased over time, it was dominated by non-nationals and researchers from a few countries. In interpreting these findings it is worth considering that research output in conservation has generally increased, the number of authors on papers has increased, and nationals are increasingly included as coauthors, though at least in some cases this may be to satisfy the requirements of granting agencies and reviewers (Chapman et al., 2019).

A substantial share of sub-Saharan Africa's research efforts involves international collaboration. In fact, in 2012, 79, 70, and 45% of all research by southern Africa, East Africa, and West and Central Africa, involved international collaborations (Musiige and Maassen, 2015; Akuru, 2019). This high percentage partially reflects the low funding from African countries directed toward research and development. Together, countries in sub-Saharan Africa spent only $11.1 billion on research and development in 2013, which is 1.3% of global research spending and can be contrasted to the US at $398 billion, Germany at $85.7 billion, or Mexico with $7.2 billion (Arvanitis and Mouton, 2019). Much of the conservation-related research is done by researchers at universities, and international funding, while significant, is small and government funding can be insignificant. For example, between 2000 and 2012, Makerere University in Uganda received $15.2 million a year in research funding, and the government's contribution was only $1.2 million for research (0.82%: note they contributed salary funds, etc.) (Arvanitis and Mouton, 2019).

Unfortunately, lack of national funding leads to research often having little to do with the conservation priorities of African countries (Musiige and Maassen, 2015; Akuru, 2019), and research is often short-term (e.g., 3–5 years). International collaborators are often required by their home research culture and their funding support to advance theory that is not directly relevant to African conservation needs. If international researchers diverge too far from their funding criteria, their chances of securing funding to continue working in Africa declines, as do their chances of continuing their careers. The time has come for wealthier countries to openly fund collaborative international research that benefits less wealthy countries.

Ways forward

Africa is home to remarkable biodiversity that is under threat, and without intervention, these threats will increase substantially in the coming decades. We consider four key questions that may help guide African conservation.

The cost to protect Africa's biodiversity

Given Africa's current modest capacity to address its biodiversity crisis, additional funding is required. McCarthy et al. (2012) estimated it would cost US$76 billion annually to conserve the global terrestrial species. Lindsey et al. (2018) estimated an additional $US 0.9–2.1 billion annually to protect Africa's protected areas containing lions. Bernstein et al. (2022) derived estimates of the operating costs of parks and estimated it would cost $US 10.2 billion annually to protect Africa's biodiversity in 1812 national parks that cover 3.1 million km^2. While these are sizeable estimates, the world's GDP is $US 88,000 billion, Africa's GDP is $US 2,600 billion, Jeff Bezos's net worth is $US 178 billion, and the cost of emerging zoonoses

caused by people encroaching on biodiversity is US$520 billion a year (Bernstein et al., 2022). Estimates of the cost of conserving Africa's biodiversity do not include the costs of improving associated institutions and infrastructure, such as the education system.

International donors, particularly the World Bank, could engage more with managing Africa's biodiversity by building schemes to offset national debt against progress in managing in-country biodiversity priorities, i.e., instead of paying back loans, the money is directed to managing biodiversity. Priorities and strategies need to be set by a unified conservation group formed from within sub-Saharan African countries that integrates input across regional and local scales and includes the participation of multiple stakeholders. To help ensure success, debt should only be offset against demonstrable progress and outcomes, which will take time to measure. We would be amiss if we did not add a cautionary remark that throwing money at a problem without properly assessing what is truly needed and building the capacity to accept the funding will do little to rectify the biodiversity crisis (Sheil, 2001; Sheil et al., 2017; Sarkar et al., 2021).

The will to act

Inevitably, conservation of Africa's biodiversity requires societal support. Our collective experience is that many people, be they city dwellers or members of local communities living next to protected areas, have a sympathetic attitude to conservation. Wainger et al. (2018) demonstrated that when people around the world were asked to commit money, respond to tweets, or express opinions in a survey, respondents revealed a willingness to protect and restore natural resources, regardless of their use of those resources. This willingness was not influenced by race, ethnicity, income, geographic location, age, or gender.

This sympathy for conservation can be nurtured. Education programs that emphasize the importance of natural areas (e.g., ecosystem services) and the wonders of the plants and animals they support, can go a long way in building support. Such programs should be in the local language, be accessible, consider gender roles, and should target people living near protected areas and those in urban centers as all these people vote and influence politicians. The development of this sympathetic attitude to nature can lead to self-policing that prevents excessive exploitation of resources within protected areas (Rustagi et al., 2010; Sheil et al., 2017). Furthermore, involving people in the management of their own resources is simply the ethically appropriate thing to do. The needed sympathy for conservation can be encouraged by highlighting and empowering local successes as the foundation of broader coalitions and collaborative arrangements (i.e., one community can encourage the next to adopt successful strategies).

Is conservation through development the way?

A sympathetic attitude to nature can be encouraged by providing benefits that are clearly associated with a conservation effort or area (Kirumira et al., 2019). The integration of conservation and development has frequently been advocated as an effective tool to protect biodiversity in an ethically appropriate fashion (Western and Pearl, 1989; Robinson, 1993, 2011; Hulme and Murphree, 2001). The approach emerged from the 1982 World Parks Congress in Bali, where the consensus was that "protected areas in developing countries will survive only insofar as they address human concerns" (Western and Pearl, 1989, p. 134), and it has been a widely supported conservation strategy since the report by the World Commission on Environment and Development in 1987 (the Brundtland Commission; Brundtland, 1987). Despite strong support, starting 40 years ago and still being encouraged by the Millenium Sustainability Goals (Corvalan et al., 2005), its value for protecting biodiversity is unclear, and a universal approach to combining biodiversity conservation and development has yet to be presented to policymakers.

Ecotourism and revenue sharing projects are typical examples of these approaches. Unfortunately, in many areas of Africa where human density is high, very profitable ecotourism ventures provide little to no benefit to most people near the protected areas, as there are too many people to share limited revenues. For example, before the COVID-19 pandemic, Ugandan gorilla ecotourism resulted in the local community receiving ∼$400,000 annually from park revenue sharing and tourism revenue. However, this amount was shared among approximately 160 people/km^2 living around Bwindi Impenetrable National Park (321 km^2) (Sandbrook and Adams, 2012), making the individual benefit negligible. Whether, this small amount of money can create a favorable perception of conservation among the local communities is doubtful (Karanth et al., 2012).

Another way to provide tangible benefits to people is by forming a union between the provision of health care and conservation. Extreme poverty and biodiversity hotspots are often geographically coincident (L'Roe and Naughton-Treves, 2017). Primary health care and family planning can be delivered to many people at low cost, and where these services are seen to be a direct outcome of the presence and management of protected areas, this improves park-people relations (Kirumira et al., 2019). Given the need to be prepared for future pandemics, "conservation clinics" may be a useful strategy to explore, but the value of this approach has not been fully examined.

Empirical evidence that such community projects are effective is scarce, so it is difficult to evaluate the success of integrated conservation and development projects or to distill strategies that are most likely to yield positive outcomes

(Hackel, 1999; Berkes, 2004; Eklund et al., 2016; Cetas and Yasué, 2017). A comparison of protected areas in Uganda using community-based conservation with those that did not, detected no difference in threat reduction (Mugisha and Jacobson, 2004). Similarly, the establishment of a research field station, which increased community engagement in conservation activities, established and supported schools, and provided health services/benefits to people living next to a park through a static and mobile clinic, led to more positive perceptions of the park and better park-people relations, but did not correlate with a decrease in illegal activities (Chapman et al., 2015; Sarkar et al., 2016, 2019a,b; Kirumira et al., 2019). A review of financial incentives to reduce illegal hunting, which included cases in Nepal, Kenya, Namibia, Mexico, and Sweden, concluded that the benefits provided were usually outweighed by the losses incurred by local residents, and rarely reduced illegal hunting (Dickman et al., 2011).

To more fully understand the value of integrated conservation and development projects, three important questions need to be addressed: What would biodiversity loss been if the benefit program had not been instigated? Pressures to extract resources no doubt increased over the duration of the benefit sharing project, so did the project prevent an increase rate of resource extraction? Was the investment and monitoring of the project of sufficient duration? If the benefit sharing involved education or changing attitudes of young people, then the results will take decades to accurately evaluate. If the goal of the project was to increase the population size of endangered species, it might require decades of monitoring. Were the correct indicators of protection evaluated? Often researchers present evidence to support the claim that such community projects are effective by quantifying variables such as park encroachment and poaching. However, such variables may not be the largest threat to biodiversity. Tourism, for example, may not significantly benefit local residents if the population density outside of the park is very high, but it may influence politicians to support conservation activities that raise the country's GDP and international profile.

Conservation through development is just one approach; however, the fact that the academic community cannot provide managers with more effective guidelines after 40 years suggests new approaches are needed. A redoubling of effort to understand what enhances effective conservation while addressing the wellbeing of local communities is needed.

Education and capacity building

To conserve biodiversity effectively, we must use the best available information, apply the most appropriate tools, be adaptive to changing ecological, social, political, and economic situations, and make decisions when knowledge is incomplete (Robinson, 2006). This requires knowledgeable, well-trained practitioners. We agree with the philosophy that ownership of conservation must rest with the people who ultimately bear the costs and/or reap their benefits. However, this calls for substantial improvements to the training of African researchers and practitioners. Furthermore, significant investment must be placed in building the conservation education, research, and management capacity of the 46 countries in sub-Saharan Africa. Various mechanisms are available (e.g., funding research chairs at African Universities, creating centers of excellence and training hubs based at universities and within national parks, adequately funding African scholars to slow the brain drain), and these should be implemented quickly as it will take considerable time to see gains from training and capacity building.

Ultimately, the academic community must produce science that will effectively inform policy decisions and motivate action. This requires that research outputs be salient (relevant and timely), credible (authoritative, believable, and trusted), and legitimate (developed via a process that considers the values and perspectives of all actors) in the eyes of researchers, local communities, policymakers, and agents that create action (Cook et al., 2013). The growing demand for better synergy between science and policy and their meaningful implementation has led to new environmental frameworks for both research and society (Völker et al., 2019; Watson et al., 2020). In particular, there is a move away from focusing on the gap between research findings and their implementation, toward more attention on properly contextualizing the lessons from successes, as well as challenges (Toomey et al., 2017; Cvitanovic and Hobday, 2018). Within the science-to-action context, "communication strategies" are explicitly a part of a "political strategy." All too often conservation is poorly presented to society so that it appears to be a costly trade-off where social and economic opportunity is partly forfeited to achieve conservation goals. Therefore, it is hardly surprising that biodiversity conservation is sometimes seen to be placed above society's welfare and aspirations. Ultimately, new and better ways of communicating with and educating the public and policymakers are needed—a tool kit that converts conservation actions into legally binding policy is needed. Facilitating proper communication depends on a deep understanding of local perspectives, thus facilitating relevant training and integrating local knowledge and perspectives within Africa.

The spatial and temporal scales at which conservation is needed are larger and longer than the sphere of influence and the working lifetime of the people who have sufficient motivation and authority to initiate conservation efforts. Thus, a multi-generational approach is needed. Also, conservation efforts need to involve more disciplines, approaches, and tactics than are typically brought to bear on a single conservation effort. For example, it is clear that new technologies, such as renewable energy technologies (solar, wind, and geothermal), better water management, agricultural intensification (more food from a smaller footprint), marketing of local

products, better or more accessible healthcare and family-planning, and improved education could improve the success of conservation programs.

The conservation of Africa's biodiversity must come from within Africa. Ownership of conservation must rest with the people who ultimately bear the costs and reap the benefits of conservation—stakeholders first and foremost include communities, national governments, and others who hold rights over the natural resource base (AWF, 2020a). While the benefits will be realized globally, these are the institutions, groups, and people who must make the long-term investment, without which significant, long-term protection of Africa's biodiversity is not possible. Africa has been strongly influenced by its colonial past, which have now largely been replaced by neo-colonial and market driven approaches (Domínguez and Luoma, 2020). The "fortress" style conservation that arose during the colonial period inflicts real harm on local communities and now is a time to explore sustainable solutions. Africa is a rich and diverse continent, and it has the opportunity to define innovative conservation in the twenty-first century. Many of the answers to the question of how to conserve Africa's biodiversity are already known, so now is the time for bold action.

Author contributions

CC and PO conceptualized the scope and approach of this project. DSh, DSa, MG, KA, and CC developed the conceptual framework. DSa and UK produced the figures. CC drafted the manuscript. All authors wrote sections and provided economic evaluations, and made significant contributions to the ideas and content.

Funding

We would like to thank the funding that helped us develop some of these ideas, the IDRC grant "Climate change and increasing human-wildlife conflict." CD thanks the National Research Foundation (ZA, Grant 98404). CC was supported by the Wilson Center while writing this manuscript.

Acknowledgments

We thank Claire Hemingway and John Robinson for helpful ideas and comments on this project.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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