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*Editors-in-Chief*

Jean-Jacques Braun · Raphaël M. Tshimanga · Katharine Abernethy · Suspense Averti Ifo · Denis Jean Sonwa
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# Resilience and Sustainability in the Congo Basin

## Retracing the Past, Looking to the Future

Science Panel for the Congo Basin

Panel Scientifique pour le Bassin du Congo

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SUSTAINABLE DEVELOPMENT SOLUTIONS NETWORK
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# Resilience and Sustainability in the Congo Basin

Bila-Isia Inogwabini • Bonaventure Sonké •
Lydie-Stella Koutika • Lee J. T. White
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## Retracing the Past, Looking to the Future

With 150 Figures and 42 Tables















*Editors-in-Chief*
Bila-Isia Inogwabini
Swedish University of Agricultural Sciences, Uppsala (Sweden) and School of Management, Catholic University of Congo
Kinshasa, Democratic Republic of Congo

Bonaventure Sonké
Laboratory of Plant Systematics and Ecology (LaBosystE), Higher Teachers' Training College
University of Yaoundé I
Yaounde, Cameroon

Lydie-Stella Koutika
Soil Care and Environmental Studies
Pointe-Noire, Republic of Congo

Lee J. T. White
University of Stirling, School of Natural Sciences
Stirling, UK

Institut de Récherche en Ecologie Tropicale
Libreville, Gabon



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# Preface

I am honored and profoundly moved to write the foreword to this historic report of the Science Panel for the Congo Basin. The Congo Basin deserves every superlative that we can muster, and the Science Panel has done justice to this remarkable part of humanity's biological heritage. As this report makes profoundly clear, the roughly 3.56 million $km^2$ of the Congo Basin is home for 130 million people in Central Africa, the habitat for tens of thousands of species, and a vital regulator of the Earth's climate and biophysical systems at continental and planetary scale.

The Science Panel for the Congo Basin is itself a remarkable creation, following in the path of the Science Panel for the Amazon. Both Science Panels and their third companion, the Science Panel for Borneo, are built on one main idea. The vital expertise regarding the history, management, and sustainable future of the great rainforest biomes lies with the scientists of each region, of course, in partnership with the global scientific community. The Science Panels seek to empower each region's scientists to take the lead in proposing science-based solutions for the sustainable management of the respective biomes. While outside experts play a highly constructive role, it is the scientists of each region who must be the guides and stewards of the rainforests. As such, the Science Panels serve directly the people and governments of the region, as well as the whole human community.

Moreover, the term "serve" is also on point, since the scientists are generously donating significant amounts of time as well as their unique expertise to this effort. A remarkable volume of work has been mobilized through the spirit of public service of the scientists involved. The Science Panel for the Congo has thereby gone a vast distance in producing the most comprehensive and up-to-date scientific study of the Congo Basin of recent years, and probably ever.

One hundred Eighty scientists have contributed to this report, enabling its comprehensive and panoramic perspective. This report discusses the geological history of the Congo Basin, and every aspect of the science of this wondrous ecosystem: geology, geodynamics, hydrology, climate, soils, biodiversity and its evolution, ecology, cultural diversity, land-use systems in agriculture, pastoralism, forestry, hunting, fishing, mining, and other activities, drivers of deforestation, protected areas, urbanization, and much more.

The aim of the Science Panels, of course, is not only to produce excellent science but also excellent public policy. This report fulfills that aim. After a remarkably deep,

holistic, and up-to-date scientific report on the state of the Congo Basin and the main drivers of human-induced change, this volume proceeds to holistic solutions. Our aim is not merely sustainability (in the environmental sense) but sustainable development, meaning the combination of environmental sustainability with economic well-being and social justice in the region. Farming, forestry, fisheries, mining, and other activities must continue to contribute to livelihoods and economic opportunity, but in a manner that is compatible with the environment, not contrary to it. With millions of degraded hectares of forest land, for example, the Congo Basin can be an enormous sink for carbon through regeneration of the forests. With the right incentives, through carbon markets and other mechanisms, the Congo Basin should receive tens of billions of dollars for carbon storage that recovers degraded lands, builds new livelihoods and strengthens biodiversity. The wisdom of the Science Panel is to propose win-win-win solutions, whereby local communities, biodiversity, and global humanity are all beneficiaries of the ethical, science-based, and forward-looking stewardship of the Congo Basin. The Science Panel for the Congo Basin will be a key leader in that grand initiative, supported by the wisdom in this volume.

University Professor, Columbia University Jeffrey D. Sachs
President, Sustainable Development Solutions Network

# Acknowledgments

Convener: Jeffrey Sachs

Strategic Coordinator: Emma Torres

Co-Chairs: Bonaventure Sonké, Lydie-Stella Koutika, Corneille Ewango Special Envoy: Lee J. T. White

Scientific Steering Committee: Katharine Abernethy, Suspense Averti Ifo, Jean-Jacques Braun Corneille Ewango, Maximiliano Fero, Bila-Isia Inogwabini, Lydie-Stella Koutika, Judicaël Lebamba, Simon Lewis, Georges-Noel Tiersmondo Longandjo, Danae Maniatis, Yadvinder Malhi, Alfred Ngomanda, Jean Semeki Ngabinzeke, Guy Moukandi, Florence Palla, Wilfried Pokam, Marie Sigaud, Denis Jean Sonwa, Bonaventure Sonké, Lucie Temgoua, Raphaël M. Tshimanga, Nathalie van Vliet.

Editors-in-Chief: Bila-Isia Inogwabini, Bonaventure Sonké, Lydie-Stella Koutika and Lee J. T. White.

Section Editors: Section I: Jean-Jacques Braun and Raphaël M. Tshimanga; Section II: Bonaventure Sonké and Bila-Isia Inogwabini; Section III: Katharine Abernethy and Suspense Averti Ifo; Section IV: Lydie-Stella Koutika and Denis Jean Sonwa.

Lead Authors: Katharine Abernethy, Nicola Anthony, Bakari Amuri, Marijn Bauters, Roger-Louis-Paul Kabelong Banoho, Sakaros Bogning, Jean-Jacques Braun, Aida Cuni-Sanchez, Richard Eba'a Atyi, Sarah C Hill, Bila-Isia Inogwabini, Etienne Kadima Kabongo, Richard Sufo Kankeu, Lydie-Stella Koutika, Eeva Kuisma, Moses Libalah, Georges-Noel Tiersmondo Longandjo, Danae Maniatis, Salomon Mampeta Wabasa, Ernest Molua, Richard Oslisly, Elsa Ordway, Charles Perrings, Wilfried Pokam, Birgit Ricquier, Denis Jean Sonwa, Venkataramana Sridhar, Lucie Temgoua, Delphine Takem, Hermann Taedoumg, Raphaël M. Tshimanga, Nathalie van Vliet, Lee J. T. White.

Contributing Authors: Emmanuel Abwe, Bhely Angoboy, Claudine Augée Angoué, Nicola Anthony, Sebastian Apers, Vondou Derbetini Appolinaire, Stéphane Audry, Nyong Princely Awazi, Roger-Louis-Paul Kabelong Banoho, Matti Barthel, Paul Bates, Michel Bechtold, Milena M. Beekman, Stoffenne Binsangou, Pascal Boeckx, Gode Bola, Hubert Boulet, Clay Archange Boupoya, Jean-Jacques Braun, François Bretagnolle, Carolyn H. Peach Brown, Louis Champion, Zacharie Kusamba Chifundera, Valentin Bashige Chiribagula, Daniel Cornelis, Sly

Wongchuig Correa, Aida Cuni-Sanchez, Franck Delpomdor, Damien Delvaux, Emily Denstedt, Kechnit Djamel, Donald Djossi, Atanas Dommo, Jean-Louis Doucet, Romain Duda, Jean Marcel Abate Essi, Corneille Ewango, Julia E. Fa, Adeline Fayolle, Roger Fotso, Thierry C. Fotso-Nguemo, Adam Freedman, Nicole Gottdenker, Giresse Kuete Gouanjo, Guy Merlin Guenang, Oliver Hardy, Benoit Henriet, Simon Hoyte, Wannes Hubau, Olivier Hymas, Verina Jane Ingram, Bila-Isia Inogwabini, Donald Midoko Iponga, Kathryn Jeffery, Kahumba Byanga Joh, Etienne Kadima Kabongo, Etienne Yusufu Kachaka, Hyunwoo Kang, Victor Aimé Kemeuze, Thierry Loïc Kenmou, Hyunglok Kim, Benjamin M. Kitambo, Justin Kyale Koy, Venkataraman Lakshmi, Simon L. Lewis, Anne-Marie Lezine, Simon Lhoest, Moses Libalah, Tobit Liyandja, Georges-Noel Tiersmondo Longandjo, Jacob Heen Lowenstein, Hines Mabika, Sybryn Maes, Patrick Mafwila, Fiona Maisels, Loïc Makaga, Jean-Remy Makana, Isaac Makelele, Pascal Mambwe, Danae Maniatis, Francis Manfoumbi, Emmanuela Mbangale, Billy Kakelengwa Mbilizi, Duclaire Mbouna, Vincent Medjibe, Brusil Miranda Metou, Maximiliano Fero Meñe, Caroline Michellier, Charles Mpoyi Mpoyi, Kumar Mohan, Stéphane Momo, J. M. Mondo, Wilfran Moufouma-Okia, Léa-Larissa Moukagni, Guy Moukandi, Ghislain Moussavou, Robert Moïse, Gérard Imani Mugisho, Jonas Muhindo, Danny Mukubi, Jonathan Muledi, Niel Yohan Musadji, Catherine Awidi Mushi, Minette Nago, Robert Nasi, Jean-Pierre Messina Ndomo, Jean Semeki Ngabinzeke, Patience Ngelinkoto, Frankline Nghobuoche, Alphonse Maindo Monga Ngonga, Cyriaque-Rufin Nguimalet, Sharon Nicholson, Lola Nihotte, Pascal Roger Nlend Nlend, Lotanna Micah Nneji, Mathieu Momo Nouazi, Anatole Ntelo, Emmanuel Nuesiri, Arnold Bitja Nyom, Jonas Nyumu, Philippe Négrel, Rolf Gael Mabicka Obame, Takanori Oishi, Joseph Okello, Etienne Akomo Okoue, Patrick Olomo, Sarah Olson, Fidèle Evouna Ondo, Florence Palla, Fabrice Papa, Adrien Paris, Kialo Paulin, Ghislain Noé Kougoum Piebeng, Sandra Ratiarison, Pierre Regnier, Stephanie Rupp, Sassan Saatchi, Le Bienfaiteur Sagang, François Sandrin, Ayan Santos Fleischmann, Eugenio Sartoretto, Geoffroy de Saulieu, Tracie Seimon, Cedrick Mutombo Shakalenga, Marie Sigaud, Alexandre Livingstone Smith, Thomas B. Smith, Stella Tikeng Songwe, Bonaventure Sonké, Denis Jean Sonwa, Venkataramana Sridhar, Hermann Taedoumg, Claude Tagne, Romeo Tanessong, Mahesh R. Tapas, Sagesse Nziavake Tayari, Alain Tamoffo Tchio, Nicolas Texier, Denis Thieblemont, Serge Zébazé Togouet, Thanh Nhan Duc Tran, Mark Trigg, Raphaël M. Tshimanga, Kalenga Tsingomba Urcel, Hans Verbeeck, Marie Claire Veranso-Libalah, Alice Vittoria, Nathalie van Vliet, Salomon Mampeta Wabasa, Gretchen Walters, Richard Washington, Boris Dinictri Soh Wenda, Lee J. T. White, Catherina Wilson, Christian Mikolo Yobo, Louis Zapfack, Virginia Zaunbrecher.

Peer Reviewers*: Mattia Bessone, Réné Beyers, Allard Blom, Jean-Louis Doucet, Mitsuo Ichikawa, Suspense Averti Ifo, Daniel Ingram, Kathryn Jeffery, David Lehmann, Kumar Mohan, Héritier Khoji Muteya, Willy Loyombo, Donald Midoko Iponga, Eric Nana, Aurelie Shapiro, Peter D Walsh, Jaap van der Waarde, David Watts, Robin Whytock, Sarah R Worden, David Wilkie.

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# Congo Basin Resilience and Sustainability: From the Past to the Future

## Summary for Decision-Makers

*Congo Basin Resilience and Sustainability: From the Past to the Future*, the 2025 Congo Basin Assessment Report, is the first ever, collective, and multidisciplinary work by 192 scientists active in the region. It was brought together by the Science Panel for the Congo Basin (SPCB), convened by the United Nations Sustainable Development Solutions Network (UNSDSN), and was inspired by the Science Panel for the Amazon. It features 40 chapters, which are organized into four sections dedicated to the region's geological history, the emergence of humans and their impact on the Congo Basin's ecosystems, the emergence of sustainable development models post-Rio, and a vision for the future.

The Congo Basin, as defined in the report, covers an area of 3,462,806 $km^2$, representing the world's second largest tropical rainforest ecosystem, composed principally of the lowland wet and dry "Guineo-Congolian" rainforests, along with extensive swamp, mangrove, and Afromontane forests, bordered to the north and south by a mosaic of transitional rainforests and secondary grasslands.

The Congo Basin encompasses extensive areas in six nations: Cameroon, Central African Republic, Democratic Republic of Congo (DRC), Equatorial Guinea, Gabonese Republic and Republic of Congo (RoC), and smaller areas in a further six: Angola, Burundi, Nigeria, Rwanda, South Sudan, and Uganda.

It includes 73% of the Congo River Basin, which extends into areas of wooded savanna in Tanzania, Zambia, and Angola, as well as the entire catchments of the Ogooué, Sanaga, and numerous smaller rivers. The outer limits of the biome today are somewhat subjective because they represent a transition from wetter to drier forests, which is continually changing as a function of climate variability and human activities. The eastern limit is the eastern edge of the Afromontane forests of the African Rift Valley, while the western limit is the Cross River in Nigeria.

The Congo Basin plays an important role as a regional entity in the Earth system, the African continent's "green heart," a critical natural life support system, driving atmospheric moisture recycling, which generates 60–70% of the rainfall in the region and sends moisture to the Sahel, the Angolan Highlands and Ethiopia.

The Congo Basin is the largest tropical carbon sink on Earth and is proving more resilient to climate change than the Amazon. It includes the Cuvette Centrale

peatlands, the largest tropical peatland complex covering about 145,500 $km^2$, which store around 30 billion tons of carbon (110 billion tons of $CO_2$).

It is one of the most biodiverse ecosystems on Earth, with over 10,000 species of vascular plant, 400 mammal, 1000 bird, and 700 fish species and includes the entire range of the bonobo and the two species of gorillas, and is home to three of the four subspecies of chimpanzee. Among these species, some are endemic to the Congo Basin and have very limited ranges, making them critically important for conservation. It is the only region where an intact megafauna survives, perhaps because of the long history of humans living in the forests, estimated to be at least 650,000 years.

The Congo Basin is a rich socio-ecological system where more than 600 languages are spoken. The languages encode complex taxonomies for plants, animals, and landscapes reflecting a deep place-based understanding of the environment. Traditional ecological knowledge extends beyond mere identification of species to include an understanding of ecological relationships, such as the seasonal movements of animals, the medicinal properties of plants, and the spiritual significance of certain forest locations, such as sacred forests, which are widely prevalent throughout the basin. This oral transmission of knowledge ensures that ecological literacy is embedded within cultural practices, with stories and rituals functioning as living manuals of forest stewardship, crucial for maintaining sustainable use of natural resources.

The shift from exclusively hunter-gatherer to early agricultural societies began about 4000 years ago. Human impacts on the forests increased markedly with the arrival of iron smelting and Bantu-speaking communities from the north, and the development of slash and burn agriculture from 2500 years ago. Between 2000 and 1000 years before present, there was a period of rapid human population growth, forest fragmentation, and widespread development of secondary vegetation across the Congo Basin, as human societies became ecological engineers, creating "cultural forests" shaped by their selective management of useful species, such as the native oil palm. There was a marked decline in human population between 1400 and 1200 BP, which lasted to about 800 BP, when populations recovered and expanded again.

European explorers and traders arrived from the fifteenth century onward resulting in increased trade. The Atlantic commerce in ivory, ebony, pepper, rubber precursors, and enslaved persons intensified the exploitation of natural resources. The introduction of firearms altered hunting efficiency, exacerbating pressures, particularly on elephants and other megafauna.

The arrival of European traders and the gradual penetration of trade routes and infrastructure into the Congo Basin resulted in epidemics of diseases to which people had not previously been exposed. Millions perished from diseases such as bubonic plague, smallpox, syphilis, cholera, measles, and chickenpox, compounding the social impacts of the slave trade.

The late nineteenth-century "Scramble for Africa" radically reshaped the Congo Basin. Colonial administrations, especially in the Belgian Congo and French Equatorial Africa, imposed concessionary systems that turned vast tracts of forest into rubber, timber, and mining concessions. Villages were forcibly relocated to serve as

forced labor for extraction sites, transport corridors, and plantations. Country borders were decided arbitrarily without taking sociological realities into account. In some cases, these borders separated populations belonging to the same tribe into different countries (e.g., Cameroon, Gabon, Equatorial Guinea). Forced labor was used to exploit mineral and timber resources, which were shipped to Europe for processing.

The colonial economic model was to extract natural resources which were exported to Europe, where they fed the industrial revolution and the growth of wealth, a model that continues to this day. As African development came to be seen as a threat to species and ecosystems, the colonial authorities imposed a model of "fortress" conservation, creating protected areas by banishing human populations by force.

The period between 1960 and 1992 saw the progressive independence of the Congo Basin nations and rapid urbanization. Logging and mining remained the principal economic activities but were largely replaced in the Western Congo Basin countries by oil.

The early 1990s saw significant social-ecological transformations, including the beginning of the political transition to multi-party democracy. A political vision championing the principles of sustainable development gradually emerged on the road to the Rio Earth Summit in 1992, where leaders from Congo Basin states played a key role in shaping global commitments to sustainable development, bringing both the legacy of colonial and post-colonial extraction and the enduring traditions of stewardship and ecological knowledge that had characterized the region for millennia to the table.

Forestry, historically one of the region's most destructive extractive industries, underwent significant transformations. In the 1990s and early 2000s, governments began to introduce forestry laws that required companies to operate under long-term sustainable management plans. Environmental and Social Impact Assessments (ESIAs) were gradually institutionalized, embedding safeguards into planning processes. Voluntary forestry and timber certification schemes emerged as tools for both governance and market access. The Forest Stewardship Council (FSC) became the gold standard, and countries such as Cameroon, Congo, and Gabon emerged as leaders in Africa in certifying concessions under FSC standards.

While challenges remain in ensuring compliance and addressing illegal logging, these initiatives place Central Africa at the forefront of tropical forest management and certification worldwide. More recently, there has been a move to increase local transformation and even to ban the export of unprocessed timber from the region, to maximize local economic growth and job creation. These reforms mark a profound shift from the colonial-era extract-and-export model toward one that aspires to reconcile economic use with ecological sustainability, while maximizing local economic returns and job creation.

Even as forestry has moved toward sustainability, other resource sectors have remained firmly extractive. Mining remains a significant contributor to deforestation, pollution, biodiversity loss, and social disruption. While environmental regulations and Environmental and Social Impact Assessments are now formally required, enforcement is uneven, and artisanal mining continues to devastate river systems

and forests. Industrial agriculture—particularly oil palm and rubber—has also expanded since the 1990s, often encroaching on forest frontiers and undermining biodiversity commitments. Smallholder agriculture is technologically unsupported by states, allowing widespread landscape degradation through outdated slash and burn practices to continue and intensify.

Overall, these trends illustrate the contradictions of post-Rio development: formal sustainability frameworks exist and perform well when used, but business-as-usual extractive logics also endure. Sustainable land-use planning tools are in place on paper, but weak governance, overlapping land rights, poor agricultural practices, and international demand for minerals and commodities perpetuate ecological degradation. Strengthening governance and cross-sectoral institutions is vital for ensuring resource security and aligning extractive sectors with sustainable development pathways.

Hunting and fishing remain vital for livelihoods and nutrition, but the scale and intensity of exploitation have grown since the 1990s. The wild meat trade now supplies both urban and rural markets, with an estimated 1.6–11.8 million tons consumed annually. Inland fisheries continue to provide a crucial source of protein, particularly in the DRC, but overfishing and habitat degradation have reduced catches. Customary management systems such as taboos and seasonal bans, once widespread, have eroded under the pressures of market demand and weak governance. The "empty forest syndrome," where forests remain structurally intact but devoid of large fauna, has become emblematic of these pressures, although protected areas often still preserve viable populations, preventing extinction and species becoming lost to nations forever.

Community-based management is emerging as a modern African conservation model, but success is uneven, often due to the level of degradation of wildlife communities, and to the inadequacy of alternative rural food systems. There is a growing evidence base for community management models that do deliver sustainable harvest and these could be scaled up across rural areas, but if underlying food systems are not improved, stemming biodiversity loss will remain challenging.

The key to peace and security, sustainable development and prosperity in the region are strengthened democracies, improved governance, including governance of natural resources, elimination of illegal exploitation of natural resources and better rule of law, as well as an efficient, objective, independent justice system able to fight corruption. These vital foundations for society are crucial to tackle challenges to attract the long-term investment needed to implement local processing of natural resources and to attract finance to invest in logistical infrastructure needed to optimize supply chains and ensure profitability in the private sector.

To attract the responsible investors and affordable finance needed to drive sustained economic growth, continued and accelerated improvements in democratic process, governance, rule of law, justice, and equity are needed in the Congo Basin nations. Political stability and elimination of illegality in the natural resource extraction industries are crucial to encourage international confidence and investment. Furthermore, integration and strengthening of local community involvement and rights in integrated spatial plans are also needed. International agreements such as

the African Union's Agenda 2063 and the UN Sustainable Development Goals (SDGs) can help to chart a path but need to be adapted to local circumstances through regional leadership.

There is a need to foster affordable, dependable finance and equitable investment in sustainable development for the Congo Basin nations, to provide dignified, sustainable livelihoods for their people, while continuing to supply the global ecological services that benefit all of humanity.

Preservation and enhancement of nature-based solutions provides a critical foundation to boost sustainable development and climate resilience of nations and economies. The Congo Basin countries are leading the world through the development of economies that depend on sustaining ecosystem services, banishing the model of using Africa simply as a source of cheap raw materials that provision nations far from the continent, as was the case during colonial rule.

Africa is the continent that is most susceptible to climate change because of the vulnerability of its more arid ecosystems and lack of technological and financial capacity to adapt. The ecological stewardship and environmental resilience of the Congo Basin is critical for the region and for many other parts of Africa, whose weather patterns are impacted by moisture from the "heart and lungs of the continent," the Congo Basin rainforests. Nature preservation and nature-based solutions need to be integrated into ecosystem management, urban environments, and national planning, to ensure maximal climatic resilience for ecosystems, agriculture, and people in the coming century. This is by far the most efficient and effective way of reducing the costs of adaptation, while contributing to global climate change mitigation.

Looking to the future, harnessing all possible technological advances to optimize the preservation, management of natural resources, and monitoring of local and regional changes is critical for the future of the Congo Basin. It is hard to manage something that is not well understood, and many knowledge gaps remain. There is a need to promote the formal training and capacity building for scientists, sociologists, and natural resource managers to establish effective management systems that maximize ecological resilience and benefits for the region's economies and people and to promote interdisciplinary collaboration. The Science Panel for the Amazon and its precursor, the Large-Scale Biosphere-Atmosphere Experiment Programme, provide powerful models that can be adapted to the Congo Basin.

**The Congo Basin stands at a decisive crossroads**. It is the world's second-largest tropical forest system, a vast carbon sink, and home to unparalleled biodiversity, but it is also a region of rapid population growth, particularly in Cameroon and DRC, persistent poverty, weak governance, and competing demands for development. Strengthened governance, equity, and justice; reliable finance and sustainable economies; technology and capacity; and ecological stewardship and stability are the four key foundations for the future emergence of the region. They will decide if the region's young population could become a competitive advantage.

In conclusion, the Congo Basin is a critical component of our planetary biosphere: a treasure house of biological and cultural diversity that provides key environmental services at local, regional, and global scales. After centuries of

extraction and degradation, there is real potential for a different future: one of genuine sustainable, locally led development for the welfare and benefit of its peoples and communities, where resources are sustainably managed and preserved and contribute to both African and planetary resilience in the face of inevitable impacts of climate change. Many challenges remain, including both needs and opportunities to reinforce good governance, strong institutions, and political accountability. Science, scientific institutions, and scientists themselves have important roles to play to monitor, generate evidence, and inform decision-making by those responsible for solving of collective problems and development of transformative solutions. Africa is facing a unique set of circumstances and opportunities to ensure a vibrant future. Many of these depend on the resilience of the Congo Basin's ecosystems.

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# About the Editors-in-Chief



**Bila-Isia Inogwabini** is a National Geographic and UNESCO Award-Winning Biodiversity Scholar affiliated with the Department of Aquatic Sciences and Assessment, Swedish University of Agricultural Sciences, Uppsala (External Resource), and the School of Management, Catholic University of Congo (Kinshasa). With a 30-year-long experience in Biodiversity Conservation Research, Humanitarian and Sustainable Development Programs, he published multiple dozens of peer-reviewed articles and books. He is currently Science Officer for the Science Panel for the Congo Basin.



**Bonaventure Sonké** is Professor of biodiversity of African rainforests and a plant taxonomist based at the University of Yaoundé I, Cameroon. He has been working on the dynamics of forest in Central Africa for more than 35 years during which he described more than 70 new species to science; he co-authored over 180 publications in international peer-reviewed journals and has written 2 books. He is also one of the three Co-Chairs for the Science Panel for the Congo Basin and one of the editors-in-chief of this report.



**Lydie-Stella Koutika** is a soil scientist with over 30 years of experience in applied research on agroecosystems in South America, Europe, and Africa. She has authored numerous papers on soil management and carbon and nitrogen dynamics. Over the past decade, her work has focused on improving and expanding soil knowledge in Central Africa to address climate change, land degradation, food insecurity, and biodiversity loss—contributing significantly to the scientific community and the livelihoods of local farmers.



**Lee J. T. White,** CBE, is affiliated with University of Stirling (UK). He has over 40 years of experience in the tropical rain forests of Africa; he was director of Gabon's National Parks Agency and Gabon's Minister of Water, Forests, Sea and Environment. He publishes widely on the natural history and ecology of the African rain forests and has 125 publications. He is the Special Envoy of the Science Panel for the Congo Basin and an editor-in-chief of this report.

# About the Section Editors



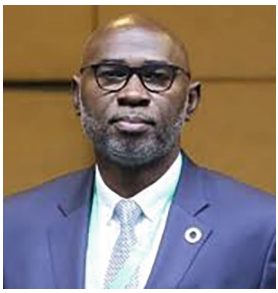
**Jean-Jacques Braun** is a Geochemistry and Soil Scientist for the Tropical Critical Zone at the Institut de Recherche pour le Développement (France). He investigates mass balance and transfer processes from small watersheds to large river basins by examining interactions among soil, rock, water, and living organisms. He is interested in how climate change, human activity, and tectonics affect chemical and physical weathering and the cycling of metals such as lanthanides and actinides in tropical soils.



**Raphaël M. Tshimanga** is Professor of Hydrology at the University of Kinshasa, Director of the Regional School of Water and CRREBaC, Democratic Republic of Congo. He integrates hydrology, biodiversity conservation, and socioeconomic resilience, influencing national and international environmental policies. He developed the Congo Basin Catchment Information System, a knowledge hub providing high-quality data on water resources, environmental processes, and societal impacts in the Congo Basin. He mentors emerging scientists, and advocates for evidence-based solutions in Africa's green transition.



**Katharine Abernethy** is an Associate Researcher at the Institute for Tropical Ecology Research in Gabon and Professor of Tropical Ecology at the University of Stirling in the UK. She has published 122 peer-reviewed articles and supervised 20 doctoral theses on the ecology and conservation of the Congo Basin during more than 30 years of research. She was awarded the 2023 British Ecological Society's President's Medal for her dedication to capacity building and long-term ecological research.



**Suspense Averti Ifo** is a Plant Ecology and Climate Change Lecturer and Researcher at Marien N'gouabi University where he is the Head of the Remote Sensing and Forest Ecology Laboratory. His work focuses on deforestation, tropical peatlands, and the functioning of tropical forests, peatlands, and greenhouse gas inventories. He has authored several publications and has supervised several master's and doctoral theses.



**Denis Jean Sonwa** is the Research, Data, and Impact Director of World Resources Institutes, Africa. He was a Senior Scientist at CIFOR (Cameroon) and was also a visiting professor at ASC-TUFS in Tokyo. Focused on forest and climate change responses, including REDD+ and cocoa agroforestry, he holds a Ph.D. from the University of Bonn (Germany), and a training certificate from University of California, Berkeley. He contributed to the IPCC climate change and land degradation report.

# Contributors

**Katharine Abernethy** Biological and Environmental Sciences, Faculty of Natural Sciences, University of Stirling, Stirling, UK

Institut de Recherches en Ecologie Tropicale, CENAREST, Libreville, Gabon

**Emmanuel Abwe** Unité de recherche en Biodiversité, gestion et Exploitation durable des Zones Humides, Faculté des sciences agronomiques, Université de Lubumbashi, Lubumbashi, Democratic Republic of the Congo

Ecole de Pêche et d'Aquaculture, Université de Lubumbashi, Lubumbashi, Democratic Republic of the Congo

National Research Foundation – South African Institute for Aquatic Biodiversity, Makhanda (Grahamstown), South Africa

**Delphine Takem Ebangha Agbor** Ministry of Scientific Research and Innovation, National Institute of Cartography, Yaoundé, Cameroon

**Etienne François Akomo Okoue** Institut de Recherche en Ecologie Tropicale, Centre National de Recherches Scientifiques et Technologies, Libreville, Gabon

**Bhely Angoboy** Forestry Division, Institut National Pour l'étude et la Recherche Agronomiques, Kinshasa, République Démocratique du Congo

**Claudine Augée Angoué** Université Omar Bongo, Libreville, Gabon

**Nicola Mary Anthony** University of New Orleans, New Orleans, LA, USA

**Sebastian Apers** Soil Service of Belgium (BDB), Willem de Croylaan, Leuven, Belgium

**Stéphane Audry** Géosciences Environnement Toulouse, IRD-CNRS-UPS, Toulouse, France

**Nyong Princely Awazi** Department of Forestry and Wildlife Technology, College of Technology (COLTECH), The University of Bamenda, Bambili, Cameroon

**Salvius Amuri Bakari** University of Lubumbashi, Lubumbashi, Democratic Republic of Congo

**Matti Barthel** Department of Environmental Systems Science, ETH Zurich, Zurich, Switzerland

**Valentin Chribagula Bashige** University of Lubumbashi, Lubumbashi, Democratic Republic of Congo

**Paul Bates** School of Geographical Sciences, University of Bristol, Bristol, UK

**Marijn Bauters** Q-ForestLab, Department of Environment, Ghent University, Ghent, Belgium

**Michel Bechtold** Department of Earth and Environmental Sciences, KU Leuven, Belgium

**Milena M. Beekmann** Department of Biology and Biotechnologies, Sapienza University of Rome, Rome, Italy

**Stoffenne Binsangou** Marien N'Gouabi University, Remote Sensing Laboratory and Forest Ecology, Brazzaville, Democratic Republic of Congo

**Achille Biwole** Department of Forest Engineering, University of Douala, Douala, Cameroon

**Pascal Boeckx** Department of Environment, Ghent University, Ghent, Belgium

**Sakaros Bogning** Université de Douala, Douala, Cameroon

**Gode Bola** Congo Basin Water Resources Research Center (CRREBaC) & the Regional School of Water (ERE), University of Kinshasa (UNIKIN), Kinshasa, Democratic Republic of the Congo

**H. Boulet** Sustainable Wildlife Management Programme, Food and Agriclture Organisation, Rome, Italy

**Clay Archange Boupoya** Herbier National du Gabon, Libreville, BP, Gabon

**Jean-Jacques Braun** Géosciences Environnement Toulouse (GET), IRD–CNRS–UPS, Toulouse, France

LMI DYCOFAC, IRD–IRGM–University of Yaoundé I, Yaoundé, Cameroon

**François Bretagnolle** UM UMR CNRS/uB 6282 Biogéosciences, Université de Bourgogne, Bourgogne, France

**H. Carolyn Peach Brown** Department of Environmental Studies, University of Ile-du-Prince-Édouard, Charlottetown, Canada

**Louis Champion** Institut de Recherche pour le Développement, (DIADE), Montpellier, France

**Zacharie Kusamba Chifundera** Département de Biologie Centre de Recherche en Sciences Naturelles, Lwiro, South Kivu Province, Democratic Republic of the Congo

**D. Cornelis** CIRAD, Montpellier, France

**Aida Cuni-Sanchez** York Institute for Tropical Ecosystems, Department of Geography and Environment, University of York, York, North Yorkshire, UK

Department of International Environment and Development Studies (Noragric), Norwegian University of Life Sciences (NMBU), Ås, Norway

**Geoffroy de Saulieu** Institut de Recherche pour le Développement (PALOC) and Agence Nationale des Parcs Nationaux, Libreville, Gabon

**Franck Delpomdor** Prairie Research Institute, Illinois State Geological Survey, University of Illinois Urbana-Champaign, Urbana, IL, USA

**Damien Delvaux** Département des Sciences de la Terre, Royal Museum for Central Africa (AfricaMuseum), Tervuren, Belgium

**Emily Denstedt** Health Program - Africa, Wildlife Conservation Society, Kigali, Rwanda

**Soh Wenda Boris Dinictri** Leibniz Centre for Agricultural Landscape Research (ZALF), Müncheberg, Germany

**Kechnit Djamel** Congo Basin Water Resources Research Center (CRREBaC) & the Regional School of Water (ERE), University of Kinshasa (UNIKIN), Kinshasa, Democratic Republic of the Congo

**Atanas Dommo** National Advanced School of Engineering, University of Yaounde 1, Yaoundé, Cameroon

School of Natural Resources, University of Missouri, Columbia, USA

**Jean-Louis Doucet** Gembloux Agro-Bio Tech / Université de Liège, Passage des Déportés, Gembloux, Belgium

**Romain Duda** Centre d'Écologie Fonctionnelle et Évolutive (CEFE), CNRS, University of Montpellier, EPHE, IRD, Montpellier, France

**Richard Eba'a Atyi** Center for International Forestry Research and World Agroforestry (CIFOR-ICRAF), CAM, Bogor, Indonesia

**Jean Marcel Abate Essi** IRGM, Yaoundé, Cameroon

**Fidèle Evouna Ondo** Station d'Etudes des Gorilles et Chimpanzes, Agence Nationale des Parcs Nationaux, Libreville, Gabon

**Corneille Ewango** Faculty of Renewable Natural Resources Management, Université de Kisangani, Kisangani, Democratic Republic of the Congo

**Julia E. Fa** CIFOR-ICRAF, Jalan CIFOR, Situ Gede, Bogor Barat, Bogor, West Java, Indonesia

Manchester Metropolitan University, Ormond Building, Manchester, UK

University of Gibraltar, Europa Point Campus, Gibraltar, Gibraltar

**Adeline Fayolle** Research Unit Forest and Societies, CIRAD (French Agricultural Research Centre for International Development), Libreville, Gabon

**Ayan Santos Fleischmann** Mamirauá Institute for Sustainable Development, Tefé, Brazil

**Roger Fotso** Wildlife Conservation Society, Yaoundé, Cameroon

**Thierry Fotso-Nguemo** Climate Change Research Laboratory (CCRL), National Institute of Cartography, Yaounde, Cameroon

**Moihamette Foupouapegnigni** Laboratory for Environmental Modelling and Atmospheric Physics, Department of Physics, Faculty of Sciences, University of Yaounde 1, Yaoundé, Cameroon

**Adam Freedman** Harvard University, Cambridge, MA, USA

**Nicole L. Gottdenker** Department of Pathology, College of Veterinary Medicine, University of Georgia, Athens, GA, USA

**Merlin Guenang** Department of Physics, Faculty of Science, University of Dschang, Dschang, Cameroon

Laboratory for Environmental Modelling and Atmospheric Physics, Department of Physics, Faculty of Sciences, University of Yaounde 1, Yaounde, Cameroon

**Olivier Hardy** Université Libre de Bruxelles, Brussels, Belgium

**Benoît Henriet** Vrije Universiteit Brussel, Brussels, Belgium

**Sarah C. Hill** Pathobiology and Population Sciences, Royal Veterinary College, Hatfield, UK

**Simon Hoyte** Extreme Citizen Science Research Group, Department of Anthropology, University College London, London, UK

**Wannes Hubau** Department of Environment, Ghent University, Ghent, Belgium

Royal Museum for Central Africa, Service of Wood Biology, Tervuren, Belgium

**Olivier Hymas** University of Lausanne, Lausanne, Switzerland

**I. Ichikowitz** Transafrica, Pretoria, South Africa

**Suspense Averti Ifo** École Normale Supérieure, Université Marien Ngouabi, Brazzaville, Republic of Congo

**Gerard Imani** Biology, Université Officielle de Bukavu, Bukavu, Democratic Republic of the Congo

**Verina Jane Ingram** Forest & Nature Conservation Policy Group, Wageningen University & Research, Wageningen, The Netherlands

Central Africa Regional Office, CIFOR-ICRAF, Yaoundé, Cameroon

**David Ingueza** Ministère des Eaux et Forêts, de l'Environnement, du Climat, Chargé du Conflit Homme-Faune, Libreville, Gabon

**Bila-Isia Inogwabini** Swedish University of Agricultural Sciences, Uppsala (Sweden) and School of Management, Catholic University of Congo, Kinshasa, Democratic Republic of Congo

**Kathryn J. Jeffery** Faculty of Natural Sciences, University of Stirling, Stirling, UK

AMAP, University of Montpellier, CIRAD, CNRS, INRAE, IRD, Montpellier, France

**Donald Jomha** Observatoire des Forêts d'Afrique Centrale (OFAC), Yaoundé, Cameroon

**Roger-Louis-Paul Kabelong Banoho** Department of Plant Biology, Faculty of Science, University of Yaoundé I, Yaoundé, Cameroon

**Etienne Yusufu Kachaka** Laval University, Quebec, QC, Canada

**Etienne Kadima Kabongo** Laboratoire de Géophysique et Géodynamique de la Lithosphère, Département de Géologie, Faculté des Sciences et Technologie, Université de Lubumbashi, Lubumbashi, Democratic Republic of the Congo

**John Byanga Kahumba** University of Lubumbashi, Lubumbashi, Democratic Republic of Congo

**Hyunwoo Kang** Washington State University, Pullman, USA

**Perez. L. Kemeni Kambiet** Mohammed VI Polytechnic University, Benguerir, Morocco

**Victor Aimé Kemeuze** Tropical Green Builder, Yaoundé, Cameroon

**Thierry Loic Kenmou** Observatoire des Forêts d'Afrique Centrale (OFAC), Yaoundé, Cameroon

Forêt Ressources Management Ingénierie (FRMi), Mauguio, France

**Paulin Kialo** Institut de Recherche en Sciences Humaines, Libreville, Gabon

**Hyung Lok Kim** Gwangju Institute of Science and Technology, Gwangju, South Korea

**Benjamin Kitambo** Congo Basin Water Resources Research Center (CRREBaC) & the Regional School of Water (ERE), University of Kinshasa (UNIKIN), Kinshasa, Democratic Republic of the Congo

Institute of Geodesy, University of Stuttgart, Stuttgart, Germany

Department of Geology, Faculty of Sciences, University of Lubumbashi (UNILU), Lubumbashi, Democratic Republic of the Congo

**Lydie-Stella Koutika** Soil Care and Environmental Studies, Pointe-Noire, Republic of Congo

**Justin Kyale Koy** Department of Political Sciences, University of Kisangani, Kisangani, Democratic Republic of Congo

**Giresse Kuete** Laboratory for Environmental Modelling and Atmospheric Physics, Department of Physics, Faculty of Sciences, University of Yaounde 1, Yaounde, Cameroon

**Eeva Kuisma** Pathobiology and Population Sciences, Royal Veterinary College, Hatfield, UK

Health Program, Wildlife Conservation Society, Bronx, NY, USA

**J. Kyale** Université de Kisangani, Kisangani, Democratic Republic of Congo

**Venkataraman Lakshmi** University of Virginia, Charlottesville, VA, USA

**Simon Lewis** University of Leeds, Leeds, UK

**Anne-Marie Lezine** Université Sorbonne, Paris, France

**Simon Lhoest** Forest is life, Gembloux Agro-Bio Tech, University of Liège, Passage des déportés, Gembloux, Belgium

**Moses B. Libalah** Department of Plant Biology, Faculty of Science, University of Yaoundé I, Yaoundé, Cameroon

Plant Systematics and Ecology Laboratory (LaBosystE), Higher Teacher's Training College, University of Yaoundé I, Yaoundé, Cameroon

**Alexandre Livingstone Smith** Royal Museum for Central Africa, Tervuren, Belgium

**Tobit Liyandja** Department of Biological Sciences, University of Toronto Scarborough, Toronto, ON, Canada

Department of Biology, Faculty of Sciences and Technologies, University of Kinshasa, Kinshasa, Democratic Republic of the Congo

Department of Natural History, Royal Ontario Museum, Toronto, ON, Canada

**Georges-Noel Tiersmondo Longandjo** Department of Oceanography, Nansen-Tutu Centre for Environmental Marine Research, University of Cape Town, Rondebosch, South Africa

Department of Meteorology, Institut Supérieur des Techniques Appliquées, Kinshasa, Democratic Republic of Congo

**Jacob Heen Lowenstein** Dogen Institute, Gyobutsuji, AR, USA

**Hines Mabika Ognandzi** University Omar Bongo – University of Lausanne, Lausanne, Gabon

**Sybryn L. Maes** Division of Forest, Nature and Landscape, Department of Earth & Environmental Sciences, KU Leuven, Leuven, Belgium

**P. Mafwila** Université de Kinshasa, Kinshasa, Democratic Republic of Congo

**Fiona Maisels** Wildlife Conservation Society, New York City, New York, USA

University of Stirling, Biological and Environmental Sciences, Stirling, UK

**Loïc Makaga** Station d'Etudes des Gorilles et Chimpanzes, Agence Nationale des Parcs Nationaux, Libreville, Gabon

**Jean-Remy Makana** Faculté des Sciences, Laboratoire D'écologie et Aménagement Forestier, Université de Kisangani, Kisangani, Democratic Republic of Congo

**Isaac Makelele** Département de Biologie, Faculté des Sciences, Université Officielle de Bukavu (U.O.B), Bukavu, Democratic Republic of Congo

**Yadvinder Malhi** University of Oxford, Oxford, UK

**Pascal Mambwe** Département de Géologie, Faculté des Sciences et Technologie, Université de Lubumbashi, Lubumbashi, Democratic Republic of the Congo

**Francis Manfoumbi** AGEOS, Libreville, Gabon

**Danae Maniatis** Central African Forest Initiative (CAFI) & School of Geography and the Environment, University of Oxford, Oxford, UK

**Sebastian R. O. Marshall** University of Virginia, Charlottesville, VA, USA

**E. Mbangale** CIFOR-ICRAF, Kisangani, Democratic Republic of Congo

**Billy Kakelengwa Mbilizi** Department of Sociology, University of Kisangani, Kisangani, Democratic Republic of Congo

**Duclaire Mbouna** World Resources Institute, Yaoundé, Cameroon

**Maximiliano Fero Meñe** Department of Management and Conservation of Natural Environment, Faculty of Environmental Sciences, National University of Equatorial Guinea, Malabo, Equatorial Guinea

**Brusil Miranda Metou** Department of Public Law, Université Yaoundé II, Yaoundé, Cameroon

**Caroline Michellier** Natural Hazard and Cartography unit, Royal Museum for Central Africa, Tervuren, Belgium

Earth and Life Institute, Université catholique de Louvain, Louvain-la-Neuve, Belgium

**Donald Midoko Iponga** Institut de Recherche en Ecologie Tropicale, Centre National de Recherches Scientifiques et Technologies, Libreville, Gabon

**Christian Mikolo** Institute of Tropical Ecology Research (IRET), National Centre for Scientific and Technological Research (CENAREST), Avenue Houphouët-Boigny, Libreville, Gabon

**Kumar Mohan** Africa Mining and Metals Group, JBC2, Cluster V, JLT, Dubai, UAE

**Robert E. Moïse** Independent scholar, Coulee Dam, USA

**Ernest L. Molua** Department of Agricultural Economics and Agribusiness, Faculty of Agriculture and Veterinary Medicine, University of Buea, Buea, Cameroon

Centre for Independent Development Research (CIDR), Buea, Cameroon

**Stéphane Momo** Congo Basin Institute (CBI) & International Institute for Tropical Agriculture (IITA), Yaoundé, Cameroon

University of Liége, Liege, Belgium

**J. M. Mondo** Université Evangélique en Afrique, Kinshasa, Democratic Republic of Congo

**Wilfran Moufouma-Okia** World Meteorological Organization, Geneva, Switzerland

**Léa-Larissa Moukagni** Institute of Tropical Ecology Research (IRET), National Centre for Scientific and Technological Research (CENAREST), Scientific and Technical Coordinator, Avenue Houphouët-Boigny, Libreville, Gabon

**Guy Moukandi** LMEI/CUSI/ENSP, Marien N'gouabi University, Brazzaville, Congo

**Ghislain Moussavou** Institute of Research in Tropical Ecology (IRET), National Center for Scientific and Technological Research (CENAREST), Libreville, Gabon

**Charles Mpoyi Mpoyi** Department of Political and Administrative Sciences, University of Mbuji Mayi, Mbuji Mayi, Democratic Republic of Congo

**J. Muhindo** SOWILD, Kisangani, Democratic Republic of Congo

**D. Mukubi** Ministère de l'Environnement, Kinshasa, Democratic Republic of Congo

**Jonathan Muledi** Département de Gestion des Ressources Naturelles Renouvelables, Faculté des Sciences Agronomiques, Université de Lubumbashi, Lubumbashi, Democratic Republic of the Congo

**Neil-Yohan Musadji** National Institute of Agronomy and Biotechnology, Department of Fundamental Engineering Sciences, Soil and Environmental Analysis Laboratory, Laboratory of Chemistry, Environments and Inorganic Materials, Franceville, Gabon

**Catherine Awidi Mushi** Department of Civil and Environmental Engineering, Ardhi University, Dar es Salaam, Tanzania

**Cedrick Shakalenga Mutombo** University of Lubumbashi, Lubumbashi, Democratic Republic of Congo

**Minette Nago** London School of Economics and Political Science (LSE), London, UK

**R. Nasi** CIFOR-ICRAF, Bogor, Indonesia

**Francis E. Ndip** Center for Development Research, University of Bonn, Bonn, Germany

**Jean-Pierre Messina Ndzomo** Faculty of Architecture, University of Notre Dame of Kananga, Kananga, Democratic Republic of Congo

**Phillip Negrel** BRGM, Orléans, France

**Patience Ngelinkoto** Département de Chimie, Faculté des Sciences, Université Pédagogique Nationale, Kinshasa, Democratic Republic of Congo

**Frankline Nghobuoche** Central Africa Regional Office, The Center for International Forestry Research and World Agroforestry (CIFOR-ICRAF), Yaoundé, Cameroon

**Alphonse Maindo Monga Ngonga** Department of Political and Administrative Sciences, University of Kisangani, Kisangani, Democratic Republic of Congo

**Cyriaque Nguimalet** Département de Géographie, Faculté des Lettres et Sciences Humaines, Bangui, République Centrafricaine

**Sharon Nicholson** Department of Earth, Ocean and Atmospheric Sciences, Florida State University, Florida, USA

**L. Nihotte** FAO, Rome, Italy

**Jervais Nkoulou** Environment and Natural Resource Management. Agriculture/ Economie Verte (GRECO), Cotonou, Republic of Benin

**Pascal Nlend Nlend** University of Yaoundé 1, Yaoundé, Cameroon

**Mathieu Nouazi** IRGM, Yaoundé, Cameroon

**Anatole Ntelo** Ministry of Agriculture and Livestock, Department of Animal Health, Brazzaville, Republic of Congo

**Emmanuel Nuesiri** Environmental Protection and Development Association (EPDA), Limbe, Cameroon

**Arnold Roger Bitja Nyom** Faculty of Science, Department of Biological Sciences, University of Ngaoundéré, Ngaoundere, Cameroon

**J. Nyumu** SOWILD, Kisangani, Democratic Republic of Congo

**S. Nziavake** SOWILD, Kisangani, Democratic Republic of Congo

**Rolf Gael Mabicka Obame** National Institute of Agronomy and Biotechnology, Department of Phytotechnology, Soil and Environmental Analysis Laboratory, Franceville, Gabon

**Takanori Oishi** African Studies Center, Tokyo University of Foreign Studies, Fuchu, Japan

**Joseph Okello** Faculty of Agriculture and Environmental Sciences (FAES), Mountains of the Moon University, Fort Portal, Uganda

**Sarah H. Olson** Wildlife Conservation Society, Health Program, New York, NY, USA

**Elsa Ordway** Department of Ecology and Evolutionary Biology and Institute of the Environment and Sustainability, University of California, Los Angeles (UCLA), Los Angeles, CA, USA

**Richard Oslisly** PALOC/ANPN, Institut de Recherches pour le Developpement, Paris, France

**Florence Palla** Observatoire des Forêts d'Afrique Centrale (OFAC), Yaoundé, Cameroon

**Fabrice Papa** Université de Toulouse, LEGOS, CNES/CNRS/IRD/UT, Toulouse, France

**Adrien Paris** Hydro Matters, 1 chemin de la Pousaraque, Le Faget, France

**Charles Perrings** Emeritus Professor, School of Life Sciences, Arizona State University, Tempe, AZ, USA

**Ghislain Noé Kougoum Piebeng** Département des Sciences Biologiques, Faculté des Sciences, Université de Maroua, Maroua, Cameroon

**Wilfried Pokam** Department of Physics, Higher Teacher Training College, University of Yaounde 1, Yaounde, Cameroon

Laboratory for Environmental Modelling and Atmospheric Physics, Department of Physics, Faculty of Sciences, University of Yaounde 1, Yaounde, Cameroon

**S. Ratiarison** FAO, Libreville, Gabon

**Pierre Regnier** Department of Geoscience, Environment and Society-BGEOSYS, Université Libre de Bruxelles, Brussels, Belgium

**Birgit Ricquier** Centre de recherche en linguistique and Centre d'anthropologie culturelle, Université libre de Bruxelles, Brussels, Belgium

**Stephanie Rupp** Lehman College, City University of New York, New York, USA

**Sassan Saatchi** California Institute of Technology, Pasadena, CA, USA

**Le Bienfaiteur Sagang** C-TREES, Pasadena, CA, USA

**F. Sandrin** WCS, Kigali, Rwanda

**E. Sartoretto** FAO, Rome, Italy

**Tracie A. Seimon** Zoological Health Program, Wildlife Conservation Society, Bronx Zoo, Bronx, NY, USA

**J. Semeki** University of Kinshasa, Kinshasa, Democratic Republic of Congo

**Marie Sigaud** Département Homme et Environnement, Muséum National d'Histoire Naturelle, Paris, France

**Tom Smith** University of California Los Angeles, Los Angeles, CA, USA

**Bonaventure Sonké** Laboratory of Plant Systematics and Ecology (LaBosystE), Higher Teachers' Training College, University of Yaoundé I, Yaounde, Cameroon

**Denis Jean Sonwa** WRI (World Resources Institute), Kinshasa, Democratic Republic of the Congo

**Venkataramana Sridhar** Department of Biological Systems Engineering, Virginia Polytechnic Institute and State University, Blacksburg, VA, USA

**Tikeng Stella** Laboratory for Environmental Modelling and Atmospheric Physics, Department of Physics, Faculty of Sciences, University of Yaounde 1, Yaounde, Cameroon

**Richard Kankeu Sufo** ESO laboratory, Le Mans University, Le Mans, France

**Hermann Taedoumg** Department of Plant Biology, Faculty of Science, University of Yaoundé I, Yaoundé, Cameroon

Plant Systematics and Ecology Laboratory (LaBosystE), Higher Teacher's Training College, University of Yaoundé I, Yaoundé, Cameroon

Tropical Green Builder, Yaoundé, Cameroon

**Claude Tatuebu Tagne** University of Yaounde 1, Yaounde, Cameroon

**Romeo Tanessong** Department of Meteorology and Climatology; Higher Institute of Agriculture, Forestry, Water and Environment, University of Ebolowa, Ebolowa, Cameroon

Laboratory for Environmental Modelling and Atmospheric Physics, Department of Physics, Faculty of Sciences, University of Yaounde 1, Yaounde, Cameroon

**Tamoffo Tchio** Climate Service Center Germany (GERICS), Helmholtz-Zentrum Hereon, Hamburg, Germany

**Lucie Félicité Temgoua** Faculty of Agronomy and Agricultural Sciences, Department of Forestry, University of Dschang, Dschang, Cameroon

**Nicolas Texier** Université Libre de Bruxelles, Brussels, Belgium

**Denis Thiéblemont** BRGM, Orléans, Cedex 02, France

**Thanh-Nhan-Duc Tran** University of Virginia, Charlottesville, VA, USA

**Mark A. Trigg** School of Civil Engineering, University of Leeds, Leeds, UK

**Raphaël M. Tshimanga** Congo Basin Water Resources Research Center (CRREBaC) & the Regional School of Water (ERE), University of Kinshasa (UNIKIN), Kinshasa, Democratic Republic of the Congo

**Urcel Kalenga Tshingomba** Observatoire des Forêts d'Afrique Centrale (OFAC), Yaoundé, Cameroon

Forêt Ressources Management Ingénierie (FRMi), Mauguio, France

**Nathalie van Vliet** Sustainable Wildlife Management Programme: FAO, Rome, Italy

CIFOR-ICRAF, Kenya, Cameroon

**Marie Claire Veranso-Libalah** Senckenberg Research Institute and Natural History Museum, Frankfurt am Main, Germany

**Hans Verbeeck** Q-ForestLab, Department of Environment, Ghent University, Ghent, Belgium

**Alice Vittoria** Social History of Capitalism research group, Vrije Universiteit Brussels Pleinlaan, Brussels, Belgium

**Derbetini Vondou** Laboratory for Environmental Modelling and Atmospheric Physics, Department of Physics, Faculty of Sciences, University of Yaounde 1, Yaounde, Cameroon

**Salomon Mampeta Wabasa** Department of Sociology, University of Kisangani, Kisangani, Democratic Republic of Congo

**Gretchen Walters** University of Lausanne, Lausanne, Switzerland

**Richard Washington** School of Geography and the Environment, University of Oxford, Oxford, UK

**Lee J. T. White** University of Stirling, School of Natural Sciences, Stirling, UK

Institut de Récherche en Ecologie Tropicale, Libreville, Gabon

**Catherina Wilson** Radboud University, Nijmegen, The Netherlands

**Sly Wongchuig** Université de Toulouse, LEGOS, CNES/CNRS/IRD/UT, Toulouse, France

**Sarah Worden** Biosphere, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

**Louis Zapfack** Faculty of Science Department of Plant Biology University of Yaoundé I, Yaoundé, Cameroon

**Virginia Zaunbrecher** University of California, Los Angeles, Congo Basin Institute, Los Angeles, USA

**H. Zébazé Togouet Serge** Department of Animal Biology and Physiology, Faculty of Science, University of Yaoundé I, Yaoundé, Cameroon

**Jules Christian Zekeng** University of Douala, Douala, Cameroon

# Introduction: Congo Basin Resilience and Sustainability: From Past to Future

1

Bila-Isia Inogwabini, Birgit Ricquier, Aida Cuni-Sanchez, Bonaventure Sonké, Lydie-Stella Koutika, Stephanie Rupp, and Lee J. T. White

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B.-I. Inogwabini (✉)
Swedish University of Agricultural Sciences, Uppsala (Sweden) and School of Management, Catholic University of Congo, Kinshasa, Democratic Republic of Congo
e-mail: bila_inogwabini@biari.brown.edu

B. Ricquier
Centre de recherche en linguistique and Centre d'anthropologie culturelle, Université libre de Bruxelles, Brussels, Belgium

A. Cuni-Sanchez
York Institute for Tropical Ecosystems, Department of Geography and Environment, University of York, York, North Yorkshire, UK

Department of International Environment and Development Studies (Noragric), Norwegian University of Life Sciences (NMBU), Ås, Norway
e-mail: aida.cuni-sanchez@nmbu.no

B. Sonké
Laboratory of Plant Systematics and Ecology (LaBosystE), Higher Teachers' Training College, University of Yaoundé I, Yaounde, Cameroon

L.-S. Koutika
Soil Care and Environmental Studies, Pointe-Noire, Republic of Congo

S. Rupp
Lehman College, City University of New York, New York, USA

L. J. T. White
University of Stirling, School of Natural Sciences, Stirling, UK

Institut de Récherche en Ecologie, Tropicale, Libreville, Gabon
e-mail: l.j.white@stir.ac.uk

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**Abstract**

This chapter introduces the 2025 Congo Basin Assessment Report, discusses the multiple definitions of the Congo Basin, defines the limits of the Congo Basin covered by the report, discusses issues of indigeneity, and describes the regional scientific capacities. The chapter argues that the best way to define the Congo Basin is to use the regional ecological features rather than focusing on the political delimitation or focusing narrowly on the basin of the Congo River itself. Broadening the question of who indigenous communities are and who they are not, the chapter argues that the name Pygmy is contested and that the politics of identity is both complex, contextual, layered, plural, and varied; calling, therefore, for caution in ways they should be used. Rather than going into detailed contents, the chapter briefly summarizes the biodiversity metrics in the Congo Basin, presents the four sections of the report and overall spirit that guided the writing up process, and provides the current status of the available capacities to conduct research in the Congo Basin.

**Keywords**

Congo Basin · Geographic extent · Autochthonous and Indigenous People · Biodiversity · Research capacity

## Introduction

*Congo Basin Resilience and Sustainability: From Past to Future* is the 2025 Congo Basin Assessment Report synthesizing existing scientific knowledge, including that of Indigenous Peoples and Local Communities, on the functioning of and threats to the Congo Basin and its ecosystems. The assessment is made of four parts that total 39 chapters, each describing the current status of an area of knowledge. This introduction covers cross-cutting issues that reoccur throughout the whole book and clarifies operational definitions that different authors have used. It is important to note that operational definitions used here were produced after long debates; they reflect the consensuses reached for each hotly debated subject, among which the most important were the definition of the Congo Basin itself, the question of which communities qualify as Indigenous people, and where to lay the lower limit of the montane forests.

## Geographic Extent of the Congo Basin

There are multiple diverging political, hydrological, geological, and ecological definitions of the Congo Basin (Fig. 1a–c). The Science Panel for the Congo Basin uses an ecological (not political) definition of the Congo Basin, based on the seminal

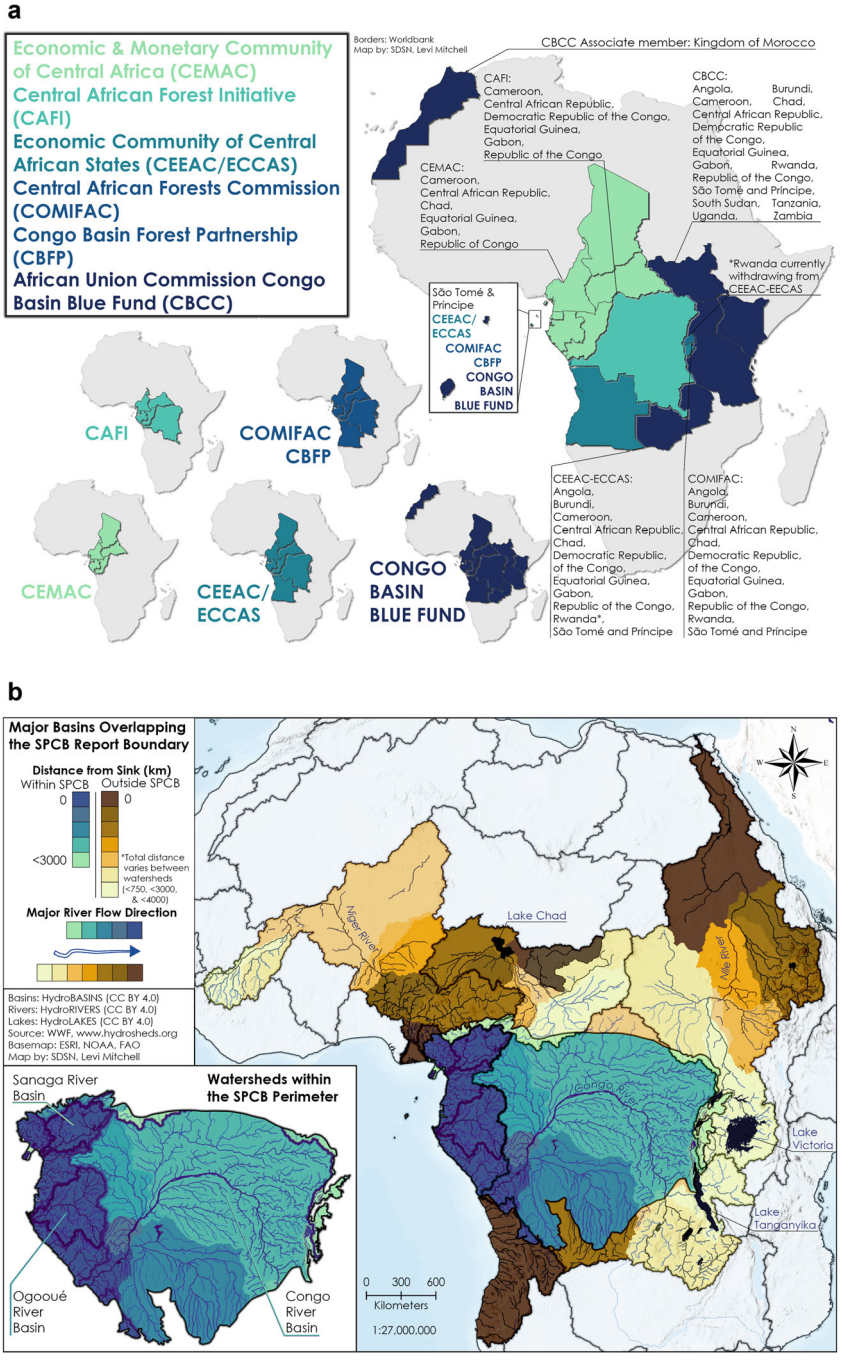



**Fig. 1** (**a**) Various political definitions of the Congo Basin/Central African region; (**b**) watersheds constituting the Congo Basin; (**c**) the extent of the Congo Craton, neighboring Cratons, and the Congo Basin

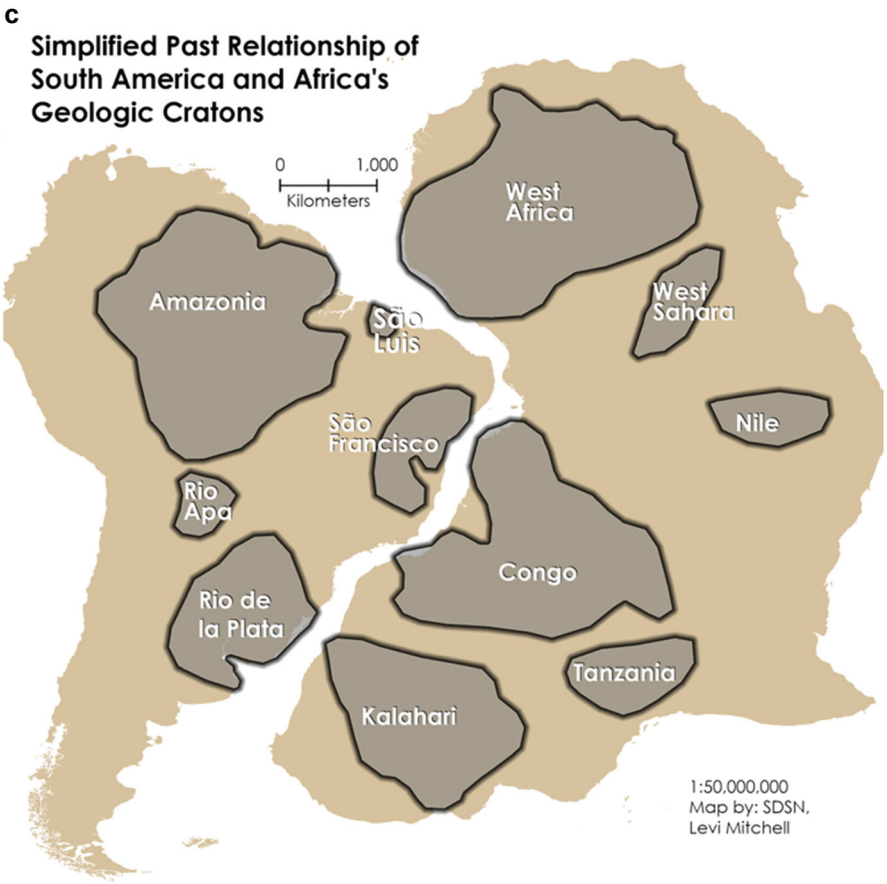



**Fig. 1** (continued)

work on the vegetation of Africa by Frank White (1986), along with the ecoregion analysis. Figure 1a shows the political definitions of the Central Africa/Congo Basin forest countries—as defined by the Central African Forest Commission (COMIFAC) and the Economic Community of Central African States (ECCAS—which have the same definition), the Economic and Monetary Community of Central Africa (CEMAC), the African Union's Congo Basin Commission and Blue Fund (CBCC), and the Central Africa Forest Initiative (CAFI). All except CAFI are definitions adopted by subsets of African nations in the Congo Basin region. Figure 1b shows the principal river basins that fall within the Congo Basin, notably the Congo, Ogooué, and Sanaga as well as the adjacent river basins. Finally, Fig. 1c shows the relative location of the principal African and South American continents and their principal Cratons in the Early Cretaceous as the Pangea supercontinent broke apart and the Atlantic Ocean opened up.

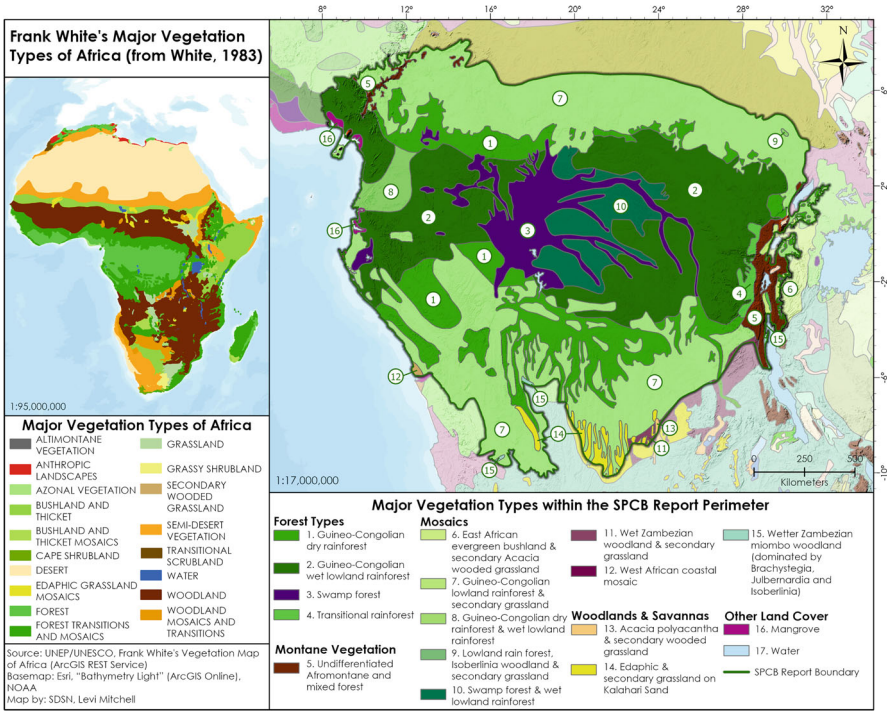



**Fig. 2** The geographic limits of the Congo Basin as defined by the SPCB

The Congo Basin as defined by the Science Panel (Fig. 2) covers an area of 3,462,806 km$^2$. It is composed principally of the lowland wet and dry Guineo-Congolian rainforests (covering 28% and 16% of the total area, respectively), along with extensive swamp (13%), mangrove (0.3%), and Afromontane forests (2.2%), bordered to the north and south by a transitional rainforest and secondary grassland mosaic (39%), as defined by White (1986; Fig. 2). The outer limits of the biome today are somewhat subjective, because they represent a transition from wetter to drier forests, which is continually changing as a function of climate variability and human activities. It includes extensive areas in six nations: Cameroon, Central African Republic, Democratic Republic of Congo (DRC), Equatorial Guinea, Gabon, and Republic of Congo (Fig. 3), and smaller areas in a further 6: Angola, Burundi, Nigeria, Rwanda, South Sudan, and Uganda. The eastern limit is the eastern edge of the Afromontane forests of the African Rift Valley, while the western limit is the Cross River in Nigeria. It does not include the volcanic islands of Sao Tomé and Principé, which have never been connected to the African continent but does include Bioko, which was connected to the mainland by a land bridge during the last Ice Age 12,000 years ago.

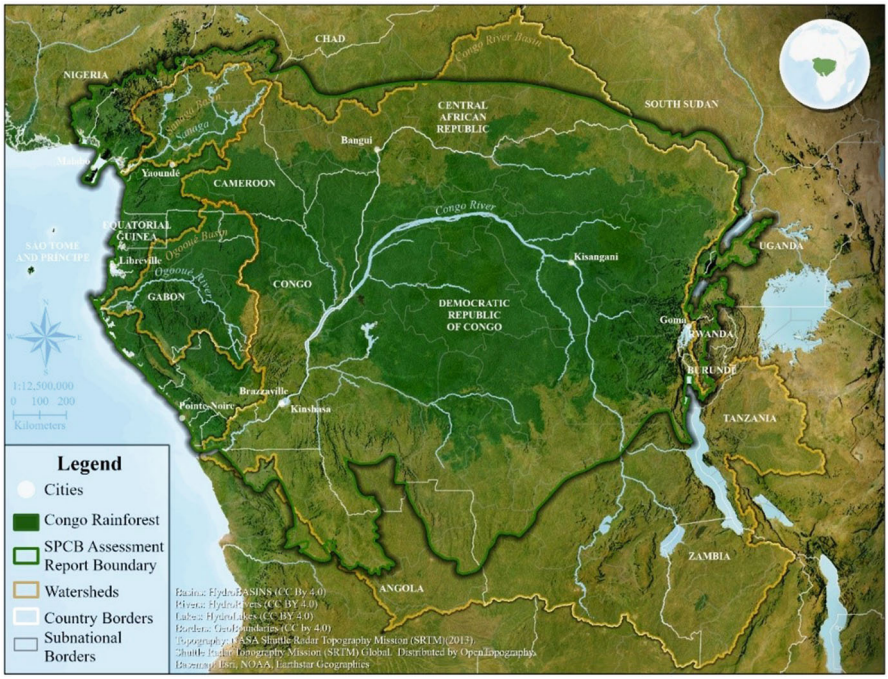



**Fig. 3** The Congo Basin in its geographical context

## The Issue of Indigenous, Autochthonous, and Local Communities and Peoples in the Congo Basin

*Homo spp.* have lived in the Congo Basin for at least 650,000 years and probably longer. *Homo sapiens* has been present for hundreds of thousands of years. During the process that led to the production of this report, questions emerged as to who should be identified as Indigenous, autochthonous, and how to name largely marginalized communities throughout the document. Some have simplistically argued that the distinction between Bantu and Nilotic people and "Pygmies" (or hunter-gatherers) in Africa is analogous to the definition of Indigenous People used by the Science Panel for the Amazon, while others feel the context in the Congo Basin is much more complex and nuanced. Vansina (1990) argued that the differentiation between pygmies as the first dwellers of the forests of the Congo Bantu has been essentially imposed from the outside; in some areas, there might also have been other (non-pygmy) peoples present before the arrival of Bantu "farmers." Then, if so, why would pygmies be considered "indigenous" and not Bantu?

The current usage of the word "Pygmy" is contested among scientists, as it is sometimes used pejoratively by non-Pygmy ethnic groups to indicate "backwardness," being less than human, or for warning someone about their unacceptable

behavior (Boyette et al. 2022). However, some Pygmy groups use the term to refer to their unique identity vis-à-vis "non-Pygmies" (e.g., Takeuchi 2014), and the term is still widely used in academic and nonacademic circles and the popular press. Some authors prefer to use the term "foragers" or "hunter-gatherers" rather than Pygmy, to refer to their traditional main subsistence mode, the way their societies are organized, other core cultural features, and how they relate to nature (see ▶ Chap. 9, "Critical Interconnections Between Cultural and Biological Diversity in the Congo Basin"). Today, not all Pygmy groups remain hunter-gatherers; some are extensively engaged in farming. We use concrete ethnic group names (e.g., Aka, Baka, Balumbe, Batswa, Mbuti, Okandé, and Téké) whenever possible, but for purposes of generalization, in some chapters authors use the word "Pygmy," given that this term is more widely known by nonacademics outside the Congo Basin.

The discussion on the usage of the word "Pygmy" led to the discussion about the cultural and political identities of forest communities throughout the Congo Basin. It was affirmed that both are complex, varied, and often fraught. The ways that any given person self-identifies are plural, layered, and contextual. Furthermore, forest communities form multiethnic, multilingual clusters, in which local identities are shaped by relationships that traverse and entangle many different social boundaries of similarity and difference, and are shaped by complex dynamics of mutuality as well as tension. Finally, the ways that peoples identify themselves and the ways that they are identified by others, and particularly by institutions, do not always align.

Since early colonial times, outside observers have used contrasting categories to distinguish the tremendous cultural, economic, and political diversity of the region: pygmies versus non-pygmies; hunter-gatherers versus farmers versus pastoralists people; and Indigenous people versus those (presumed to) have migrated into the forest. These etic (outside) categories offer conceptual handles for making sense of, and create policies for, forest communities throughout the region. At the same time, forest people identify themselves in a variety of layered, culturally and contextually specific ways; such emic (inside) identities may reflect language, clan, historical heritage, contemporary alliances, and other meaningful, dynamic, and shifting ways of expressing the self and its relations to others. Importantly, these emic identities may also include etic, outside identities such as "pygmy"—perhaps in alignment with the institutional, political, or outside expectations of the qualities, but in other cases with meanings that diverge, complicate, or even contradict and fill the category with cultural meanings that are specific to a local context in time and place. Whether a forest dweller or entire forest community is classified as a "pygmy" or a "non-pygmy," these terms flatten out a universe of salient features of ancestry, ecological connection, ritual participation, economic pursuit, marriage and alliance, and many other features of sociality that shape identities.

Administrative and academic categories have histories of their own; they are not neutral, stable, uncontested, or original categories for forest peoples themselves. Thus, as useful as such categories, "pygmy" or "hunter-gatherer" on the one hand, or "villager" or "farmer" on the other, may be to facilitate institutional or external understandings of the Congo Basin as a region, it is important to bear in mind that these categories represent just one valence of identity, a layer that is highly abstract,

imprecise, and does not fully capture the local meanings and complexities of people's identities.

Since early colonial times, and in some cases reaching back to much earlier expeditions of exploration, simplified identity categories have been used to make sense of who was who, to identify which people and communities were sought for particular purposes of observation or contact, and to control the movements, activities, and rights of different groups, in the complex, fluid social spaces of the Congo Basin (Bahuchet 1993a; Rupp 2011). Such categories allowed, and continue to allow, outside or institutional observers more easily to identify differences within forest communities who occupy the same space or adjacent spaces, and to compare social, economic, and political patterns across space. Indeed, the creation of these categories and their continued use illustrates a fundamentally significant social reality: Within the Congo Basin, communities live in complex, flexible social configurations. The local complexities of ethnicity and belonging make simple categories of delineation extremely useful, even if they are not always especially accurate. For example, throughout the basin today as in the past, not only communities tagged as "hunter-gatherers" engage in hunting and gathering as a primary economic pursuit, but also at the same time, people identified as "hunter-gatherers" often engage in, and have engaged in, horticulture, fishing, and trade over time. Furthermore, communities throughout the basin have a much longer history of economic and social diversification than reductive categories imply.

From an analytical perspective, to understand the identities, social relations, and political configurations of communities, it is essential to understand each group in relation to its neighbors. Looking holistically at the particular, local contexts of multiethnic, multilinguistic communities throughout the basin, it becomes evident that neighboring groups—even if they can be administratively slotted into contrasting categories such as "hunter-gatherers" or "villagers"—have much more in common with each other and share contemporary realities locally, than either administrative group may share with "pygmy" or "villager" groups in some other region of the vast Congo River Basin. While local divisions and tensions also may well exist, it is essential to understand the local iterations of competition and cooperation, and not to assume that social identities all map neatly onto intellectual and administrative categories derived by external, institutional, and often (but not always) Euro-American observers. To take one group within a plural setting as the object of investigation or policy is to offer a partial, or incomplete, understanding and to the risk of designing and implementing a partial, or biased, policy.

Today, the politics of identifying who counts as an "indigenous person" is similarly fraught, particularly when conventions on "indigenous people" offer rights of access to protected areas of the forest, or rights to hunt in particular ways, to some forest peoples and not all. The diverse and dynamic human history in the Congo Basin renders such simplistic demarcations of "indigenous" and "non-indigenous" both impossible and foolish. While linguistic and genetic research demonstrates that certain language communities that have been identified as "pygmy" groups since the mid-nineteenth century were the first human inhabitants of the Congo River Basin, such ancient origins do not preclude movement within the basin over time. Furthermore, being identified as a "pygmy" group in a particular region does not necessarily

mean that the community is an autochthonous or Indigenous person in the particular region where they live today. "Pygmy" communities, for example, the Baka and Aka, also have histories of displacement, migration, arrival, and contact with preexisting forest communities in the particular areas of the basin where they live today (Bahuchet 1992, 1993b). Furthermore, the deep histories of Bantu-language speaking forest communities (a linguistic group that also includes numerous "pygmy" communities) span at least 5000 years. Is habitation of a region for 5000 years by one's ancestors not "long enough" to be considered Indigenous? Identifying who counts as "indigenous" is a contrived and politically motivated exercise, which has more to do with the politics of resource allocation than with accurate understandings of Congo Basin history. It is also frequently undertaken in efforts to align the Congo Basin with the Amazon, where there is a complex sociopolitical relationship between communities who arrived some 10,000–15,000 years ago and others who arrived around 500 years ago and thereafter. The reality is that human societies have existed in the Congo Basin since our species emerged from other hominins and their collective histories are much more complex than those of inhabitants of the Americas.

Reliance on static, homogenizing categories of social and political identities leaves outside observers with the impression that the people of the Congo River Basin, and the forest itself, can be reduced to archetypes, and furthermore that these distilled simplifications of identity are sufficient, even appropriate, to use as categories to designate political and economic policies that impact and regulate the complex realities of forest peoples today. Outside observers, whether they are fellow national citizens and officials living in cities and towns rather than forests, academic scholars and students, policymakers and nongovernmental organization staff, or officers of international bureaucracies that administer ecological resources in the forest context, fall back on these archetypal identities for the sake of expediency and clarity. Forest people themselves today often assume such categories of identity for themselves and apply them to others in contexts where they are useful for a variety of reasons: to align with policies that might offer preferential access to resources; to make oneself and one's community visible and understandable to institutions; and to celebrate or denigrate particular social relations, playing on the stereotypical values that inhere in a category such as "pygmy." The identity politics of forest communities throughout the Congo River Basin region are complex, dynamic, and varied.

In this report, we use reductive categories of identity sparingly and only where they offer value in synthesizing information that pertains across communities; otherwise, we refer to forest communities simply as "forest communities," "communities," or simply "people," to avoid layering in distilled categories of identity that can have administrative, political impact on the people of this vast forest region.

## A Diversity of Ecosystems

The Congo Basin includes an extraordinary variety of ecosystems. The region is the world's second-largest tropical rainforest and supports more than 400 mammal species, 1000 bird, and 1200 fish species, about 300 species of reptiles and

amphibians, countless insect species, and over 10,000 plant species (Harrison et al. 2016). It is home to both species and all four subspecies of gorillas, Cross River gorillas (*Gorilla gorilla diehli*), Western lowland gorilla (*Gorilla gorilla gorilla*), Eastern lowland gorilla (*Gorilla beringei graueri*), and Mountain gorilla (*Gorilla beringei beringei*); it also shelters three subspecies of chimpanzees, Nigeria-Cameroon chimpanzee (*Pan troglodytes ellioti*), Central chimpanzee (*Pan troglodytes troglodytes*), and Eastern chimpanzee (*Pan troglodytes schweinfurthii*), and the Bonobo (*Pan paniscus*), found exclusively in DRC. Congo Basin's other notable species include forest elephants (*Loxodonta cyclotis*), which are found across the forested area (while African savanna elephants (*Loxodonta Africana*) are present at the edges of the Northern Congolian Forest-Savanna Mosaic) and the okapi (*Okapia johnstoni*).

The region's fish species form a crucial ecosystem component that are important in the wildlife food chain, nutrient cycling, and human food security. As with other taxa, many fish species are regionally endemic. Recent studies have identified at least 280 species of reptiles within the Congo Basin, including the dwarf crocodile (*Osteolaemus tetraspis*), the critically endangered slender-snouted crocodile (*Mecistops cataphractus*), various monitor lizards (*Varanus* spp.), and snakes, such as the Gabon viper (*Bitis gabonica*). Thompson (2024) compiled studies describing new species from the region (e.g., Hart et al. 2012; Tilbury and Tolley 2015; Hughes et al. 2017; Giarla et al. 2020; Freitas et al. 2022; Prozorov et al. 2023) and noted that in 10 years running from 2013 to 2023, some 742 species new to science were discovered in the Congo Basin.

Efforts to mitigate the decline in biodiversity and global poverty of the Congo Basin human populations go hand-in-hand with efforts to preserve biodiversity on which most people living in the basin depend. The most prominent aspect of these efforts consists of 199 protected areas (Fig. 4) of all categories that governments of the Congo Basin countries have set aside to protect biodiversity and to sustain human economic development.

The Basin plays a vital role in global climate regulation, biodiversity conservation, and sustaining the livelihoods of millions of people (Shapiro et al. 2021). While Dyer et al. (2017) showed how inextricably connected the Congo Basin is to both Atlantic and Indian Oceans in terms of its moisture and precipitations, recent studies also have shown the critical role this region plays in providing rainwaters that sustain other regions of Africa, such as the Ethiopian highlands (e.g., Gebrehiwot et al. 2018). While habitats within the Congo Basin are still relatively better preserved compared to many other African ecosystems, they are undergoing rapid

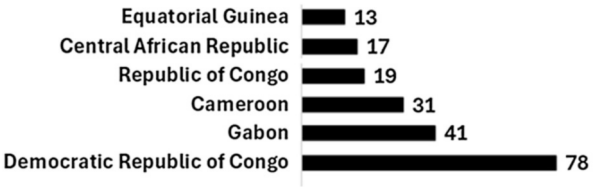



**Fig. 4** Protected areas in each country of the Congo Basin. (Data from OSFAC Database 2025)

transformation due to human activities (James et al. 2013; Fonteyn et al. 2023; Beekmann et al. 2024). Human activities that are detrimental to the Congo Basin's wealth of biodiversity and the regional sustainability are described in section "Geographic Extent of the Congo Basin" of this report.

## The Contents of This Report

This report, prepared by the Science Panel for the Congo Basin (SPCB), documents existing knowledge and identifies critical gaps in our understanding. It does not include new field data, but rather it is a meta-analysis of published materials and ongoing research on the Congo Basin, a synthesis of most available knowledge on various aspects of the Congo Basin ecosystems. The themes of this report are not restricted to the ecosystems that exist in the Congo Basin but also document aspects of human history and economics needed to understand the past, present, and future of the region.

The report assesses the knowledge the scientific community possesses on the Congo Basin in 2025 as well as knowledge gaps. However, it is more than a simple compilation of dispersed published materials. It brings together diverse knowledge from various areas of scientific inquiry and assembles them in a coherent set of new metaknowledge which we hope will help to guide future decisions that will impact the Congo Basin. The report assesses the past and present conditions of the Congo Basin; it assembles available knowledge on the long-term geological and ecological history and processes in the region and explains how that history led to the present. Beyond the history and current state of the Congo Basin, the book examines possible likely future pathways if current trends remain constant. In this perspective, the Congo Basin scientists provide scenarios to help policymakers ensure that economic activities are not detrimental to essential ecological functions and the vibrancy of the cultural diversity of the Congo Basin.

The report consists of four sections. Section One covers the long-term geological, ecological, and human history, examining the processes that have shaped the Congo Basin we encounter today. It presents biological and cultural diversities as they developed before human activity began to drive change in nature. Section Two gathers peer-reviewed knowledge on the positive and negative effects human activities have had on biological and cultural diversity and presents the current status of biodiversity in the Congo Basin. Section Three models future trajectories the Congo Basin might take given current knowledge and management options. Section Four strives to show how science can help decision-makers formulate ecologically, climatically, culturally, socially, and poverty-sensitive practices to sustain the development of the Congo Basin.

## State of Knowledge and Scientific Capacity in 2025

In writing this report, we have been able to identify gaps in knowledge, which has proven to be one of the key features of all areas covered in this book. Despite the contributions of more than 180 authors, it is clear that we are currently constructing

the future of the Congo basin on the basis of fragmented and incomplete scientific knowledge. Indeed, the broad conclusion emerging from the development of this report is that scientific capacity and knowledge in the Congo Basin remains inadequate and needs to be greatly developed in the coming decade, if the region aspires to achieve sustainable management of its resources based on sound scientific knowledge. This conclusion is in line with and further supports the conclusions of a paper published by a group of leading scientists and politicians from the region in the lead in the Glasgow Climate COP (White et al. 2021).

During the inception phase, the UN Sustainable Development Solutions Network (UNSDSN) undertook an exercise to identify scientific initiatives, networks, institutions, and scientists involved in research in the Congo Basin. An effort was undertaken to compile a list of all researchers whose names appear on traditional peer-reviewed papers featuring the Congo Basin. The place where researchers are currently based was taken to be the affiliations they included in their publications, which may have changed over time, and their main fields of expertise were noted. Using a minimum H-Index as an indication of scientific productivity, 447 researchers with an H-Index of 10 or more were identified. Slightly more than 25% of these were from the Congo Basin region (Fig. 5).

Put simply, close to 74% of researchers in the Congo Basin reside outside of the basin itself. The majority (88%) of the researchers based in the Americas (Central and Northern) are found in the USA. This can be explained by the fact that research bodies in the USA were, until a very recent past, given significantly more resources than most other countries to conduct research in the Congo Basin. Initiatives such as the Congo Basin Forest Partnership, the Central African Regional Program on Environment, and the International Branch of the US Forest Service were funded by the US Government; the access to the funds disbursed via these mechanisms made easier for US-based institutions to access and work in the Congo Basin, which may at least partially explain the predominance of the US-based organizations as hosting establishments for research on the Congo Basin.

In Europe, Belgian and French researchers, when combined, make about half (50.7%) of the researchers from outside, but when combined with UK, they become a much larger majority (ca 85%). That Belgian and French researchers make up 50.7% of the researchers is hardly surprising, given the colonial legacy of these two countries in Congo Basin. They colonized the largest area of the Congo Basin and began conducting scientific research therein at least a century ago. The surprising element of the figure is that UK comes above of both countries. In the Congo Basin itself, there are many more recorded scientists essentially in DRC and Cameroon.

Lumping things from H-index >20 as it is done above does not say much about differences between researchers based outside of the Congo Basin and scientists of the Congo Basin. Decomposing the higher tier (H-index >20) (Fig. 6) gives some important lessons about how the scientific careers evolve in the Congo Basin for the scientists of the region.

While the distribution of the top scientists is even for scientists from North America and Europe combined, a larger proportion of the scientists from the Congo Basin is packed within the bracket of H-index = 21–25. Several reasons may explain this situation; among the most important are the facts that many young

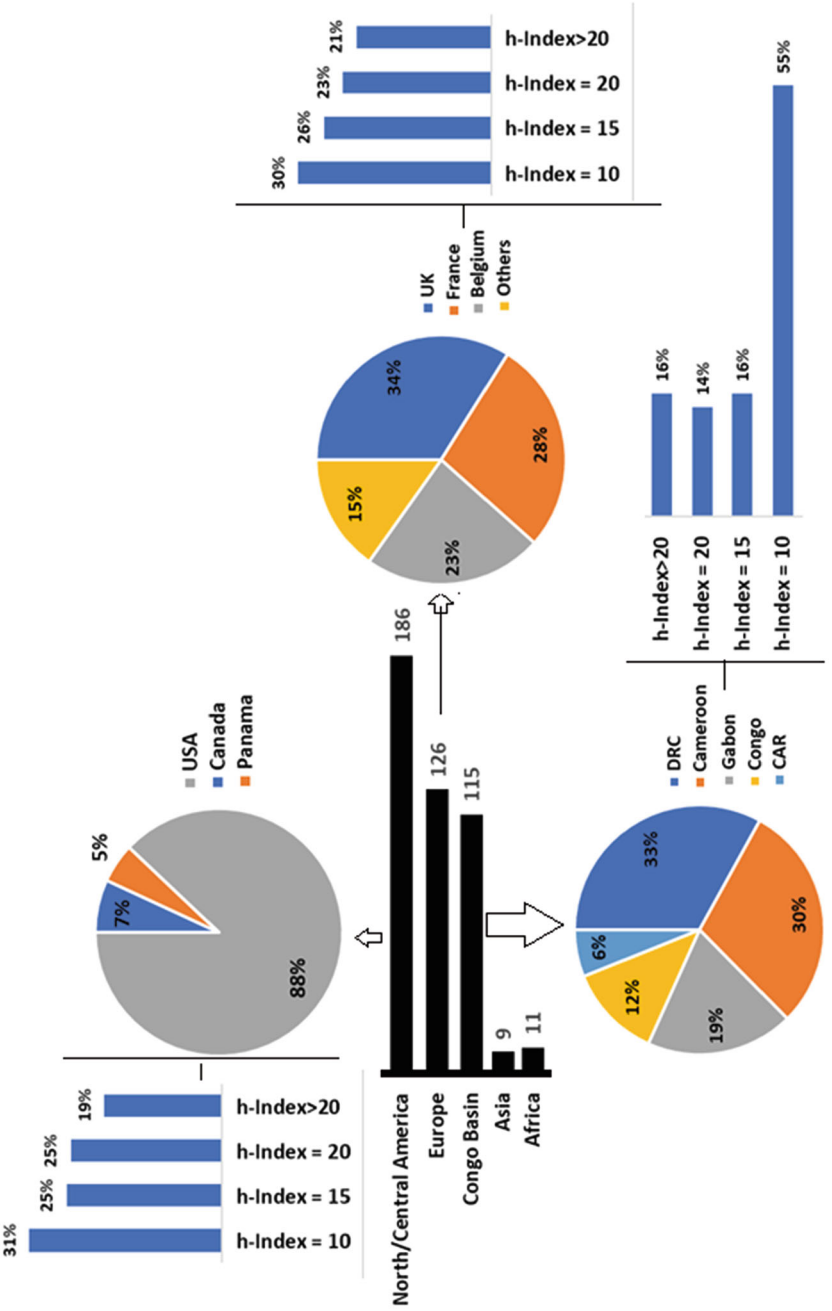



**Fig. 5** Number of scientists working in the Congo Basin (sorted by H-Index ≥10). (Source: Inogwabini 2023)

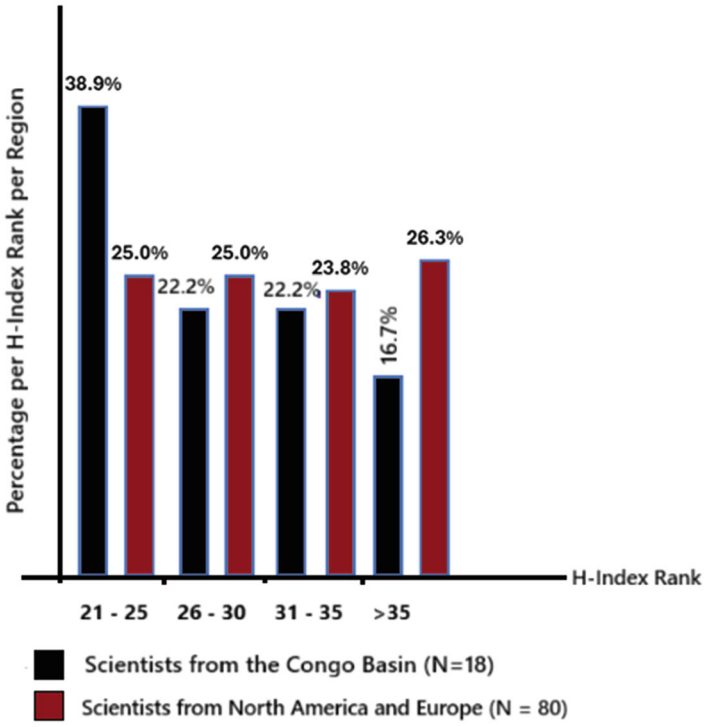



**Fig. 6** Decomposed proportions of scientists with H-Index ≥20 in the Congo Basin. (Source: Inogwabini 2023)

scientists come back with a PhD and are immediately appointed to an administrative position; lack of a formal system of postdocs, where young scientists are paid to focus on further developing their experience and getting more publications out; and very little funding for science; so it is mostly only people who manage to develop international collaborations and those that work with international biodiversity conservation structures that are successful. The other important factor is the use of English to publish in most important scientific journals, which prevents most scientists from the Congo Basin whose language is principally French to publish continuously after they graduate (although modern translation and AI tools are helping with this issue today).

While we did not conduct a similar analysis of scientists active in the Amazon, the Large-Scale Biosphere-Atmosphere Experiment in Amazonia program, known as the LBA, comprised 1700 participants, 990 of whom were Brazilians (White et al. 2021), indicating that there is probably at least an order of magnitude of more native South American scientists active in the Amazon. The UNSDSN assessment of scientific knowledge of the Congo Basin demonstrated that significant gaps in knowledge and capacity exist. It was this that motivated the creation of the Science Panel for the Congo Basin (SPCB), following on from the success of a similar

initiative in the Amazon, as well as its sister organization, the Congo Basin Science Initiative (CBSI).

It is our hope that this first effort led by the SPCB, with 180 coauthors, including a majority of Congo Basin nationals, will paint as comprehensive as possible a picture of the state of knowledge of the formative processes that have created the Congo Basin as we know it today, as well as the environmental, social, and economic changes underway that will shape it in the future. Furthermore, by identifying critical gaps in both capacity and knowledge we hope to set in motion a process of scientific endeavor and training such that future assessments will be more comprehensive and authoritative, resulting in the preservation and sustainable management of the Congo Basin, one of Earth's critical life support systems and havens of biodiversity and people.

**Competing Interest Declaration** The author(s) has no competing interests to declare that are relevant to the content of this manuscript.

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# Section I

# The Function of Congo Basin Ecosystems as a Regional Entity, and Their Influence on the Changing Earth System

# Geology and Geodynamics Evolution of the Congo Basin

2

Jean-Jacques Braun, Etienne Kadima Kabongo, Stéphane Audry, Franck Delpomdor, Damien Delvaux, Pascal Mambwe, Mathieu Nouazi, and Denis Thiéblemont

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J.-J. Braun (✉)
Géosciences Environnement Toulouse (GET), IRD–CNRS–UPS, Toulouse, France

LMI DYCOFAC, IRD–IRGM–University of Yaoundé I, Yaoundé, Cameroon
e-mail: jean-jacques.braun@ird.fr

E. Kadima Kabongo (✉)
Laboratoire de Géophysique et Géodynamique de la Lithosphère, Département de Géologie, Faculté des Sciences et Technologie, Université de Lubumbashi, Lubumbashi, Democratic Republic of the Congo
e-mail: kabongok@unilu.ac.cd

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**Abstract**

The Congo Basin is a vast intracratonic sedimentary basin in Central Africa, covering about 3.7 million km$^2$. It plays a critical role in global biodiversity and carbon storage, supporting the world's second-largest rainforest and a major tropical peat carbon reserve. This chapter offers an overview of the basin's geology and geodynamic evolution, focusing on its formation, structural features, and sedimentary processes. The basin's geological history is tied to major tectonic events, including the Pan-African orogeny (~600–500 Ma), the breakup of Gondwana, and later extensional tectonics. It is underlain by an Archean to Mesoproterozoic basement formed through successive orogenic cycles. The Congo Basin developed as an intracratonic depression influenced by rifting and subsidence, resulting in thick sedimentary accumulations from the Meso-Neoproterozoic to the Cretaceous. Geophysical data reveal a complex internal structure marked by tectonic reactivation. Lateritic covers and regolith formations provide insight into long-term weathering and erosion, important for reconstructing past climate and environmental changes. The basin is also rich in geological resources, including hydrocarbons, metals, and weathering-derived deposits of economic value. This synthesis highlights the need for an interdisciplinary approach to studying the Congo Basin, integrating geological, hydrological, and ecological dimensions. A deeper understanding of its evolution is vital for sustainable resource management, conservation, and evaluating its role in global biogeochemical cycles.

**Keywords**

Congo Craton · Intracratonic basin · Pan-African orogeny · Greenstone belts · Sedimentary sequences · Neoproterozoic belts · Regolith · Geological resources

S. Audry
Géosciences Environnement Toulouse (GET), IRD–CNRS–UPS, Toulouse, France
e-mail: stephane.audry@get.omp.eu

F. Delpomdor
Prairie Research Institute, Illinois State Geological Survey, University of Illinois Urbana-Champaign, Urbana, IL, USA
e-mail: fdelpomd@illinois.edu

D. Delvaux
Département des Sciences de la Terre, Royal Museum for Central Africa (AfricaMuseum), Tervuren, Belgium
e-mail: damien.delvaux@africamuseum.be

P. Mambwe
Département de Géologie, Faculté des Sciences et Technologie, Université de Lubumbashi, Lubumbashi, Democratic Republic of the Congo

M. Nouazi
IRGM, Yaoundé, Cameroon

D. Thiéblemont
BRGM, Orléans, Cedex 02, France

## Introduction

The Congo Basin is a vast, multifunctional region defined in three interrelated ways: as a central African rainforest with exceptional biodiversity (~1.6 million hectares); as a major watershed—second only to the Amazon—known as the Congo River Basin (CRB); and as a large intracratonic sedimentary basin rich in mineral resources, termed the Intracratonic Congo Basin (ICB). This complexity underscores the need for an interdisciplinary perspective integrating ecology, hydrology, and geology.

Geologically, the Congo Basin spans ~3.7 million km$^2$ across Central Africa, mostly within the Democratic Republic of the Congo, and lies within the stable interior of the African Plate. Despite its cratonic location, geophysical evidence suggests reactivation of ancient structures.

Its evolution has been shaped by major tectonic events. The Pan-African orogeny (~600–500 Ma) defined the basement structure, followed by extensional phases linked to Gondwana's breakup (Carboniferous–Cretaceous). The opening of the South Atlantic further influenced the basin's morphology, producing an east-to-west gradient with uplift and erosion in the east and sediment accumulation in the west.

This chapter explores the basin's geological and geodynamic evolution, emphasizing its role in shaping the Congo River system, sustaining tropical rainforest ecosystems, and storing a significant share (~28%) of global tropical peat carbon.

## Geological Diversity of the Congo Basin

### Basement Complex

#### Central Africa in the Gondwana Background

The Congo Basin is underlain and surrounded by Precambrian blocks amalgamated and stabilized during Paleoarchean to Neoproterozoic times (c. 3.5–0.54 Ga) (Fig. 1).

This basement reached is final configuration at the end of Precambrian, through the amalgamation of former cratons of Archean to Mesoproterozoic age, as the result of the Neoproterozoic Pan-African orogeny (Fig. 2).

A large piece of mainly crystalline rocks covering most of Central Africa and designated as the Congo Craton forms the main and central part of this basement (Fig. 2). It was initially part of the west Gondwana supercontinent.

The Congo Craton consists of three main Archean sub-units (De Wit and Linol 2015; Fig. 3): (i) the Southwestern Congo Craton (SWCC), uniting the Kasai-Cuango and Chaillu-Ntem blocks; (ii) the Northeastern Congo Craton (NECC), including the Bomu-Kibalian, West-Nile, and Uganda blocks; and (iii) the Central Congo Craton (CCC), buried beneath Congo Basin sediments.

These cratonic blocks form the oldest basement units of the Congo Basin, shaped by successive geological events that remobilized early cratons and accreted peripheral orogens. Post-Archean orogenic belts developed during three main periods:

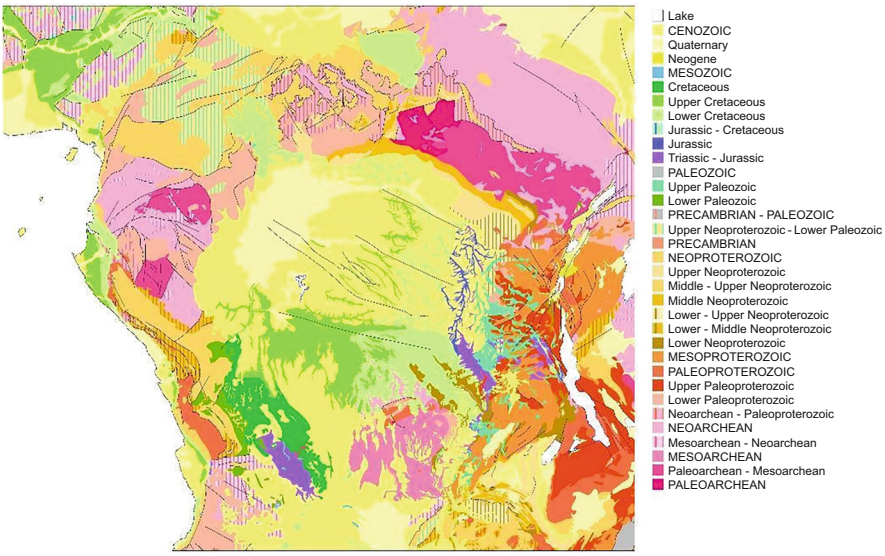



**Fig. 1** Geological map of the Congo Basin prepared from the 3rd edition of the Geological map of Africa at 1/10,000,000 scale (Thiéblemont et al. 2016). Terrains are classified according to their age. Note that the precision in the age is variable from one unit to another according to the quality of the available geochronological data. For instance, terrains reported as "Neoproterozoic" may belong to any period of this era. On the other hand, terrains reported as "Upper Neoproterozoic" are indeed Neoproterozoic but with a higher degree of resolution in the determination of their age. Note that many new ages have been published since the publication of this map that have not been considered as they would require a new edition of the map to be prepared, which is beyond the scope of this chapter

(i) the Paleoproterozoic West-Central African Belt; (ii) the Mesoproterozoic Kibaran Belt; and (iii) Neoproterozoic belts including the Lufilian (Katanga), West-Congo, and Oubanguides (Central African) systems (Fig. 3). These are detailed chronologically in the following sections.

## Archean Blocks

The underlying figure (Fig. 4), derived from the 3rd edition of the Geological map of Africa at 1:10,000,000 scale (Thiéblemont et al. 2016), classifies the Archean terrains of Central Africa according to their lithology and age on the basis of the geochronological data available before 2016.

Archean terrains are dominated by TTG-type (tonalite–trondhjemite–granodiorite) granitoids and orthogneisses, with greenstone belts as the second principal component. These belts—elongated volcanic-sedimentary units composed mainly of basic to ultrabasic rocks—contain banded iron formations (BIF), key for iron and gold exploration. While greenstone belts are intensely deformed, their metamorphism varies widely, from greenschist to granulite facies, as seen in the Chaillu–Ntem Block (Thiéblemont et al. 2009).

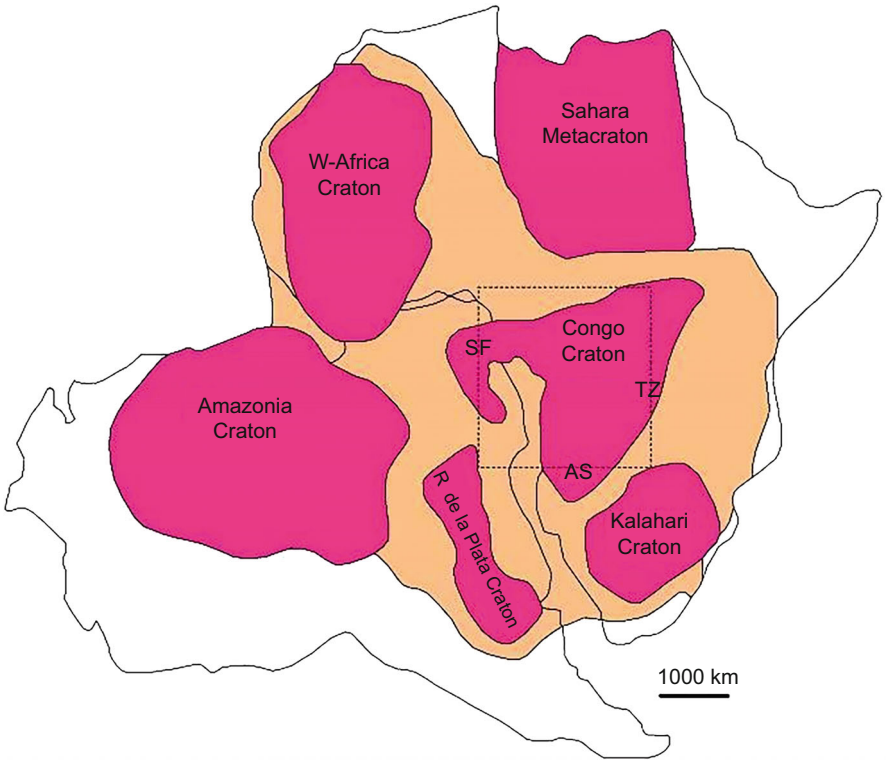



**Fig. 2** Simplified geological sketch showing the outline of western Central Africa (rectangle in the middle of the figure) relative to cratonic blocks (pink) and Pan-African belts (ocher) issued from Gondwana amalgamation. (Redrawn from Tack et al. 2024). In South America, the Congo Craton extends to the São Francisco Craton (**SF**). East of the Congo Craton, the Tanzania Craton (**TZ**) was amalgamated to the Congo Craton during Mesoproterozoic (see text). South of the Congo Craton, the Angola Shield (**AS**) stands as a southward extension of the Congo Craton of mainly Paleoproterozoic age

The nature of TTG–greenstone relationships remains debated. Greenstone belts often show lower-grade metamorphism than surrounding TTG plutons, suggesting they were emplaced atop older TTG basement. However, intrusive TTG bodies also cut across some belts (e.g., Thiéblemont et al. 2009; Akame et al. 2020). Poor geochronological resolution for greenstone lithologies further complicates interpretation.

In northeastern DRC, Archean geological mapping has seen little revision since the 1:2,000,000 national map (Lepersonne 1974; Fernandez-Alonso et al. 2016), constrained by limited pre-1980s geochronological data (Cahen et al. 1984). Two main crustal blocks are recognized (Fig. 4): The W-Nile Block—depicted as undifferentiated Neoarchean gneisses—and the NE-Congo Block, composed of a Paleoarchean Bomu Block in the west and a Paleo- to Mesoarchean domain to the east.

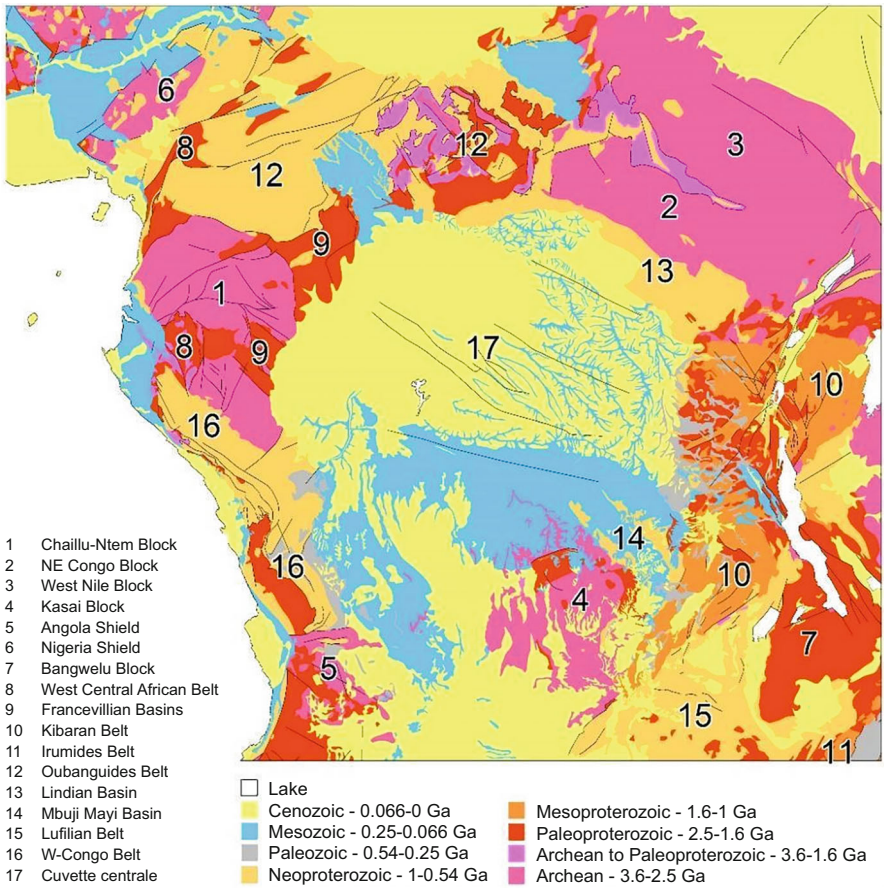



**Fig. 3** Simplified geological map of the Congo Basin prepared from the 3rd edition of the Geological map of Africa at 1/10,000,000 scale (Thiéblemont et al. 2016). Precambrian terrains are classified according to their era and the geological domains described in this note are listed and identified by numbers

Recent U-Pb zircon dating (Turnbull et al. 2021) reveals two plutonic episodes in the NE-Congo Block: a potassic-poor phase (2670–2600 Ma) and a potassic-rich phase (2600–2530 Ma). In the W-Nile Block, ages of 2720–2620 Ma have been reported, along with a single 3200 Ma gneiss, but overall geological understanding remains limited due to sparse field data.

To the west, the Chaillu–Ntem Block is well mapped in Gabon, Cameroon, and northern Congo (Thiéblemont et al. 2009; Delor et al. 2021; Blein et al. 2024), with detailed work refining the Ntem Complex in Cameroon (Akame et al. 2020). At the continental scale, three Archean units are distinguished: (i) a Paleo- to Mesoarchean TTG basement (3000–2800 Ma), (ii) Meso- to Neoarchean greenstone belts, and (iii) Neoarchean granitoids (2700–2600 Ma). Greenstone emplacement in Cameroon and Gabon is dated between 2883 ± 20 Ma and 2750 Ma (Chombong and Suh 2013).

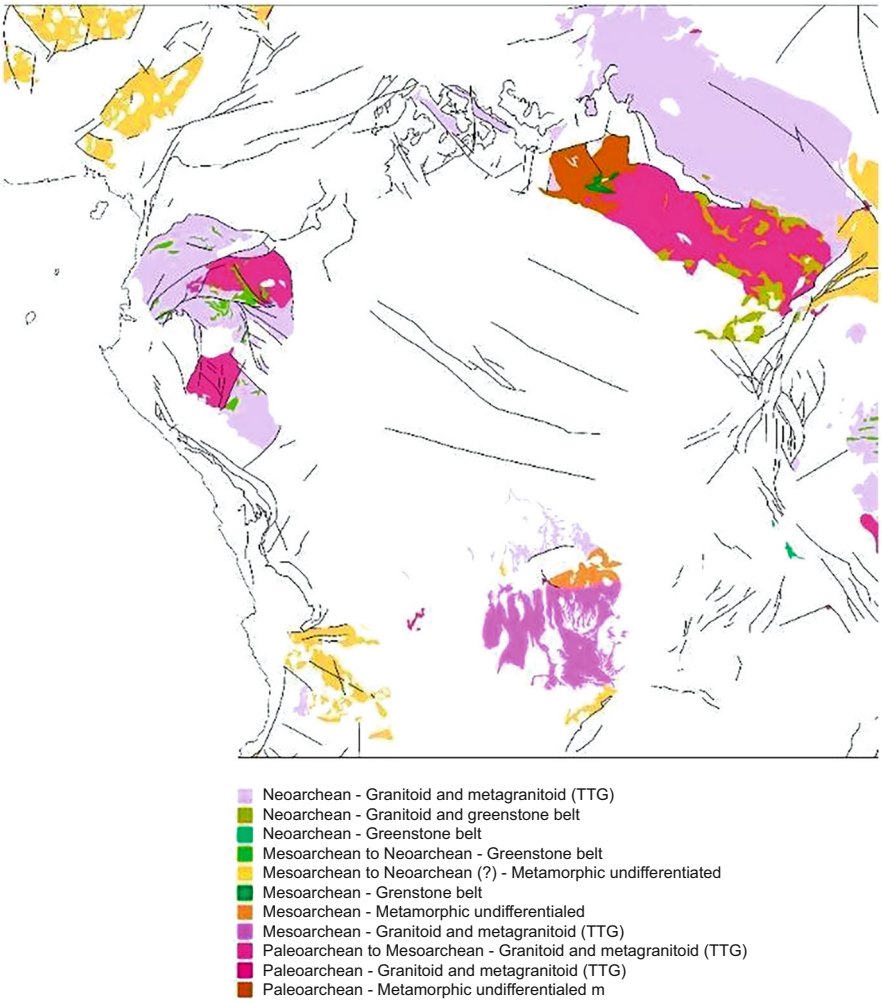



**Fig. 4** Broad lithological classification of Archean terrains localized in the Congo Craton distinguished according to their age

The Chaillu–Ntem Block's simplified evolution includes TTG basement formation, greenstone belt emplacement, and later tectono-metamorphism with granitoid intrusions.

Further south, the Kasaï Block comprises undifferentiated granito-gneissic complexes—Mesoarchean in the south, Neoarchean in the north—along with high-temperature charnockitic intrusions. These lithologies correlate with those in the Chaillu–Ntem Block, supporting the grouping into a unified Southwestern Congo Craton (De Wit and Linol 2015). No greenstone belts are yet identified in the Kasaï Block.

The Central Congo Craton, a major basement element of the Congo Basin, remains poorly constrained due to thick sedimentary cover. A possible late Neoproterozoic mobile belt (Kiri High) has been hypothesized beneath the basin (Delvaux et al. 2021; Maddaloni et al. 2021), though tomographic data (Raveloson et al. 2015) suggest the absence of Proterozoic lithosphere. In the absence of direct field data, the Central Congo Craton is inferred to host TTG-type gneisses, metavolcano-sedimentary sequences, granitoids, and mafic intrusions, similar to surrounding Archean blocks.

### Paleoproterozoic Belts

Paleoproterozoic terrains are widespread in Central Africa's Precambrian basement, primarily in two major zones (Fig. 3):

- The West-Central African Belt (WCAB)—a 3000-km-long orogenic belt extending from Angola to the Central African Republic, including associated foreland basins such as the Francevillian and Sembé-Ouesso basins
- The Bangweulu Block in the southeastern region, composed of plutonic and volcano-sedimentary rocks emplaced between 2000 and 1800 Ma (De Waele et al. 2006)

Other Paleoproterozoic exposures include the Kasaï region, near the Archean basement, and the Kibara Belt, where they form the basement beneath Mesoproterozoic cover sequences.

In the West-Central African Belt, attributed to the Eburnean orogenic cycle (~2.0 Ga), an east-west transect across Gabon reveals the following:

- Foreland basins, such as the Francevillian series, unconformably overlying the Archean Chaillu–Ntem Block. These unmetamorphosed sedimentary-volcanic sequences (up to 2.5 km thick) show limited deformation.
- A folded and metamorphosed internal domain, where Paleoproterozoic supracrustal rocks and Archean basement were buried to ~25 km, reaching P–T conditions of ~8 kb and 550 °C, with widespread granitic intrusions.
- An innermost zone comprising reworked Archean basement intruded by Eburnean granitoids (c. 2.0–2.1 Ga).

High-temperature metamorphism at ~2.5 Ga in internal zones suggests a long-lived reworking from 2500 to 2000 Ma.

Northward, the WCAB extends into Cameroon, where it forms the basement of the Pan-African Belt. Here, Archean gneisses and greenstone belts (Delor et al. 2021) experienced Paleoproterozoic metamorphism (Toteu et al. 1994), but without equivalents to the metamorphosed Paleoproterozoic series of Gabon.

However, the **foreland Francevillian basins** extend into the Republic of the Congo, Cameroon, and the Central African Republic (Rolin 1995), where deformation once linked to late Eburnean events may instead relate to the Mesoproterozoic

Kibaran orogen (Fullgraf et al. 2024). These formations typically overlie Archean TTG-type rocks, except in the CAR, where they rest on supracrustal rocks (2900–2450 Ma) intruded by Eburnean granites (~2150 Ma).

To the south, the WCAB continues along the Atlantic margin in SW-Gabon, Congo, DRC, and Angola (e.g., Callec and Fullgraf 2015), forming the crystalline basement of the Pan-African West Congo Belt (Fig. 3).

In the **Kasaï Block** (Figs. 3 and 5), despite minimal changes since the original mapping (Lepersonne 1974), three Paleoproterozoic units are distinguished:

- The Lueta Complex (~2400 Ma), a deep-seated gabbronoritic unit (~200 km long).
- The Luiza Group (~2000 Ma), resting on Lueta, composed of quartzites, micaschists, BIFs, and rare conglomerates.
- The Lulua Group (~2000 Ma), resting unconformably on Archean rocks, comprising quartzites, schists, and tholeiitic volcanics indicating rift settings.
- Eburnean granites (2135–2040 Ma) occur both along the Archean margins and as large plutons (~20–30 km wide) within the block.

These supracrustal units extend southwest into **Angola (Cuango Craton)**, where the Lovua (lower) and Upper Groups correlate with the Luiza and Lulua groups, respectively (Pereira et al. 2003). Both Kasaï and Cuango are intruded by dolerite dykes, ultramafic bodies, and diamondiferous kimberlites (Batumike et al. 2008).

Paleoproterozoic rocks also dominate the eastern Congo Basin margin, forming the basement for younger orogenic belts. The **Kibara Belt** basement may correlate with the Luiza–Lulua unit (Debruyne et al. 2019), while the **Lufilian Belt** basement likely corresponds to the Eburnean Bangweulu Block (De Waele et al. 2006).

### Mesoproterozoic Belts

The main Mesoproterozoic domain in the crystalline basement of the Congo River Basin is the Kibaran orogen (Figs. 5 and 6), a south-southwest-north-northeast-oriented belt of some 1500 km long forming the eastern flank of the basin.

The Kibara Belt comprises a thick sedimentary sequence (10,000–20,000 m; Cahen et al. 1984) divided into two groups separated by an unconformity and a decrease in metamorphism (Kokonyangi et al. 2006). Felsic volcanism accompanied deformation of the basal group, while mafic rocks and ophiolitic remnants are absent (Tack et al. 2010). The succession spans ~450 Ma (ca. 1400–950 Ma), constrained by crosscutting granites (Cahen et al. 1984), and includes four granite suites: two synorogenic and two post-orogenic. Major magmatic events occurred at ca. 1400–1350 Ma, ~1200 Ma, and ~1000–950 Ma (Tack et al. 2010). Structurally, the belt features NE-trending, west-verging folds and thrusts formed under moderate P–T conditions. Two main tectonic phases are inferred: an early northward thrusting (~1380 Ma) and a later folding phase (~1080 Ma) preceding emplacement of economically significant tin-bearing granites.

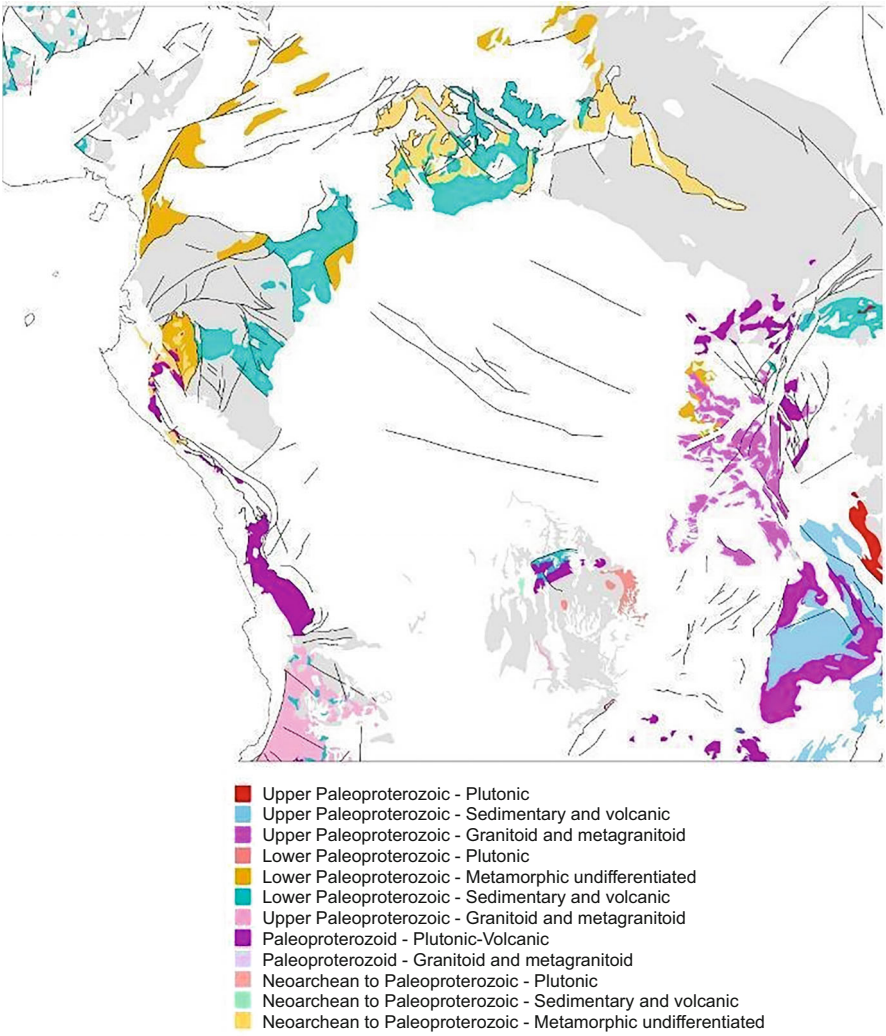



**Fig. 5** Broad lithological classification of Paleoproterozoic terrains localized in the Congo Craton distinguished according to their age. Undistinguished gray zones correspond to Archean terrains preexisting to Paleoproterozoic

## Neoproterozoic Belts

The Neoproterozoic fold belts underlying the Congo River Basin were formed in response to the Pan-African orogenic cycle, a major tectonic event that led to the amalgamation of African cratons during the assembly of West Gondwana (Fig. 2). Although these belts formed during the same overall geodynamic context, they exhibit marked differences in their structural, metamorphic, and magmatic histories, reflecting distinct geodynamic evolutions.

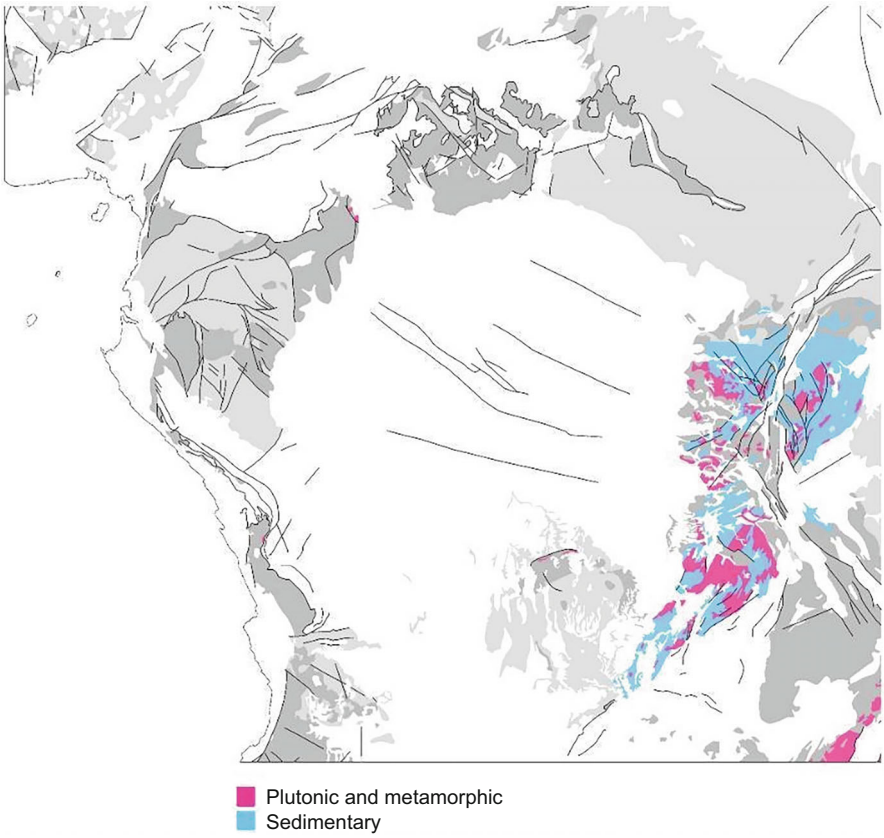



**Fig. 6** Broad lithological classification of Mesoproterozoic terrains localized in the Congo Craton distinguished according to their age. Gray zones correspond to terrains preexisting to Mesoproterozoic: light gray, Archean; medium gray, Paleoproterozoic

To the north of the basin, the Central African Orogenic Belt (CAOB)—also known as the Oubanguide Belt (Figs. 3 and 7)—extends across Cameroon and the Central African Republic. It formed as a result of the collision between the Congo Craton (south) and the Saharan Metacraton (north) (Fig. 2). This belt is characterized by high-temperature metamorphism and intense syn- to post-tectonic plutonism, indicative of a deep crustal orogenic system involving substantial crustal thickening and thermal input.

In sharp contrast, the West Congo Belt on the western margin of the basin (Figs. 3 and 6) and the Lufilian (or Katanga) Belt in the southeastern corner exhibit moderate metamorphism and lack tectonically related plutonic intrusions. These differences suggest that, while all three belts participated in the Pan-African convergence, they did so under varied tectonic settings—ranging from continental collision with deep crustal melting (CAOB) to foreland fold-and-thrust dynamics (West Congo and Lufilian Belts).

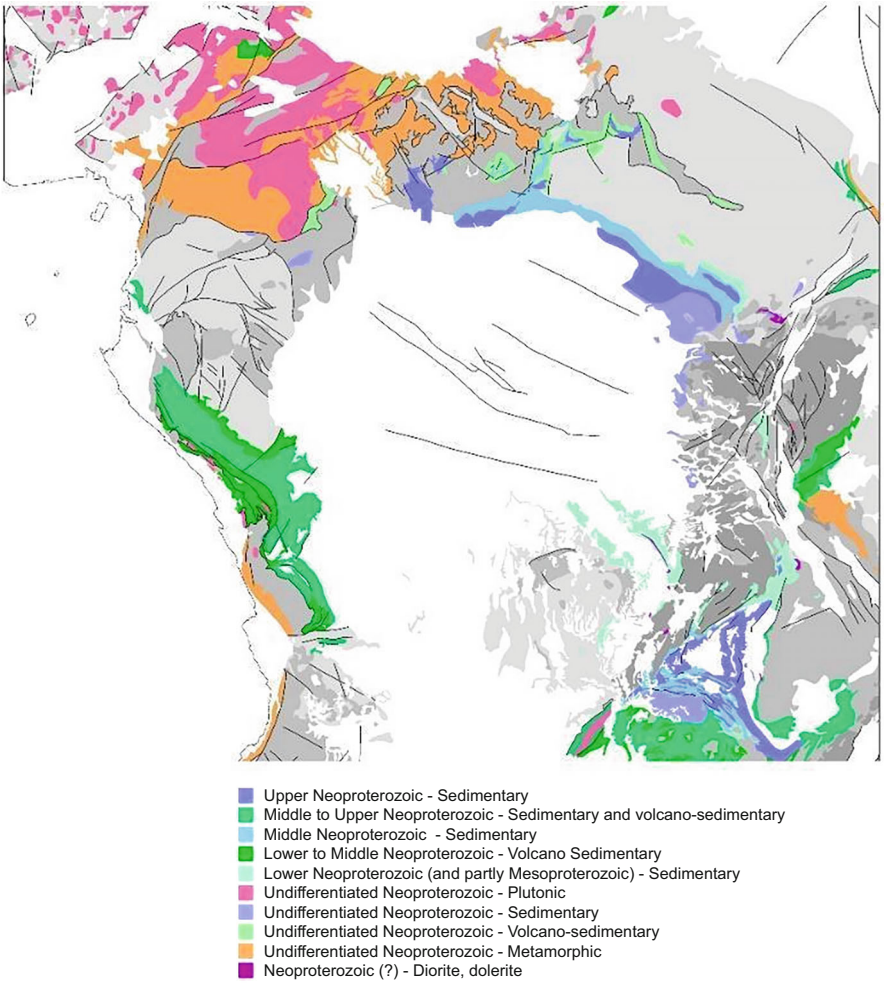



**Fig. 7** Broad lithological classification of Neoproterozoic terrains localized in Central Africa distinguished according to their age. Gray zones correspond to terrains preexisting to Neoproterozoic belts: light gray, Archean; medium gray, Paleoproterozoic; dark gray, Mesoproterozoic

The presence of high-temperature metamorphic rocks, particularly granulites, in the Central African Fold Belt and the adjacent Chaillu–Ntem Craton (Fig. 3) has been recognized since the earliest geological surveys. Initially, these rocks were attributed to a widespread Archean "basal complex" believed to extend across southern Cameroon and the Central African Republic (Mestraud 1964). However, subsequent isotopic dating confirmed that the Ntem Complex in southern Cameroon is of Mesoarchean age (Lasserre and Soba 1976).

To the north of the Chaillu–Ntem Craton, the metamorphic terranes of the Oubanguide Belt were reinterpreted as part of a Neoproterozoic orogenic system,

with geochronological data confirming high-temperature metamorphism of Neoproterozoic age (Pin and Poidevin 1987). These granulitic rocks, extending from the Central African Republic into Cameroon, reflect a crustal-scale south-verging nappe system formed during the thrusting of the Central African Fold Belt onto the Congo Craton (Rolin 1992).

Despite advances, the overall geodynamic architecture of the belt remains debated (Delor et al. 2021; Toteu et al. 2022). Key features contributing to current geodynamic models include the following:

- **Extreme metamorphic conditions**: Peak temperatures of 600–800 °C and pressures of 9–12 kbar suggest deep burial (~25–35 km) under a high thermal gradient, followed by tectonic exhumation via thrusting.
- **Prolonged magmatic activity**: A sequence of magmatic events spanning ~500 million years (c. 1050–550 Ma), reflecting long-lived crustal evolution (Delor et al. 2021).
- **Relicts of older basement**: Inliers of Archean to Paleoproterozoic rocks embedded within Neoproterozoic units suggest the presence of a **crustal block** located between the **Congo Craton** and the **Saharan Craton or Metacraton** (Toteu et al. 2022).
- **Discontinuous ophiolitic remnants**: Found along the contact between the basal Pan-African nappe and the Chaillu–Ntem Block, these suggest the former existence of a **now-closed oceanic domain** to the north (Kundu et al. 2022).
- **Arc-related magmatism**: The occurrence of volcanic rocks with **subduction-related geochemical signatures** in northwestern Cameroon supports the hypothesis of a **north-directed subduction zone** during Neoproterozoic orogenesis (Toteu et al. 2022).

Together, these elements point to a **complex, multiphase tectonic evolution**, involving ocean closure, continental collision, deep burial and exhumation, and crustal-scale thrusting—hallmarks of a **high-grade collisional orogen** formed during the Pan-African event.

The **West Congo Belt** is a prominent Neoproterozoic orogenic belt that stretches parallel to the Atlantic coast (Fig. 7). It is morphologically and structurally divided into two distinct domains. To the west, the Mayombe Massif forms a high-relief internal domain composed of deformed and metamorphosed rocks. To the east, the Niari–Nyanga Basin constitutes a low-lying foreland domain made up of slightly deformed sedimentary rocks. These sedimentary sequences rest unconformably on the Congo Craton and are locally overlain by younger sediments of the Cuvette Centrale in southern DRC and Angola.

Crystalline rocks of Eburnean age crop out at the western margin of the Mayombe Massif and are considered to represent the basement of the internal domain (Callec and Fullgraf 2015; Thiéblemont et al. 2018). At the northern boundary of the belt, the sedimentary units of the Niari–Nyanga Basin are in direct contact with cratonic rocks, suggesting that the orogen resulted from the closure of an intracontinental rift basin, with no evidence of an intervening oceanic domain (Tack et al. 2001).

The Neoproterozoic formations of the West Congo Belt are grouped within the so-called West Congo Supergroup, although a consistent lithostratigraphic framework remains elusive, particularly in the internal domain. In the Republic of the Congo and DRC, the lower part of this supergroup begins with a granitic magmatic phase dated to ~1.0 Ga, followed by clastic sediments and a thick basaltic unit (~1600–2400 m) dated to ~920 Ma. Although this unit was once interpreted as ophiolitic, more recent studies affirm a within-plate, rift-related setting (Tack et al. 2001).

Above the basalts lies a thick sequence (3000–4000 m) of volcanoclastic and felsic volcanic rocks, emplaced between 920 and 910 Ma, followed by a second basaltic phase. In Gabon, similar but less extensive magmatism occurred between ~905 and 875 Ma, contemporaneous with volcano-sedimentary formations that constitute a large part of the Mayombe Massif.

The upper part of the West Congo Supergroup is dominated by sedimentary rocks, including two glaciogenic diamictites that correspond to the Sturtian (~740 Ma) and Marinoan (~650 Ma) glaciations. These are followed by post-glacial carbonate and detrital sequences that filled the Niari–Nyanga Basin, which formed in a foreland position east of the Mayombe Massif. This infill includes a basal carbonate platform along the margins and a central clastic succession, reflecting the synclinorial structure of the basin.

Structurally, the West Congo Belt is a classic fold-and-thrust belt, with deformation intensity and metamorphic grade increasing from the external to the internal domain. In the Mayombe Massif, metamorphic conditions reached mesozonal grades (biotite–garnet paragenesis). Ar–Ar ages indicate that peak metamorphism ended before ~566 Ma (Frimmel et al. 2006). Detrital zircon and illite K–Ar ages from the upper clastic units suggest sedimentation continued into the late Neoproterozoic, during the uplift and exhumation of the Mayombe Belt, in a foreland molasse setting (Callec and Fullgraf 2015).

To the southeast of the Congo Basin lies the **Lufilian Belt**, an arcuate Neoproterozoic orogen extending across southwestern DRC and northern Zambia, and hosting the world-class Central African Copperbelt (Cailteux et al. 2005). The Lufilian Arc, to the south, curves from the Irumide Belt in the east to the Kibara Belt and Kasaï Block in the west, while the Kundelungu Plateau in the north represents a foreland basin bounded by the Bangweulu and Kibara belts (Figs. 3 and 7).

The Lufilian Belt exposes the Katanga Supergroup, a volcano-sedimentary succession 5–10 km thick, deposited atop a Paleoproterozoic basement (~2.05–1.85 Ga). The supergroup is classically divided into four groups (from oldest to youngest):

- The **Roan Group**, consisting of alternating siliciclastic, dolomitic-carbonate, and pyroclastic rocks, with minor hematite and cherts
- The **Nguba Group**, which begins with a glacial diamictite overlain by a cap carbonate and transitions to siliciclastics

- The **Kundelungu Group**, also glacially initiated and capped by carbonates, followed by fine- to medium-grained siliciclastics
- The **Biano Group**, comprising coarse-grained conglomerates, arkoses, and sandstones

Tectonically, the belt is a north-verging fold-and-thrust system, subdivided into three structural zones. The Kundelungu foreland forms a triangular, relatively undeformed northern zone. South of this, the intermediate zone displays the most complete stratigraphy of the Katanga Supergroup, deformed by thrusts and low-grade metamorphism. The internal zone, to the south, contains basement inliers and experienced higher-grade metamorphism (up to amphibolite facies), suggesting the presence of nappes that juxtapose metasediments and basement rocks (Eglinger et al. 2016).

The tectono-metamorphic evolution of the Lufilian Belt spanned ~500 million years, from early Neoproterozoic sedimentation (1000–800 Ma) through successive orogenic phases (800–500 Ma), with major deformation events between 800 and 710 Ma (Kampunzu and Cailteux 1999). Recent geothermobarometric and geochronological data reveal a Cambrian high-pressure metamorphic event (~530 Ma), with P–T conditions up to 13 kbar and 750 °C, interpreted as the result of continental collision during the terminal stages of belt evolution (Eglinger et al. 2016). This interpretation challenges the traditional view of the Lufilian Belt as a solely rift-related fold-and-thrust system and points to a more complex orogenic history involving deep crustal processes.

## Sedimentary Basins

The Congo Basin, also known as the Cuvette Centrale, developed atop the Archean-Paleoproterozoic Congo Craton, which comprises Archean blocks amalgamated by Paleoproterozoic and Mesoproterozoic belts and bordered by Neoproterozoic mobile belts (De Wit and Linol 2015).

Its internal structure was first investigated during major exploration campaigns in 1952–1956 and the 1970s, involving seismic, gravity, magnetic surveys, and four deep boreholes (up to 4560 m). These studies formed the basis for several syntheses of the basin's tectonic and stratigraphic evolution (Kadima et al. 2011; Delvaux et al. 2021).

The basin originated as a NE–SW-oriented failed rift, extending into the Kasaï region where the Mbuji-Mayi Supergroup (1174–888 Ma) crops out (Delpomdor et al. 2013; François et al. 2023). This Stenian–Tonian age is considered the initiation stage of the basin. Sedimentation ceased in the Late Cretaceous, with an estimated post-depositional erosion of ~1000 m (Sachse et al. 2012). The basement depth is estimated between 8 and 12 km based on seismic and gravity data (Maddaloni et al. 2021).

The stratigraphy is divided into four major seismo-stratigraphic sequences (Delvaux et al. 2021):

- Stenian–Tonian: Rift-related clastics and carbonates of the Mbuji-Mayi Supergroup, overlain by glacial diamictites in the south (Delpomdor et al. 2013, 2015).
- Neoproterozoic: Post-rift subsidence carbonates, clastics, evaporites, and Cryogenian siliciclastics of the Lindi Supergroup—linked to the Rodinia breakup.
- Paleozoic–Triassic: After the Pan-African orogeny, deposition of red sandstones (Banalia Group) from Cambrian to Devonian correlated with the Inkisi Group (West Congo Supergroup) and Biano Group (Katanga Supergroup) (Cailteux and De Putter 2019). A sedimentary gap occurred during the Gondwana glaciation. Sedimentation resumed in the late Carboniferous with deglacial lacustrine deposits, followed by Triassic sandstones and mudstones of the Karoo Supergroup.
- Jurassic–Cretaceous: After a major unconformity (800–1200 m depth), deposition resumed in the Late Jurassic (Kimmeridgian) with fluvial-lacustrine sediments, followed by Cretaceous calcareous sandstones, black shales, marls, limestones, and chromiferous kimberlites of the Congo Supergroup (Caillaud et al. 2017).

## Lateritic Regoliths and Landform Evolution of the Congo Basin

The Congo Basin, located within the latitudinal band of 27°N–27°S known as "Low Africa" (Doucouré and de Wit 2003), hosts one of the most extensive and well-preserved lateritic regolith mantles in the tropical belt (Burke and Gunnell 2008; Jones et al. 2013; Chardon 2023). Sustained by warm, humid climates, this deep weathering mantle underpins a vital bio-geosystem—supporting soil resources (Jones et al. 2013), groundwater (Trigg and Tshimanga 2020), mineral deposits (Milési et al. 2006), and tropical rainforests (Shapiro et al. 2021).

The complex lateritic capping system offers a unique record of regolith–landform evolution and has important implications for critical zone processes, such as land degradation, rejuvenation, and geohazards. Laterites extend from lowland interior plains on cratonic and Pan-African terrains to highland plateaus (up to 2000 m) shaped by mantle-driven uplift (Guillocheau et al. 2017; Nouazi Momo et al. 2024).

Lowland terrains, dominated by rainforest, exhibit gently rolling etchplains and pediplains formed under limited mechanical erosion and low denudation (10–200 $t/km^2/yr$) (Regard et al. 2016; Moquet et al. 2021). Here, in situ geochemical weathering and iron accumulation predominate (Temgoua et al. 2002; Bitom et al. 2004), with climate seasonality driving Holo-Pleistocene sedimentation and pedogenesis, especially in floodplains such as the Cuvette Centrale, which covers ~32% of the Congo Peneplain (Bwangoy et al. 2010; Runge et al. 2013).

In contrast, highland swells—including the Adamaoua and CAR swell (north), Mayombe and Bié swells (south), and the Albertine Rift shoulder (east)—feature dissected topographies with multi-level lateritic sequences (Guillocheau et al. 2017; Grab 2016). On the Adamaoua Plateau, five stepped lateritic surfaces between ~1300 and 800 m reflect alternating phases of weathering and incision, largely climate

driven. In the Albertine region, uplift-induced base-level drops led to rapid dissection and the development of successive regolith benches (Nouazi Momo et al. 2024).

The best-preserved surfaces—thick Al-rich laterites (bauxites and kaolinites)—form remnants of the "African Surface," a Paleogene weathering surface developed during greenhouse conditions between ~59 and 45 Ma (Guillocheau et al. 2017; Nouazi Momo et al. 2024). Its incision was associated with major geological, climatic, and topographic changes that influenced Central African biodiversity (Couvreur et al. 2020).

Beneath these bauxitic caps, subsequent post-Eocene seasonal climates promoted mechanical erosion, leading to duricrusts of varied geochemical signatures (ferricretes, Al-Fe crusts), as observed across sequences such as the Adamaoua Plateau (Burke and Gunnell 2008) (Figs. 8 and 9).

## Structural Features

The current morphology of the Congo Basin, largely inherited from the Miocene, is shaped by the Congo River watershed and enclosed by elevated morpho-tectonic provinces forming prominent plateaus (Fig. 10). These include the following:

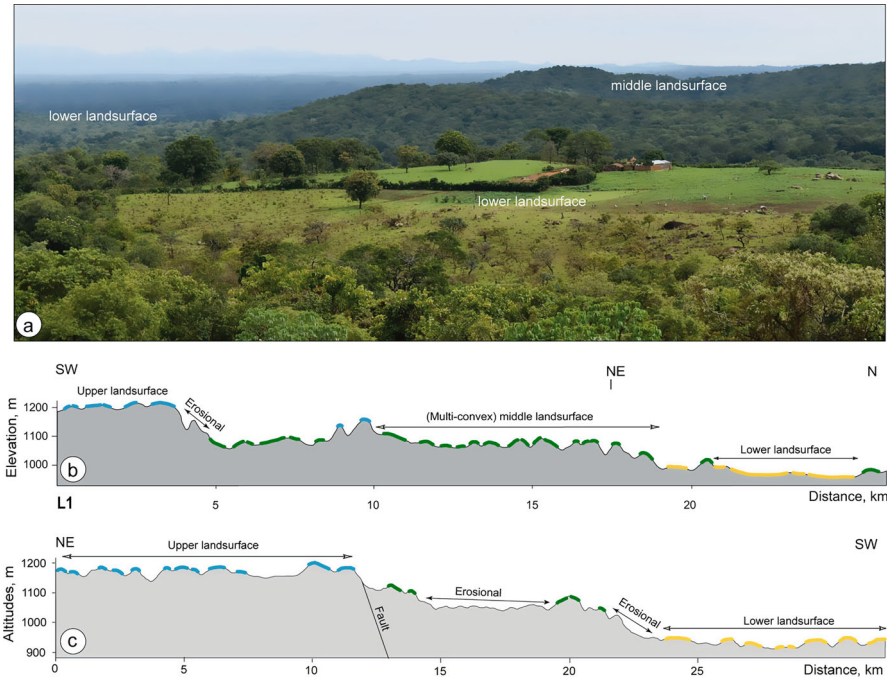



**Fig. 8** (**a**) Landscape of Adamaoua highland with the middle and the lower land surface. (**b** and **c**) Topographic sections across successive lateritic land surfaces of the Adamaoua highland over granitic basement. (Adapted from Nouazi Momo et al. 2024)

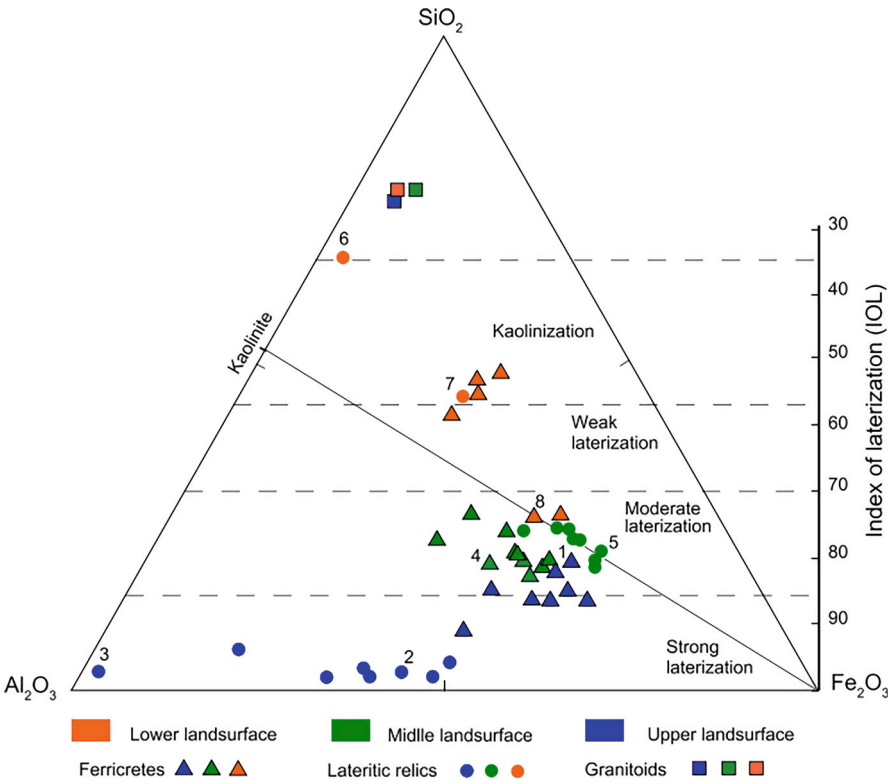



**Fig. 9** Composition diagram ($SiO_2$-$Al_2O_3$-$Fe_2O_3$) for parent rocks and lateritic duricrusts sampled in regolith of three land surfaces, including the vertical IOL. (Adapted from Nouazi Momo et al. 2024)

- The Adamalia and Congo-Nile plateaus (NW and NE)
- The East African bulge (east)
- The crustal uplifts of North Zambia, Bié, and Mayombe (SE to W) (Burke and Gunnell 2008)
- Within the basin, the central structural pattern has been inferred from drainage anomalies and lineament analyses (Deffontaines and Chorowicz 1991), revealing two main conjugate sets of structural directions:
  - Northwest–southeast lineaments: Associated with Meso- to Neoproterozoic tectonics, as seen in the Mbuji-Mayi Basin (SW) and Lindi Basin (NE).
  - Northeast–southwest structures: Linked to the Pan-African orogeny, Atlantic opening (in the west), and SREA-related deformation (in the east) (Kadima et al. 2011).

In the southern basin, an additional pattern of ESE–WNW structures overlain by NE–SW trends has been interpreted as evidence of tilted crustal blocks within the southwestern Congo Craton, reflecting complex reactivation histories.

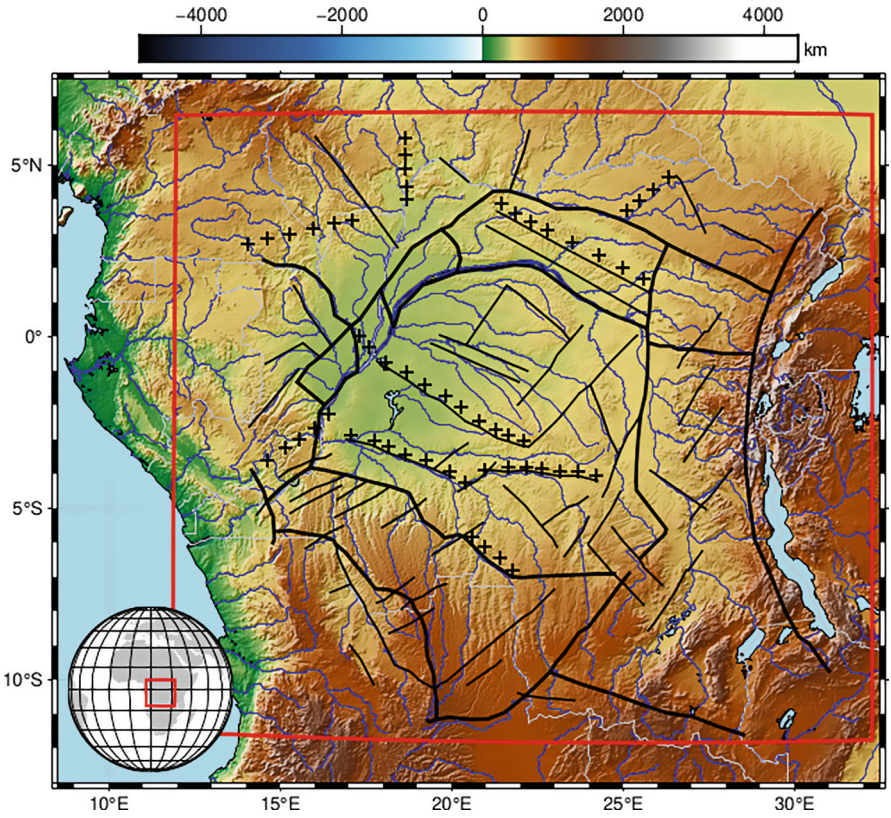



**Fig. 10** The current shape of the Congo Basin, inherited from the Miocene, is shaped by the Congo River watershed and is surrounded by morpho-tectonic provinces

## Internal and External Geodynamics of Central Africa

### Craton Formation

Among the Archean blocks of the Congo Craton, the Chaillu–Ntem Block is the best-studied, thanks to detailed national mapping at 1:200,000 scale and extensive geochronological data acquisition.

The block is dominated by a widespread TTG-type (tonalite–trondhjemite–granodiorite) basement, emplaced between ~3000 and 2850 Ma. This gray granitoid crust contains mafic enclaves, indicating early injection of mantle-derived magmas. Zircons dated up to ~3500 Ma—notably from the Bomu Complex at the western edge of the NE-Congo Block (Cahen et al. 1984)—suggest continental crust formation may have begun in the Paleoarchean.

Following TTG crust formation, several key events reshaped the block (Thiéblemont et al. 2009):

- Transformation of TTG into charnockites via high-temperature metamorphism
- Intrusion of potassic pink granites as large massifs or smaller-scale veins
- Emplacement of greenstone belts

Geochronological constraints indicate these three events occurred nearly synchronously, between ~2850 and 2800 Ma, likely during a phase of crustal extension and injection of mantle-derived magmas.

A later regional tectonometamorphic event (~2750 Ma) further deformed the greenstone belts, imposed a second metamorphic overprint on the crystalline basement, and triggered the intrusion of a second generation of potassic granites (~2700–2500 Ma).

## Proterozoic Mobile Belts and Pan-African Orogeny

### Paleoproterozoic Belts

The best-exposed Paleoproterozoic belt around the Congo Basin is the West Central African Belt (WCAB), with its full section preserved in Gabon. Its current configuration results from east-directed thrusting of metamorphic units over a foreland basin, followed by erosion.

The WCAB evolved through alternating extensional phases, marked by sedimentation, and compressional phases, responsible for deformation and metamorphism (Thiéblemont et al. 2009). It shows similarities with modern orogens, including: (i) a metamorphic-to-undeformed gradient from core to foreland (e.g., Francevillian basins), (ii) an orogenic prism of stacked nappes, and (iii) a remobilized continental block intruded by abundant granites, reflecting intense crustal exhumation.

These features support its interpretation as a continental collision zone, formed by convergence between the Congo Craton (east) and the São Francisco Craton (west) (Weber et al. 2016).

Geochronological data suggest a protracted evolution spanning ~500 million years (c. 2450–2000 Ma)—twice the duration of typical Wilson Cycle orogens. Unlike many modern orogens, the WCAB lacks preserved ophiolites and high-pressure/low-temperature metamorphic rocks (e.g., blueschists, eclogites), indicating a different tectonic style.

Paleoproterozoic units elsewhere in the Congo Basin have been reworked during later orogenies and remain poorly constrained. Nonetheless, Feybesse et al. (1998) noted structural and lithological analogies between the WCAB and Paleoproterozoic terranes of the Kasaï Block, suggesting similar tectonic histories.

### Mesoproterozoic Belt

The Kibara Belt is the only Mesoproterozoic belt identified in the Congo Basin region (Fig. 6). Its geodynamic evolution remains debated, with two contrasting models:

- A subduction–collision model involving eastward subduction of oceanic crust, largely consumed without leaving high-pressure/low-temperature metamorphic evidence (Kokonyangi et al. 2006; Debruyne et al. 2015).
- An intracontinental deformation model (Cahen et al. 1984; Tack et al. 2010) suggesting the ~1375 Ma Kibaran event reflects bimodal magmatism and crustal extension within an intracratonic setting, followed by mild compression possibly linked to distant tectonic forces.

Both models fall within a plate tectonic framework, differing chiefly in whether oceanic subduction was involved in the orogenic process.

### Neoproterozoic Belts

Despite attributed to the same orogenic cycle (Pan-African orogeny), the three belts, Central African, Lufilian, and West Congo, display strongly different features: (i) intense metamorphism, widespread syn- to post-tectonic plutonism, and crustal scale thrusting in the first case; (ii) limited magmatism but important sediment accumulation in the second; and (iii) important pre-tectonic magmatism and limited tectonic exhumation in the third.

Two of these belts are interpreted because of craton amalgamation (Fig. 3): (i) between the Congo Craton and Sahara Metacraton for the Central African Belt and (ii) between the Congo Craton and the Kalahari Craton for the Lufilian Belt. On the other hand, the West Congo Belt is attributed to the closure of an intracontinental rift.

Nevertheless, the timing is the same for the three belts, with a common interval of about 450–500 Ma from the first extensive movements (sediment deposition and/or rift-related magmatism) to the completion of convergence.

Considering the huge quantity of work so far accumulated in a recent mountain belt such as the Western Alps, and the questions still remaining open, one can infer the considerable work remaining to do on African orogens, with high-scale geological mapping being probably the first priority.

## Erosion and Chemical Weathering

### Critical Zone Observations in the Humid Tropics: Lessons from the Nyong River Basin

The critical zone (CZ)—Earth's outer layer where rock, soil, water, air, and life interact—regulates essential processes such as chemical weathering, erosion, carbon cycling, and water flow. Understanding these interactions requires long-term, integrated monitoring of hydrological and hydrochemical parameters. While critical zone observatories (CZOs) have expanded over the past 25 years, few are located

in the humid tropics, despite their importance as biodiversity hotspots, carbon reservoirs, and regions experiencing rapid land use change.

Since 1994, such monitoring has been conducted in the Nyong River basin (Cameroon), on both local (<1 $km^2$) and regional (18,500 $km^2$) scales, as part of the M-TROPICS CZO network (https://mtropics.obs-mip.fr/). Located on the periphery of the Congo Basin but within the same geological unit, this long-term dataset provides rare insight into tropical critical zone processes.

Studies based on the M-TROPICS data have the following:

- Characterized water reservoirs in humid tropical catchments (Boeglin et al. 2003; Viers et al. 1997, 2000)
- Identified key controls on chemical weathering and physical erosion, including the role of organic matter (Oliva et al. 1999) and colloids (Dupré et al. 1999)
- Quantified elemental fluxes, saprolite production, and denudation rates (Braun et al. 2005, 2012; Cary et al. 2005; Regard et al. 2016)
- Modeled streamflow partitioning among hill aquifers, marsh runoff, and groundwater (Maréchal et al. 2011)
- Identified marsh zones as hotspots of weathering activity
- Revealed non-conservative behavior of chloride in tropical rivers (Viers et al. 2001)
- Contributed to carbon budgeting and greenhouse gas emission estimates (Borges et al. 2015; Boeglin et al. 2004; Brunet et al. 2009)
- Traced Fe and Zn cycling across the soil–plant–water continuum using isotope geochemistry (Poitrasson et al. 2008; Akerman et al. 2014; Viers et al. 2007)

These datasets offer a foundation for future assessments of climatic impacts, including droughts and extreme monsoons, and for predictive modeling of elemental transport under global change scenarios (temperature shifts, monsoon variability, land use change).

However, the Nyong CZO also reveals the challenges ahead. Over the past 25 years, solute concentrations at the outlet of a small tributary have shown non-stationary behavior, likely linked to evolving hydrology and land use—underscoring the need for continued long-term monitoring.

This need is especially acute in the Congo Basin, where the paucity of hydrochemical data severely limits our ability to understand and predict the region's response to global environmental change.

## Issues, Gaps, and Challenges

### Geological Resources

The mineral and energy resources of the Congo Basin are closely linked to the geological evolution of both its sedimentary cover and Precambrian basement. Various commodities formed during distinct geological events and tectonic phases, reflecting the complex history of the basin and its surrounding cratonic margins.

Sedimentary units of the Congo Basin and ancient Karoo rifts host hydrocarbon resources such as coal and bituminous shales.

The Archean to Neoproterozoic basement encircling the basin contains a wealth of mineral deposits, including the following:

- Archean greenstone belts—gold (Au), iron (Fe)
- Early Neoproterozoic granites and pegmatites—lithium (Li), tin (Sn), tantalum (Ta), niobium (Nb), tungsten (W)
- Neoproterozoic alkaline-carbonatite intrusions—rare earth elements (REE), zirconium (Zr), niobium (Nb), phosphorus (P)
- Neoproterozoic sediments—copper (Cu), cobalt (Co), uranium (U), gold (Au)
- Carboniferous–Permian deposits—coal
- Jurassic strata—bituminous shales
- Cretaceous kimberlite pipes—diamonds, later dispersed by fluvial transport

Tectonic reactivations over geological time enhanced fluid circulation and led to the remobilization and concentration of elements such as Au, Cu, and Co. Subsequent Cenozoic weathering and denudation further oxidized sulfide deposits and produced supergene enrichment in Mn, Cu, Co, and Al.

## Hydrocarbon Resources

The hydrocarbon potential of the Congo Basin remains controversial, with past claims of prolific oil reserves largely speculative and aimed at attracting investment. Current data do not support the existence of an active, commercially viable petroleum system (Delvaux and Fernandez 2015).

Five stratigraphic levels with potential source rocks have been identified (Sachse et al. 2012; Delpomdor et al. 2018):

- Mbuji-Mayi Supergroup (Stenian–Tonian) and Alolo Subgroup (Neoproterozoic): Rich in Type I–II kerogen but now thermally overmature with low organic content; they are considered fossil systems.
- Lukuga Group (Permo-Carboniferous): Contains Type III–IV kerogen with very limited gas potential, in early maturity stage.
- Stanleyville Group (Upper Jurassic): Composed of lacustrine argillites with excellent Type I kerogen and high oil-generating capacity. However, the rocks are immature to early mature and often exposed at the surface or at shallow depths.
- Loia Group (Lower Cretaceous): Contains Type I–II kerogen, but similarly immature, with limited generation.
- Bituminous shales of the Stanleyville Formation, between Kisangani and Ubundu, exhibit high oil potential—generating up to 980 mg HC/g TOC with up to 25% organic carbon. Deposited in a lacustrine setting above the Basal Jurassic unconformity, these rocks remain thermally immature and have not been economically mined.

In contrast, **coal resources** are more substantial. Mining has occurred at the following:

- **Kalemie (Lake Tanganyika)**
- **Luena Basin (Katanga)**

where several seams at the base of the **Karoo Supergroup** (Late Carboniferous–Early Permian) were exploited for rail transport and cement production (Jamotte 1950).

## Mineral Resources

The Congo Basin is underlain and bordered by Archean to Neoproterozoic basement rocks (Kadima et al. 2011; De Wit and Linol 2015; Debruyne et al. 2019), which host world-class deposits of critical and base metals (e.g., Cu, Co, Ta, Nb, W, Sn, Fe, Mn, Ni, Au), nuclear minerals (Th, U), precious stones (diamond, ruby, sapphire, beryl), and industrial materials (mica, olivine, dolostone, limestone) (Milési et al. 2006; Thiart and de Wit 2015; Dewaele et al. 2013; Villeneuve et al. 2022; Mpaka et al. 2024). These mineralizations are linked to distinct global tectonic events and metallogenic epochs (Robb 2004).

The Central African Copperbelt, spanning southeast DRC and northern Zambia, represents the world's largest sediment-hosted Cu-Co (Ni, U) province. The region is estimated to hold over 5 billion tons of Cu ore and 6 million tons of Co ore—accounting for ~53% of global cobalt reserves. Mineralization in the Neoproterozoic–Cambrian Katanga Supergroup followed a multistage evolution, from early diagenesis (~800–650 Ma) to syn-orogenic (~560–500 Ma) and post-orogenic (~475–470 Ma) phases (Muchez et al. 2015; Mambwe et al. 2023, 2024). Cu-Pb-Zn mineralization in the Nguba and Kundelungu Groups is dated between 454 ± 14. Sulfide ores (e.g., chalcopyrite, carrollite, bornite, chalcocite, sphalerite, pyrite) underwent supergene alteration in weathering zones, producing secondary minerals such as malachite and heterogenite.

The Shinkolobwe deposit is historically the most important deposit hosted the U, and producing >50,000 t of $U_3O_8$ between 1921 and 2004 in the Katanga Supergroup. The mineralization occurred with breccias enriched in Co, Ag, Ni, Bi, and As and genetically linked to Cu-Co ores (Decrée et al. 2014). Two distinct U remobilization phases have been identified:

- Pre-orogenic phase (~876–652 Ma): Related to the opening of the Katanga Basin and early proto-oceanic rift development, with U remobilized by hydrothermal fluids during early basin evolution and early Lufilian orogeny.
- Syn-orogenic phase (~530 Ma): Linked to tectonic inversion and collision between the Congo and Kalahari cratons, further remobilizing U during orogenesis (Loris et al. 1997).

Smaller Cu-Pb-Zn occurrences are also found in the Neoproterozoic West Congo Belt of the DRC and Republic of Congo (e.g., Boko-Songho, Mfouati, Mindouli,

Mbamba-Kilenda) (Kampunzu et al. 2009). In the West Congolian and Niari basins, Cu-Pb-Zn mineralization was structurally controlled by late- to post-Pan-African faulting and later Mesozoic rifting related to the opening of the Atlantic (Dewaele et al. 2016).

Special attention is given to cassiterite, wolframite, and columbo-tantalite, which form significant placer and eluvial deposits, as well as primary mineralization in granitoids along the Mesoproterozoic Kibara Belt (e.g., Manono-Kitotolo) and Karagwe–Ankole Belt (e.g., Kalima) in the DRC (Dewaele et al. 2013). Although these deposits are currently exploited through artisanal and small-scale mining (ASM), notably, they have not yet been reported within the Congo Basin itself. Nevertheless, the presence of Archean and Proterozoic basement rocks—the known source of these ore minerals—highlights the high exploration potential for critical metals in Central Africa (Thiart and de Wit 2015).

The DRC accounts for approximately 8.3% of global tin production, with the Bisie mine (Walikale district, eastern DRC) ranking as the third-largest tin-producing mine globally (~6% of world production), containing an estimated 165,000 t of tin reserves. In the same region, the Manono deposit hosts around 220,000 t of tin ore, along with substantial lithium reserves. The Kivu Province also contains 60–80% of global niobium-tantalum (Nb-Ta) reserves.

Primary Sn–Nb–Ta–W–Li mineralization in the Kibara and Karagwe–Ankole belts is associated with pegmatites related to the differentiated G4 granite, emplaced during the early Neoproterozoic (990 ± 1–923.3 ± 8.3 Ma), while the earlier G1–G3 granites are typically barren. The mineralization occurred through mixing of magmatic and meteoric fluids, triggering oxidation and precipitation of ore minerals like cassiterite (Makutu et al. 2024). Pegmatites and related Sn–Nb–Ta–W veins were emplaced in fault zones within metasedimentary rocks and dolerites during the late Kibaran orogenic phase. Mineral deposition was driven by magmatic-hydrothermal processes, particularly fractional crystallization (Ngulube 1994; Dewaele et al. 2016).

Iron (Fe) and nickel-chromium (Ni-Cr) mineralization in Central Africa is primarily associated with Neoarchean greenstone belts and Proterozoic banded iron formations (BIFs). In the DRC, Fe and Ni-Cr are chiefly mined from the Kibalian greenstone belt (2630–2625 Ma) on the northeastern margin of the Bomu Complex, with notable deposits including Karagba, Chauffeur, and Durba for Fe; Kanda Kanda (BIF-hosted); and Nkoko for regolith-hosted Ni-Cr in the central Kasai Block (Makutu et al. 2024).

In the Republic of the Congo, the Zanaga deposit is among Africa's largest high-grade Fe ore bodies, with 2.1 billion tons at an average 33.9% Fe. The Mayoko-Moussondji deposit holds 383 million tons at 34.5% Fe, including 22.1 million tons of high-grade colluvial hematite.

Gabon's Belinga deposit is one of the most significant untapped high-grade iron ore reserves globally, with over 1 billion tons grading >60% Fe. In the DRC, major BIF-hosted deposits occur in the Upper Ituri Basin (900 Mt @ 45% Fe) and Upper Uele Basin (1350 Mt @ 68% Fe) near the headwaters of the Uele and Kibali Rivers.

Banded Iron Formations (BIFs) are the principal host rocks for Fe mineralization across the DRC, the Republic of the Congo, and Gabon, formed between 3.5 Ga and 500 Ma by chemical sedimentation, involving oxidation of $Fe^{2+}$ to $Fe^{3+}$ and precipitation of hematite and magnetite alongside quartz. The simultaneous presence of Fe and Si reflects their origin from Fe- and silica-saturated ocean water. At Zanaga, Belinga, and in the Kasai and Bomu regions, BIFs were metamorphosed into itabirite (Mpaka et al. 2024).

Though Ni-Cr deposits in the southern Congo Craton (DRC) are not currently exploited, they represent a strategic reserve. At Nkoko, mineralization is hosted in a 37-m-thick regolith profile developed over serpentinized ultramafic rocks, resulting from prolonged climate-controlled weathering. Indeed, the distribution and grade of Ni and Cr are strongly controlled by lateritic profile development (Mukonki et al. 2018).

Gabon holds over 25% of the world's manganese reserves (~150 million tons), ranking second globally after South Africa. The Moanda Mine in Haut-Ogooué Province is the country's major Mn-producing site. In the southeastern Kasaï Block of the DRC, both primary and supergene Mn deposits—such as the Kisenge deposit—occur in Paleoproterozoic metasedimentary rocks (De Putter et al. 2015). The formation of these supergene Mn ores coincides with the alteration of Cu-Co-(Pb-Zn) sulfide ores into supergene minerals (e.g., chrysocolla, malachite, heterogenite) during the Cenozoic, indicating a regional-scale weathering event across the southeastern Congo Basin.

In Gabon, five uranium deposits—Boyindzi, Mikouloungou, Mounana, Okélobondo, and Oklo—occur in the Francevillian Basin, hosted by Paleoproterozoic unmetamorphosed sandstones. Between 1961 and 1999, these deposits produced a total of ~26,000 t. Notably, the Oklo site hosted a natural nuclear fission reactor, making it unique in the geologic record.

The genesis of U mineralization in the Francevillian Basin differs markedly from that of the Katanga Basin and involves two key stages (Bankole et al. 2015; Lecomte et al. 2020):

- Diagenetic stage: Quartz dissolution and hydrofracturing during burial and uplift create the porous reservoir.
- Mineralization stage: Hydrocarbon generation from black shales leads to mixing with U-bearing brines, promoting thermochemical sulfate reduction (TSR) and co-precipitation of U, Cu, and Fe sulfides.

Additional U occurrences have also been documented in the Bakouma region of the Central African Republic, including Berbérati and Bangassou.

Gold placer deposits in the Congo Basin are primarily reported in three key areas:

- Eastern DRC, near major goldfields such as Kibalian, Karagwe–Ankole, and Kivu, with notable deposits at Kilo-Moto, Kamituga, Twangiza, Namituga, Namoya, and Imonga-Saramabila (De Groote et al. 2023).

- The Ngounié Province in Gabon, around Eteke, where ~40 t of proven alluvial gold reserves are concentrated in Quaternary sediments.
- The northeastern Gabon Mountain Complex, where gold placers are associated with world-class iron ore deposits.

At Eteke (Gabon), primary gold mineralization occurred via hydrothermal fluid migration during the Eburnean orogeny, with sulfidation and carbonation processes leading to gold precipitation along breccias, fractures, and faults (Bouchot and Feybesse 1996). In the Bomu Complex (DRC), gold is hosted in meta-conglomerates, associated with pyrite, suggesting early diagenetic precipitation during initial basin development (Mpaka et al. 2024). A subsequent fold-thrusting phase induced by tectonic inversion enhanced fluid migration and led to syn-orogenic gold precipitation. Hydrothermal remobilization and multi-phase alteration along fault zones linked to successive brittle deformation events are commonly observed. A multistage model for gold mineralization has thus been proposed for the Congo Craton, encompassing the DRC, the Republic of the Congo, Gabon, and Cameroon, with gold emplacement spanning diagenetic to syn-orogenic stages (Mpaka et al. 2024).

In the Congo Basin, diamond and gold are the primary mineral resources (De Wit and Jelsma 2015). The region hosts extensive alluvial systems formed through erosion and incision of basement terrains, particularly where kimberlite intrusions and goldfields are exposed. These processes have generated widespread placer deposits, which continue to form today within the Congo River drainage system (e.g., Kwango; Kosman et al. 2016). In addition, eluvial diamond deposits have developed in and around the subsurface zones of kimberlite bodies (De Wit and Jelsma 2015; Mukonki et al. 2022).

Two main kimberlite regions are recognized in the DRC:

- Plateau de Kundelungu (Katanga foreland, Katanga Supergroup): (1) Kimberlite pipes here are generally barren or low-grade, intruding Paleoproterozoic basement and Neoproterozoic sediments (conglomerates, sandstones, shales) and (2) radiometric dating places the intrusions in the Eocene–Oligocene, e.g., Mafwa and Katalwa (~32.3 ± 2.2 Ma) and Katuba (~23 ± 1.8 Ma) (Batumike et al. 2009, 2019).
- Kasai Province (Bakwanga Kimberlite Field): (1) These Upper Cretaceous kimberlites (~70 Ma) have high diamond potential, especially in pyroclastic facies; epiclastic facies are typically barren (Mukonki et al. 2022) and (2) the pipes intrude both Archean basement of the Kasai Craton and the overlying Neoproterozoic Mbuji-Mayi Supergroup (Batumike et al. 2009).

Diamonds formed in the upper mantle were transported by kimberlitic magma to the surface, crystallizing within ultramafic kimberlite rocks following volcanic emplacement (Robb 2004). Beyond primary deposits, widespread placer diamond deposits are documented across the southern and central DRC, northern Angola, Gabon, eastern and western Cameroon, and parts of the Central African Republic,

even in areas without known kimberlite pipes. These occurrences reflect the role of mechanical and chemical weathering, erosion of kimberlite host rocks, and subsequent transport and concentration of diamonds in alluvial systems (De Wit and Jelsma 2015). In Angola, a clear relationship exists between diamond placer distribution and the Upper Cretaceous Calonda Formation, composed of gravels, conglomerates, and sandstones, which serve as the main host for diamond-bearing placers (Pereira et al. 2003; Jelsma et al. 2004; Kjarsgaard et al. 2022).

The industrial aggregate and construction minerals such the gravels to sand materials and carbonates rocks (dolostone and limestone) constitute a second group of resource potential in the Congo Basin.

## Regolith

Early regolith mapping efforts in Central Africa (e.g., Boulvert 1976; Jamet and Rieffel 1976; Muller and Gavaud 1979; Martin 1981) in countries such as Congo, Cameroon, Gabon, and the Central African Republic provided foundational data on regional regolith distribution and characteristics. These pioneering studies—later complemented by the Africa Soil Atlas (Jones et al. 2015)—highlighted petrographical, geochemical, and pedogenetic processes shaping soil evolution across various landscapes.

While these datasets remain valuable, they are fragmented and often lack resolution, with most high-resolution regolith maps available only for localized areas. Such maps detail regolith attributes at hillslope scale (e.g., lateritization, geochemistry, texture, mineralogy), which are difficult to generalize regionally due to sparse and inconsistent coverage.

Existing maps and regolith project data—many available online or upon request—offer a useful base for both technical and non-technical applications. However, developing an interactive regolith information system for the Congo Basin will require the following:

- Integration of additional field and analytical data
- Consideration of anthropogenic impacts on regolith dynamics
- A regional coordination of efforts across political and institutional boundaries

This initiative must begin with capacity building, ensuring local expertise in standardized data acquisition, analytical methods, and data management. Despite dependence on external funding, Central African geological research institutions should collaborate under transparent national frameworks to build a unified regolith database.

Such a database would be instrumental in the following:

- Linking mineral distribution to regolith profiles under tropical conditions
- Understanding bio-geosystem dynamics
- Supporting geotechnical assessments in rapidly urbanizing environments

## Tectono-Sedimentary Evolution and Depocenter Migration of the Congo Basin

The Congo Basin is an intracratonic basin characterized by long-term subsidence and a progressive migration of its depocenter over geological time. Stratigraphic logs from four key boreholes and regional geological mapping reveal this evolution.

- The basin originated during Neoproterozoic rifting, a regional event that also initiated surrounding peripheral basins.
- Through the Cambrian to early Paleozoic, the region remained relatively flat, resulting in the coexistence of Cambrian and post-Cambrian sedimentary units across different sub-basins.
- By the end of the Paleozoic, south-eastern tilting led to the progressive deposition of Permo-Carboniferous (Karoo) and Triassic units in the south, southeast, and east of the basin.

During the mid-Mesozoic, higher sedimentation rates occurred in the central-eastern sector, depositing the following:

- Jurassic Kisangani Formation (central)
- Cretaceous Loia Group (east)

From the Oligocene onward, the SREA (Sub-Regional Epeirogenic Activity) began influencing basin filling, which became concentrated first in the central zone and more recently in the western part of the basin.

Tectonically, the basin currently lies in a compressional regime, resulting from the differential movements of the following:

- Continental rifting to the east (East African Rift System)
- Atlantic Ocean widening to the west

The shift of the active depocenter westward reflects a faster eastward extension compared to westward opening—an observation supported by the distribution of Tertiary to Recent sediments.

## Synthesis

**Multidimensional Definition of the Congo Basin**

- It is an extensive rainforest ecosystem, a major global watershed, and a significant intracratonic sedimentary basin.
- Its geological evolution has directly influenced the biodiversity and hydrology of Central Africa.

**Tectonic and Geological Evolution**

- The Congo Basin developed as a stable intracratonic depression within the African Plate.
- Major tectonic influences include the following:
  - The **Pan-African Orogeny (~600–500 Ma)**, which shaped the regional basement structure
  - The **break-up of Gondwana**, leading to extensional tectonics and subsidence
  - The **Cretaceous Rifting Event**, which further influenced basin sedimentation and structural reactivation

**Basement Geology and Structural Features**

- The basin is underlain by Precambrian cratonic blocks (Congo Craton) that amalgamated over billions of years.
- It is structurally framed by Neoproterozoic and Proterozoic mobile belts, with ancient faults periodically reactivated.
- Basement heterogeneity has implications for mineralization and fluid migration.

**Sedimentary Evolution and Basin Architecture**

- The Congo Basin contains multiple sedimentary sequences deposited from the Neoproterozoic to the Cretaceous.
- Four key stratigraphic sequences have been identified as follows:
  - Stenian–Tonian (late Mesoproterozoic-early Neoproterozoic) sediments from failed rift systems (~1.1 Ga)
  - Neoproterozoic sequences, including post-rift carbonate and evaporite deposits
  - Paleozoic-Triassic deposits, representing fluvial, deltaic, and glacial sedimentation
  - Jurassic-Cretaceous sequences, which include hydrocarbons and diamondiferous kimberlite intrusions
- The central basin is filled with sediments up to 8–12 km thick, with significant tectonic subsidence recorded.

**Geodynamic Processes and Surface Evolution**

- Long-term weathering has led to extensive lateritic covers, influencing soil fertility and mineral resource distribution.
- The landscape has been shaped by mantle-driven uplift and erosion cycles.

**Natural Resources and Economic Significance**

- **Mineral deposits**: Includes gold, diamonds, copper, cobalt, iron, lithium, niobium, tantalum, and rare earth elements.
- **Hydrocarbons**: Potential but controversial petroleum reserves exist, mainly in Mesozoic formations.

- **Regolith resources**: Extensive bauxite and lateritic deposits result from prolonged tropical weathering.
- **Groundwater and ecosystem services**: The basin plays a key role in regional hydrology and carbon sequestration.

**Challenges and Knowledge Gaps**
- Limited hydrocarbon exploration and uncertain petroleum viability.
- Poor geophysical and geological data in remote areas.
- Need for an integrated approach combining geology, climate science, and biodiversity conservation.
- Importance of long-term monitoring to assess environmental changes and geohazards.

## Conclusion

The Congo Basin represents a geologically complex and ecologically vital region that has evolved through a series of tectonic and climatic events. Its sedimentary and tectonic history holds critical insights into continental evolution, resource formation, and environmental stability. A multidisciplinary approach is essential for future research, sustainable resource management, and conservation strategies.

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# Climate of the Congo Basin

3

Wilfried Pokam, Sharon Nicholson, Derbetini Vondou, Giresse Kuete, Georges-Noel Tiersmondo Longandjo, Merlin Guenang, Romeo Tanessong, Atanas Dommo, Tamoffo Tchio, Tikeng Stella, Richard Washington, Venkataramana Sridhar, Thierry Fotso-Nguemo, and Moihamette Foupouapegnigni

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W. Pokam (✉)
Department of Physics, Higher Teacher Training College, University of Yaounde 1, Yaounde, Cameroon

Laboratory for Environmental Modelling and Atmospheric Physics, Department of Physics, Faculty of Sciences, University of Yaounde 1, Yaounde, Cameroon

S. Nicholson
Department of Earth, Ocean and Atmospheric Sciences, Florida State University, Florida, USA

D. Vondou · G. Kuete · T. Stella
Laboratory for Environmental Modelling and Atmospheric Physics, Department of Physics, Faculty of Sciences, University of Yaounde 1, Yaounde, Cameroon

G.-N. T. Longandjo
Department of Oceanography, Nansen-Tutu Centre for Environmental Marine Research, University of Cape Town, Rondebosch, South Africa

Department of Meteorology, Institut Supérieur des Techniques Appliquées, Kinshasa, Democratic Republic of Congo

M. Guenang
Department of Physics, Faculty of Science, University of Dschang, Dschang, Cameroon

Laboratory for Environmental Modelling and Atmospheric Physics, Department of Physics, Faculty of Sciences, University of Yaounde 1, Yaounde, Cameroon

R. Tanessong
Department of Meteorology and Climatology; Higher Institute of Agriculture, Forestry, Water and Environment, University of Ebolowa, Ebolowa, Cameroon

Laboratory for Environmental Modelling and Atmospheric Physics, Department of Physics, Faculty of Sciences, University of Yaounde 1, Yaounde, Cameroon

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**Abstract**

This chapter provides an overview of the current understanding of the key features of the Congo Basin's climate. It presents the main features that characterize the dynamics of air masses, the hydrological cycle, and the spatial and temporal variability of precipitation. The lower tropospheric circulation is dominated by low-level westerlies, which transport moisture from the Atlantic Ocean inland and sustain deep convection and rainfall throughout the year. This moist air converges with dry easterly air along the Congo Air Boundary, marking the southern limit of convection. Mass convergence causes ascent and warming of moist air parcels, destabilizing the atmosphere and causing upward motion. This is balanced by a mid-tropospheric easterly flow, leading to a shallow east-west overturning circulation known as the Congo Basin cell. Although the cell does not regulate rainfall, it may play a role in rainfall distribution through the position of the rainfall maximum. Mesoscale convective systems (MCSs) are the principal rainfall producers, accounting for up to 80% of annual precipitation and contribute to exceptionally high lightning activity. The hydrological cycle is strongly modulated by evapotranspiration and rainfall recycling, with evidence that local vegetation contributes significantly to atmospheric moisture supply. Regional climate variability reflects complex teleconnections with Atlantic, Indian, and Pacific Ocean sea-surface temperature, though the strength and consistency of these links remain debated. A persistent challenge is the scarcity of reliable, long-term observational data, particularly

A. Dommo
National Advanced School of Engineering, University of Yaounde 1, Yaoundé, Cameroon

School of Natural Resources, University of Missouri, Columbia, USA

T. Tchio
Climate Service Center Germany (GERICS), Helmholtz-Zentrum Hereon, Hamburg, Germany

R. Washington
School of Geography and the Environment, University of Oxford, Oxford, UK

V. Sridhar
Department of Biological Systems Engineering, Virginia Polytechnic Institute and State University, Blacksburg, VA, USA

T. Fotso-Nguemo
Climate Change Research Laboratory (CCRL), National Institute of Cartography, Yaounde, Cameroon

M. Foupouapegnigni
Laboratory for Environmental Modelling and Atmospheric Physics, Department of Physics, Faculty of Sciences, University of Yaounde 1, Yaoundé, Cameroon

rainfall and upper-air records, which undermines model validation and projection accuracy. Addressing these gaps is essential for improving climate prediction and informing sustainable management of this critical climate-regulating region.

**Keywords**

Congo Basin · Precipitation recycling · Low-level westerlies · African Easterly Jet · Congo Basin cell · Precipitation · Shallow meridional circulation

## Introduction

At the heart of the world's second-largest tropical rainforest lies the Congo River, Africa's second longest, flowing through vast floodplains, swamps, and dense forests. This river system and the surrounding rainforest exert a powerful influence not only on local weather but also on regional and global climate (Balas et al. 2007; Nicholson and Dezfuli 2013; Dezfuli and Nicholson 2013; Siam et al. 2013; Akkermans et al. 2014; Sorí et al. 2017). From the cooler, humid equatorial core to the warmer transitional zones merging with savannah grasslands, where thermal lows develop seasonally (Longandjo and Rouault 2024), the Basin encompasses diverse climatic conditions shaped by multiple land–atmosphere–ocean interactions.

Understanding the climate of the Congo Basin is critical for over 100 million people who depend on vulnerable, rain-fed agriculture and other water-related activities, making them highly sensitive to changes in rainfall magnitude and variability. Yet despite its significance, the Congo Basin remains one of the least studied tropical regions, largely due to a persistent lack of observational data (Nicholson et al. 2019).

This chapter examines the main controls of rainfall, regional and large-scale circulations, and temperature contrasts, while exploring their connections to surrounding and global systems. It establishes a foundation for understanding how the Basin's climate influences natural processes across multiple timescales and how its stability will shape environmental and socio-economic futures.

## Main Meteorological and Climate Features

### Atmospheric Circulation

This section summarizes the current state of knowledge on atmospheric circulation and the hydrological cycle. It presents the main winds that dominate atmospheric circulation from the lower to the upper atmosphere, as well as their interaction in modulating key elements of the water cycle in the Congo Basin.

#### Lower-Level Westerlies

The climate of the Congo Basin results from a complex interplay of regional and global drivers, with low-level westerlies (LLWs) emerging as a key local factor.

These winds transport moisture from the Atlantic Ocean into Central Africa, forming a crucial control on rainfall variability throughout the year (McCollum et al. 2000). Although LLWs are present year-round (Fig. 1), their intensity peaks between July and September, when they deliver the greatest moisture influx into the Basin. This period coincides with the region's second and main rainy season in September–October, during which maximum rainfall is observed (Moihamette et al. 2022).

The low-level moisture flux from the Atlantic Ocean is a primary control of the moisture content of the entire atmospheric column (Pokam et al. 2012) and in turn rainfall regime over the Congo Basin. By strengthening the zonal circulation, LLWs favor ascent through the effect of orographic uplift of the highlands next to the coastal region, leading to an increase in rainfall in these regions (Vondou et al. 2010).

Pokam et al. (2014) identified two mechanisms controlling LLW. North of 6°N, LLWs primarily result from rotational flow within a cyclonic circulation driven by the heat low of the West African monsoon. This northern branch is prominent from June to August, associated with the rainy season over the northernmost Congo Basin but diminishes during the dry season (December to February). South of 6°N, LLWs are

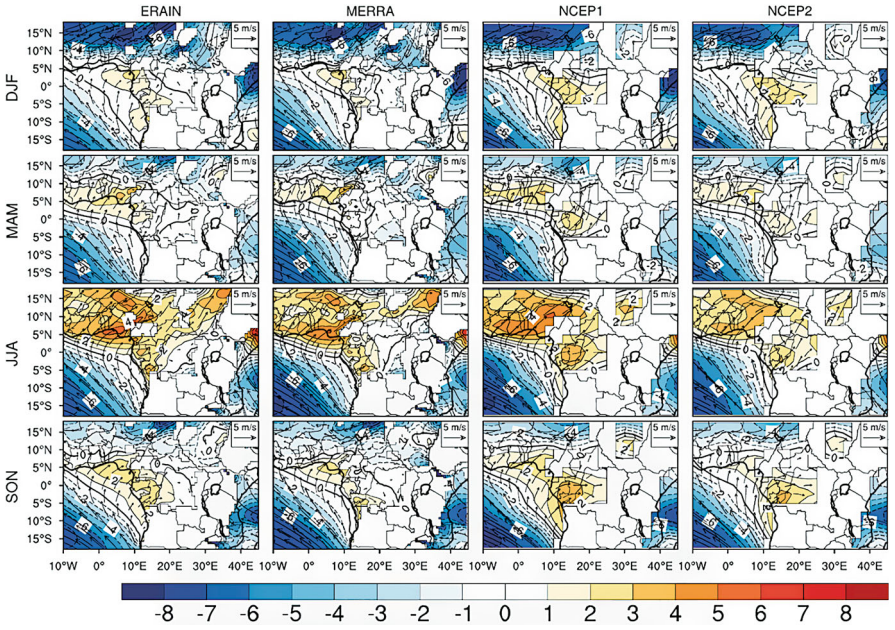



**Fig. 1** Seasonal means of the circulation at 925 hPa for (left)–(right) the European Centre for Medium-Range Weather Forecasts Interim Re-Analysis (ERAI), the Modern-Era Retrospective Analysis for Research and Applications (MERRA), the National Centers for Environmental Prediction–National Center for Atmospheric Research reanalysis (NCEP1), and the NCEP–US Department of Energy Atmospheric Model Intercomparison Project phase 2 reanalysis (NCEP2 for the period 1989–2003). Contours and shading indicate the zonal wind speed, with westerlies shown in red and easterlies in blue. The zero contour indicates the boundaries of westerlies (positive values on solid lines). Inland white areas indicate grid points below the topography. (Figure from Pokam et al. 2014)

influenced by the temperature contrast between the cooling ocean and the warming Congo Basin. The seasonal variability of LLWs in this region is primarily controlled by the strength of this heating contrast between the cooling associated with the heat sink over the southeast Atlantic Ocean due to the prevalence of stratocumulus cloud and heating driven by latent heat release by condensation within the deep convection over the Congo Basin. LLWs are weakest in MAM, strengthen in JJA, and remain stronger in SON. LLWs penetrate the continent as far as the Rift Valley Highlands, forming the lower branch of zonal overturning circulation cells over the Congo Basin.

### Shallow Overturning Circulations in the Mid–Lower Troposphere: The Congo Basin Cell and the Shallow Meridional Circulation (SMC)

Many papers (Neupane 2016; Cook and Vizy 2016; Longandjo and Rouault 2020, 2024) report that deep and shallow east-west overturning circulations coexist over the Congo basin year-round, due to its position that spans from the Sahel to southern Africa and from the Atlantic Ocean to the Rift valley highlands. In the zonal direction, the zonal surface pressure gradient—between the warm vegetated Central Africa landmass and the cold Atlantic Ocean—triggers the LLWs. These LLWs therefore constitute the lower branch of both the shallow and deep east-west overturning circulations that develop over Central Africa (Fig. 2a). While moving further into the landmass, mass convergence is produced over the Congo Air Boundary, such that it provides an upward motion to warm moist air parcels and destabilize the atmosphere over Central Africa (Fig. 2a). This forms the upward branch of both the shallow and the deep overturning cells (Fig. 2a). To balance the deep convection associated with the saturation and associated rainfall, the easterly jet forms at mid-levels as the mechanical work (Longandjo and Rouault 2020), constituting the return branch of the shallow circulation (Fig. 2a). Aloft, the convection is further reinforced to form the east-west overturning cell (Fig. 2a). Over the cold Atlantic, the subsiding branch closes the shallow circulations. This zonal shallow circulation is referred to as the Congo Basin cell. This distinct, unique, closed, counterclockwise zonal shallow overturning circulation operates throughout the year, with its maximum intensity and width in August/September and a minimum intensity and width in May (Longandjo and Rouault 2020). This shallow cell extracts the energy from the warm Central Africa landmass and advects it into the cold Atlantic Ocean. Although the Congo Basin cell does not regulate the rainfall over Central Africa, it may play a role in rainfall distribution through the position of the rainfall maximum. All this indicates that both the zonal shallow and deep east-west overturning cells coexist over Congo Basin (Fig. 2a), with the shallow mode associated with the Congo Basin cell.

On the other hand, in the meridional direction, due to the local evaporative cooling effect related to the Congo Basin rainforest, the foot of the ascending branch of meridional overturning (Hadley) cells occurs over the Sahel heat low, where the temperature is the warmest (Longandjo and Rouault 2024). This results in the distortion of the southern Hadley cell, forming its bottom-heavy structure (Fig. 2b). As a consequence, one can see that both the deep and the shallow Hadley cells are superimposed over Central Africa (Fig. 2b). The deep mode is associated

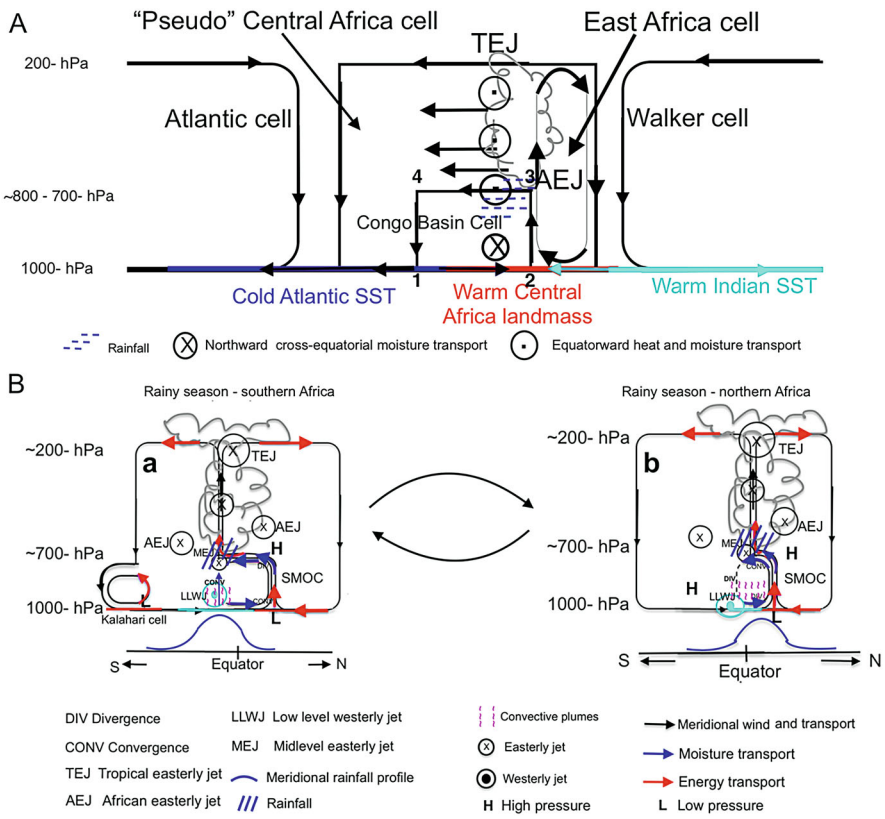



**Fig. 2** Schematic diagram representing the (**a**) longitude-height and the (**b**) latitude-height large-scale circulations over Congo Basin. (Figure adapted from Longandjo and Rouault 2020, 2024)

with the poleward transport of atmospheric energy at the upper troposphere (Fig. 2b). The shallow mode is characterized by a shallow meridional circulation, with its moisture transport vanishing and converging in the mid-troposphere rather than the lower troposphere (Longandjo and Rouault 2024). However, Zhai and Boos (2017) found that this SMC may limit the rainfall amount by drying up the mid-troposphere through the equatorward advection of dry air into the convective region. This SMC can strengthen or shrink should the convective region and its associated rainfall maximum be in the southern or northern hemisphere (Fig. 2b).

## African Easterly Jet

African Easterly Jets (AEJs) are major mid-tropospheric climate features located over the African continent (Cook 1999; Adebiyi and Zuidema 2016; Kuete et al. 2019) composed of the North African Easterly Jet (AEJ-N) and the South African Easterly Jet (AEJ-S). AEJ-N is discernible year-round at 700 hPa with a meridional migration ranging from 3°N in January to around 12°N in August, while AEJ-S appears from September to November at 600 hPa and has its axis around 8°S

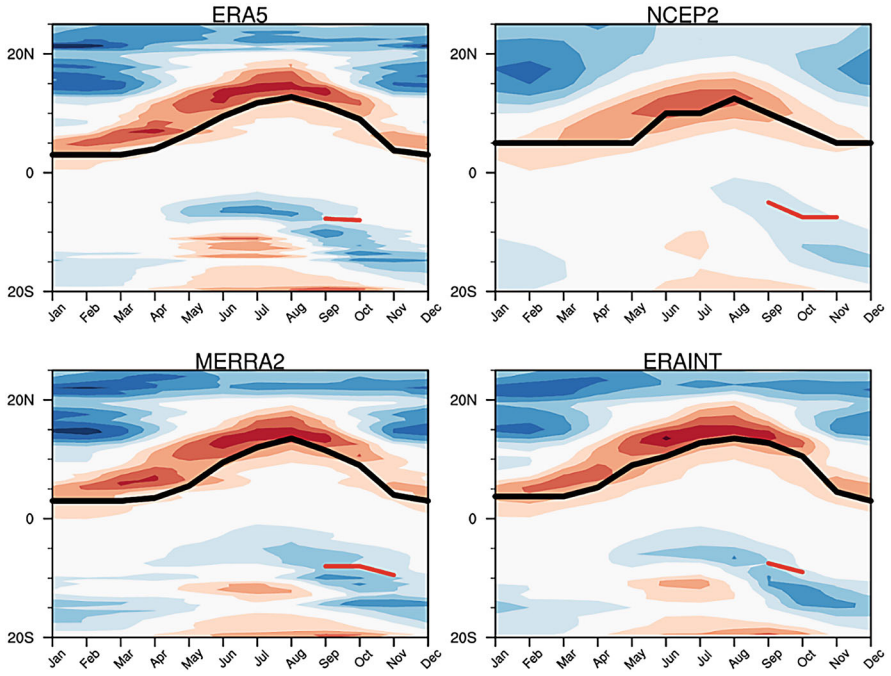



**Fig. 3** Latitude/time evolution of the 925 hPa surface temperature gradient (shading) with overlay mean locations of AEJ components core. The black solid line in the north represents AEJ-N and the red solid line in the south is the AEJ-S. All variables are averaged between 12°E and 24°E. (Figure from Kuete et al. 2019)

(Fig. 3). Studies have highlighted the critical role of both AEJ components in shaping the climate of the Congo Basin. During the September–November rainy season, when the highest rainfall amount is recorded over the Congo, these jets play a key role in the region's convective rainfall regime by influencing mid-tropospheric circulation and moisture advection (Pokam et al. 2012; Dyer et al. 2017). The AEJ components also contribute to interannual rainfall variability over the Congo region, with research indicating that wetter years are typically associated with a weaker AEJ, while drier years correspond to a stronger jet (Nicholson and Dezfuli 2013; Dezfuli and Nicholson 2013). Moreover, the jet-streak-like circulation associated with the AEJ-S creates strong convergence that contributes to the intense storms occurring in the Congo Basin (Jackson et al. 2009).

The strength and location of the AEJ components are determined by a complex interplay of factors, with the atmospheric baroclinic thermal structure characterized by temperature gradients and differential heating being a key component (Nicholson and Grist 2003). This thermal structure varies significantly across Africa, influencing the AEJ-N through the strong and positive temperature contrast between the hot, arid Sahara and the more humid Congo Basin, while the AEJ-S is shaped by the negative thermal differences between the semi-arid Kalahari and the sub-humid Congo region (Kuete et al. 2019).

The AEJ-S has received less attention than AEJ-N. Kuete et al. (2019) demonstrate that AEJ-S is dominated by rotational circulation and is maintained by a mid-level high that forms over the Kalahari region from September to November. At the core of this high, anticyclonic circulation is induced and maintained, AEJ-S is located at the northern flank of the high. The AEJ-S is influenced by the Kalahari thermal low, which is characterized by intense surface heating, associated uplift, and dry convection (Attwood et al. 2024). This dry convection is superimposed by upper-level subsidence, leading to mid-level divergence. From September to November, strong positive vorticity reinforces this mid-level divergence circulation. An analysis of the atmospheric energetics shows that the Coriolis divergence is less pronounced in the AEJ-S region than in the AEJ-N region. Consequently, the strength of the AEJ-N is mainly determined by other factors, such as the well-developed North African divergence centers over the Chad-Sudan region.

A significant difference between the dynamics of the AEJ-N and AEJ-S over the Congo region resides in the shape of the African continent. As the southern component region is relatively smaller compared with its northern counterpart, less surface instability is produced. In Northwest Congo, the AEJ-N generates synoptic atmospheric disturbances known as African Easterly Waves, which modulate the convection and, in turn, rainfall regime, in that region, and Atlantic tropical cyclone genesis (Fischer et al. 2024). But, the AEJ-S is less likely to exhibit significant easterly wave patterns. However, the AEJ-S does respond to extratropical westerly waves crossing southern Africa and which are able to disrupt the strong AEJ-S and in turn modulates the Congo rainfall during SON (Kuete et al. 2019).

### Tropical Easterly Jet

The Tropical Easterly Jet is a key feature of the general atmospheric circulation in the tropics. The jet is located in the upper-troposphere (150–200) hPa over Africa and the Asian sector, reaching its core speed around 35–40 $m.s^{-1}$ between July and September (Nicholson and Klotter 2020). It owes its existence to the temperature gradient between the warm land masses of Asia and Africa and the colder Indian Ocean (Chen and Yen 1993). Although the Tropical Easterly Jet is an important component of the general circulation, studies of this jet and its influence on climate in Africa, particularly its influence on rainfall variability in equatorial Africa and the Congo Basin, are very limited. Its influence on rainfall in equatorial Africa is generally associated with other climatic features of the regional circulation, such as the African Easterly Jet and the Low-level Westerly circulation (Dezfuli and Nicholson 2013; Nicholson and Dezfuli 2013). The jet regulates rainfall over equatorial Africa through upper tropospheric divergence, which in turn generates thunderstorms and convective systems (Nicholson 2018). This upper tropospheric divergence is important because it is associated with low-level moisture convergence from the Atlantic westerlies, thereby controlling rainfall seasonality. Intensification of the TEJ has also been observed during wet years in equatorial Africa (Dezfuli and Nicholson 2013).

## Congo Air Boundary

From August to November, the southern edge of the Central African rain belt is characterized by an extreme gradient in near-surface dew point temperature along a southwest to northeast (Fig. 4) oriented on a line known as the Congo Air Boundary (CAB). Moist, tropical air with dew points typically in the low 20 °C advected by northerly flow converges with the dry easterly flow where the dew point is near zero. The convergence line typically lies on the high ground of the Katanga plateau along the Zambian-DRC border (Howard and Washington 2019). It curves northward along the Albertine Rift, suggesting that topography has an important effect on the line. The CAB is an example of a feature that has erroneously been identified as the Inter Tropical Convergence Zone, a term which is not appropriate to the circulation characteristics of Africa (Nicholson 2018). The CAB demarcates the southern limit of Congo Basin convection. At intraseasonal timescales, the CAB is not a steady-state feature (Torrance 1979; Taljaard 1986). Prior to the onset of tropical rains in southern Africa, the CAB breaks down several times, before reforming after 2–3 days. The breakdown has been traced to breaking Rossby waves in the circumpolar westerlies over southern Africa (Knight and Washington 2024). By December the CAB is no longer evident as a circulation feature. Future drying trends projected for the southern edge of the tropical rain belt have been traced to a later breakdown of the CAB in the seasonal cycle (Howard and Washington 2020).

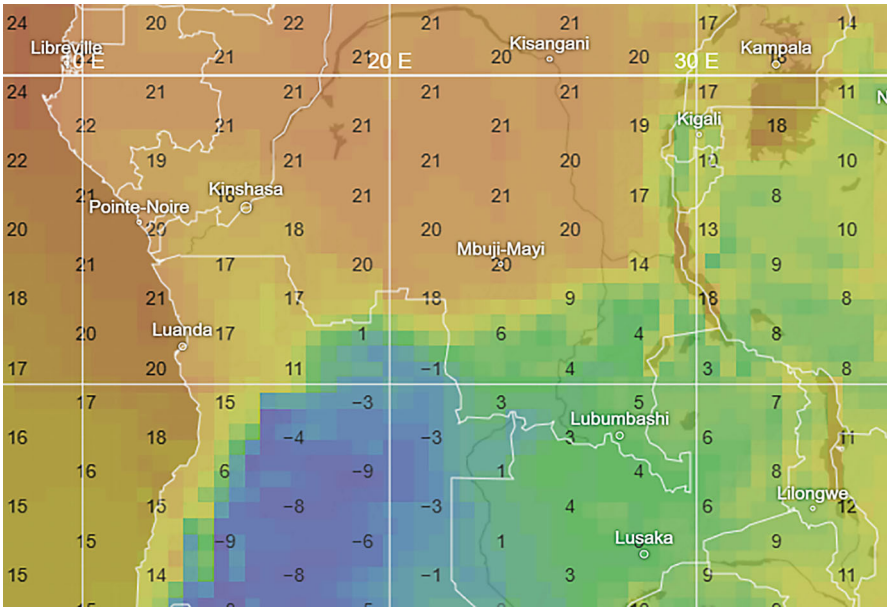



**Fig. 4** Surface dew point temperatures at 0300 UTC on 5 September 2024 from the fifth-generation European Centre for Medium-Range Weather Forecasts reanalysis (ERA 5)

## Hydrological Budget

### Evapotranspiration and Precipitation Recycling

Across the Congo Basin, the variability in evapotranspiration (ET) is influenced by factors such as forest density, land cover changes, and seasonal climatic conditions. During the wet season, higher ET rates are typically observed, which significantly contribute to local rainfall patterns and sustain the forest's hydrological cycle. Conversely, in the dry season, reduced ET levels result in a lower recycling rate, making the region more dependent on external moisture sources, such as the Atlantic and Indian Oceans.

The Central African forest is predominantly concentrated in the equatorial part of the Congo Basin (Burnett et al. 2020) and plays a significant role in supplying the region with a substantial amount of water vapor (Worden et al. 2021) through the process of ET. It can be reasonably inferred that rainfall recycling makes a significant contribution to the total amount of local rainfall.

Over the last few decades, many studies have been carried out to assess moisture recycling and its role in the hydrological cycle of the Congo Basin. The first attempt to assess moisture recycling in a regional framework was made by Shem (2006) using the CAM3/CLM3 coupled climate models and found a recycling rate between 15% and 20%. Pokam et al. (2012) made the first assessment of the spatial and temporal variation of moisture recycling for the Congo Basin. They used the general 2D bulk recycling model and found a recycling rate of 38%. Following this study, research on the contribution of recycling to total precipitation has intensified. Dyer et al. (2017) used the water tagging capability of the National Center for Atmospheric Research's Community Earth System Model version 1.2 (CESM1.2) to assess the impact of different moisture sources on the water cycle in Central Africa. They found a recycling rate of more than 24%. Meanwhile, Sorí et al. (2017), who also assessed moisture sources in the Congo River Basin, used the Lagrangian model FLEXPART and found that recycling provides more than 50% of the total water vapor contributing to local rainfall. Applying the same method to a study of the spatiotemporal variability of droughts in the same region, Sorí et al. (2022) confirmed the key role of recycling in the basin's water balance. They found that the region contributed almost 60% of the total water vapor that is locally precipitated. More recently, Worden et al. (2024) assessed the net surface water flux using the water balance approach and found a recycling rate of over 70%. This provides further evidence for the substantial recycling of moisture in the Congo Basin. The sensitivity of the results to the models and data used to perform the water balance simulation could probably explain the significant differences in the recycling rates observed in each of these studies.

Burnett et al. (2020) employed the water balance method to estimate evapotranspiration in the Congo Basin. They observed a strong correlation between the seasonal cycles of ET and precipitation. Nevertheless, a notable discrepancy was identified in the seasonal patterns of ET and rainfall. In contrast to the expected peak during the September to November season, ET exhibited a maximum in the March to May season. This discrepancy in the seasonal characteristics of these two key water

fluxes was also been observed by Crowhurst et al. (2020). Indeed, they identified tree transpiration as a significant contributor to the total ET in the Congo Basin. Transpiration accounts for a large portion of the seasonal variability, driving the differences in ET rates between the March–May and September–November seasons. Furthermore, they found that factors like forest cover, tree species, and soil moisture significantly influence transpiration rates. This highlights the critical role of vegetation in shaping ET dynamics and indicates that deforestation or land use changes could substantially alter the seasonal water cycle, potentially affecting regional climate patterns and water availability.

In a related study, Worden et al. (2021) found that the deficit in ET moisture supplied during the second rainy season in comparison to the first is a consequence of increased moisture advection from the ocean during the September to November rainy season. This seasonal shift suggests that while local ET is critical for maintaining atmospheric moisture, external moisture sources become increasingly important later in the year, influencing the timing and distribution of rainfall across the region.

### Atmospheric Moisture Convergence

The seasonal cycle of the atmospheric moisture flux convergence is strongly correlated with that of precipitation over the Congo Basin (Cook and Vizy 2022). Cook and Vizy (2022) and Longandjo and Rouault (2024) showed that precipitation does not follow a bimodal cycle in the North-equatorial (0–10°N, 7–33°E) or in South-equatorial Central Africa (0–15°S, 7–33°E)—instead, the bimodal annual cycle results from averaging over an area spanning the equator. Nicholson (2022) and Mba et al. (2022) also argued the existence of a bimodal rainfall regime over the equatorial band of 2°N–2°S. Indeed, North Central Africa features a rainy season spanning from April to October and dry conditions for the remainder of the year. During the wet season, moisture convergence predominates in the region, with monthly precipitation amounts exceeding the monthly total evaporation rate. Conversely, dry conditions feature moisture divergence with monthly rainfall amounts smaller than the monthly total evaporation rate. South Central Africa features wetness from September to April and dryness for the remainder of the year, in association with patterns of moisture convergence.

Cook and Vizy (2022) decomposed atmospheric moisture flux convergence into convergence and advection terms. They found that throughout the Congo Basin, the convergence term is the main conveyor of atmospheric moisture flux convergence during rainfall peaks. In April, moisture convergence north of Central Africa (5–10°N) is sourced from the Central Congo Basin, in association with strong low level ($\leq$900 hPa) meridional northward moisture transport. Western convergence (~15°E) originates from the Atlantic Ocean and southerlies. In the upper layers (800–500 hPa), moisture convergence caps low-level divergence, driven by meridional moisture transport. In October, zonal low-level moisture convergence from west to east crosses the basin and characterizes the region. Local moisture convergence enhances and differentiates between the wetter character of October

compared to April. The upper layer of October's moisture convergence and transport are similar to those of April.

It is now clearly established that the Inter Tropical Convergence Zone paradigm is not the driver of rainfall seasonality in Central Africa (Nicholson 2018). Longandjo and Rouault (2024) highlighted the controlling role of a shallow meridional overturning circulation on the alternation of seasons. They showed that mid-layer moisture divergence overlays low-level moisture convergence over the Sahel throughout the year. However, the dry season over the Sahel from November to March is associated with westward advection of dry air that balances low-level moisture convergence. Simultaneously in North Central Africa, low-level moisture convergence is stronger than mid-tropospheric divergence, thereby triggering shallow convection that induces low rainfall. Over South-Central Africa where it is the rainy season, the shallow meridional overturning circulation expands and induces atmospheric instability, thereby deepening the convection through rising moist air which feeds mesoscale convective systems. When it is the rainy season over North-Central Africa from April to October, the southern component of the shallow meridional overturning circulation displaces northward across the equator and causes low-level moisture divergence over Central Africa. During this time, the return outflow of the shallow meridional overturning circulation induces important mid-tropospheric moisture convergence, triggering intense convection. The wet season over the Sahel from June to September features a shrunk shallow meridional overturning circulation in association with strong low-level moisture convergence. Subsequently, surface warm moist air uplifting is blocked by mid-layer moisture divergence through mid-tropospheric horizontal advection, thereby limiting the convection. Although the same situation applies to South-Central Africa, the mid-tropospheric moisture convergence is too weak to initiate convective rainfall, leading to low rainfall.

Moisture convergence feeding strong convection mainly originates from the mid-troposphere over Central Africa, in association with a top-heavy structure of the vertical velocity. This moisture convergence is the main conveyance of the total moisture flux convergence over convective regions, and its seasonality mimics that of the shallow meridional overturning circulation. Shallow convection is associated with moisture advection and its seasonality is driven by the zonal circulation.

## Convective Processes

Convection is a dominant process over the Congo Basin. It is essentially a cooling mechanism to deal with the large, positive net radiation budget of the tropics and is also the key rainfall producing process. Convective Available Potential Energy, which is proportional to the kinetic energy that drives updrafts in thunderstorms, is typically non-zero in nearly all parts of the basin during the rainfall seasons (Fig. 5), reflecting the high values of near surface specific humidity and temperature. Not surprisingly, the basin is one of three key regions of tropical diabatic heating (Webster 1983), the other two being the Amazon and the warm-pool region of the West Pacific. In other words, the Congo Basin is one of three key areas that drives the tropical and subtropical circulation system of the planet. The intensity of convection

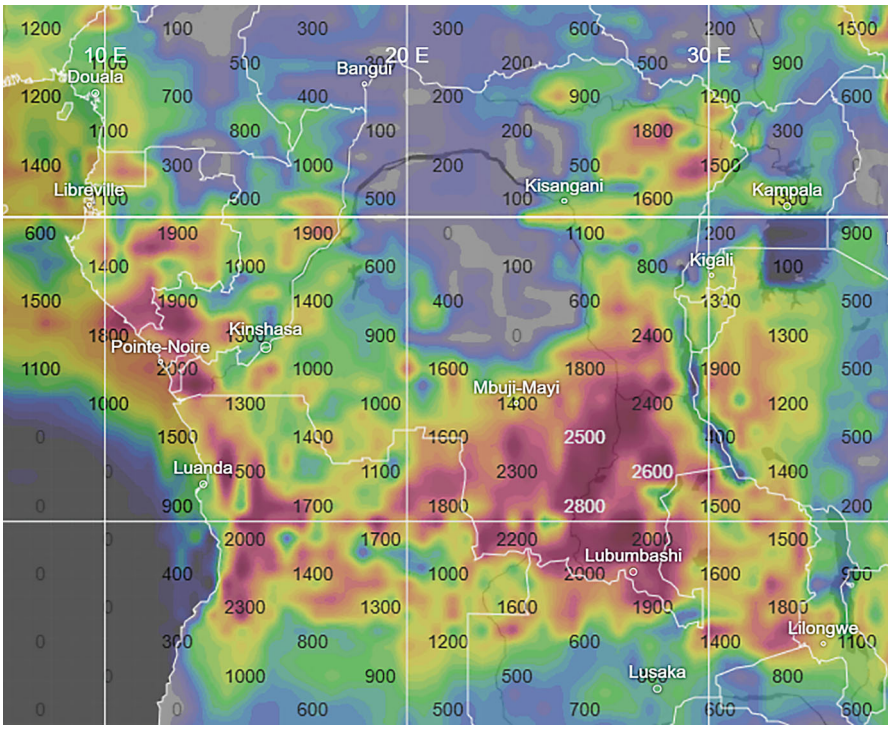



**Fig. 5** Convective Available Potential Energy in $J.kg^{-1}$ at 1500 UTC on 6 April 2024 from Global Forecast System. Purple indicates low Convective Available Potential Energy values while dark red indicates high values

is reflected in the fact that 50% of the planet's top 500 locations for highest lightning frequency occur in the basin (Albrecht et al. 2016).

A key characteristic of Congo Basin convection is the extremely high frequency of occurrence of mesoscale convective systems (MCSs) (Nesbitt and Zipser 2003; Jackson et al. 2009). MCSs produce between 70% (Nesbitt et al. 2006) and 80% (Andrews et al. 2024) of the basin's rainfall. Whereas thunderstorms tend to cover tens of kilometers and last for about 2 hours, MCSs cover hundreds of kilometers with a duration of longer than 6 hours. They are extremely efficient forms of energy cycling.

MCS initiation occurs frequently downwind of topographical features, for example, the highlands west of the lee of the Great Rift Valley, the Cameroon highlands, and the Lake Victoria region, with a peak between 1500 and 1800 UTC (Laing et al. 2011; Hartman 2021; Tikeng et al. 2024). Storms have an east to west phase speed of 8–16 $m.s^{-1}$ (Laing et al. 2011). Rainfall peaks at 1500 UTC (Andrews et al. 2024).

Rainfall associated with MCSs also exhibits a diurnal cycle, with a significant peak at 15:00 UTC (Andrews et al. 2024). As the systems expand, stratiform rain begins to dominate over convective rain (Jackson et al. 2009), with a secondary rainfall peak at around 04:00 UTC, though this varies seasonally and meridionally. A minimum in activity occurs at 10.00 (Andrews et al. 2024).

## Clouds

Over Western Central Africa (WCA) bounded by 5°S–8°N and 8°E–25°E, Vondou (2012) found that the peak at 220 K (Fig. 6) corresponding to deep convective clouds is observed at 16LST with the lowest percentage. During nighttime, a second peak is observed at 265 K corresponding to mid-level clouds (Fig. 6) followed by a decreasing underpinning a transition toward clear sky. Overall, all the graph exhibit peak between 280 K and 300 K, therefore a threshold of 285 K was proposed to detect cloudy pixels.

The spatial pattern of the deep convective and high-level clouds is controlled by the topography: the highest values are observed over West Cameroon highlands and the Mandara mountains and the lowest values over the Adamaoua and south Cameroon plateaus (Vondou et al. 2010). Therefore, topography plays an essential role in cloud formation through air lifting on its slopes through the southwest monsoon flow crossing the region and moisture convergence at low level. Minima of deep convective clouds are observed over the Atlantic Ocean, the Benue and Niger valleys and the Lac Tchad (Vondou 2012).

The spatial structure of low clouds over western equatorial Africa (WEA) bounded by 5°S–5°N and 8°E–18°E (Fig. 7) reveals a predominance of low stratiform clouds with high frequency on the Atlantic seaboard extending up to 15°E (Gabon, South Congo, Equatorial Guinea, Cameroon coast) during the June–September season (Dommo et al. 2018). This reduces solar radiation to the point where the region receives the least amount of sunlight during the dry season, in contrast to the interior of equatorial Africa where the main dry season is the brightest (Philippon et al. 2019).

With a peak diurnal cycle between 04LT and 07LT (Dommo et al. 2018; Champagne et al. 2023) over the coast and windward slopes, low clouds over WEA also

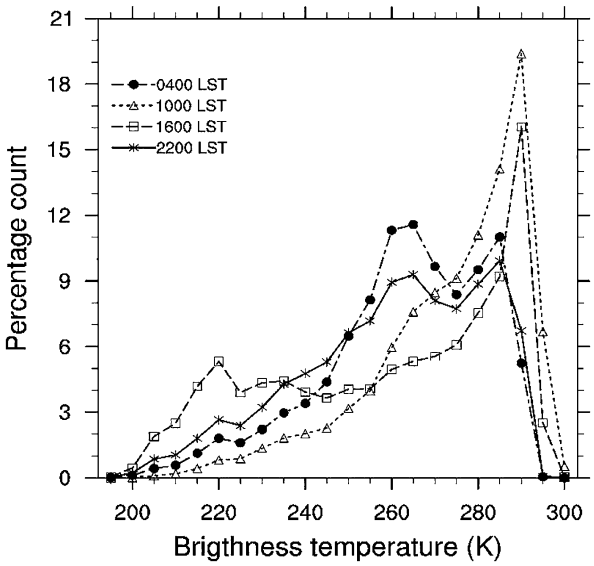



**Fig. 6** The evolution graph of the percentage for which brightness temperature occurred within each 5 K interval, between 190 and 300 K during the daytime and the nighttime, over Western Central Africa bounded by 1°N–8°N & 1°E–17°E for June–August 1998–2002 (Vondou 2012)

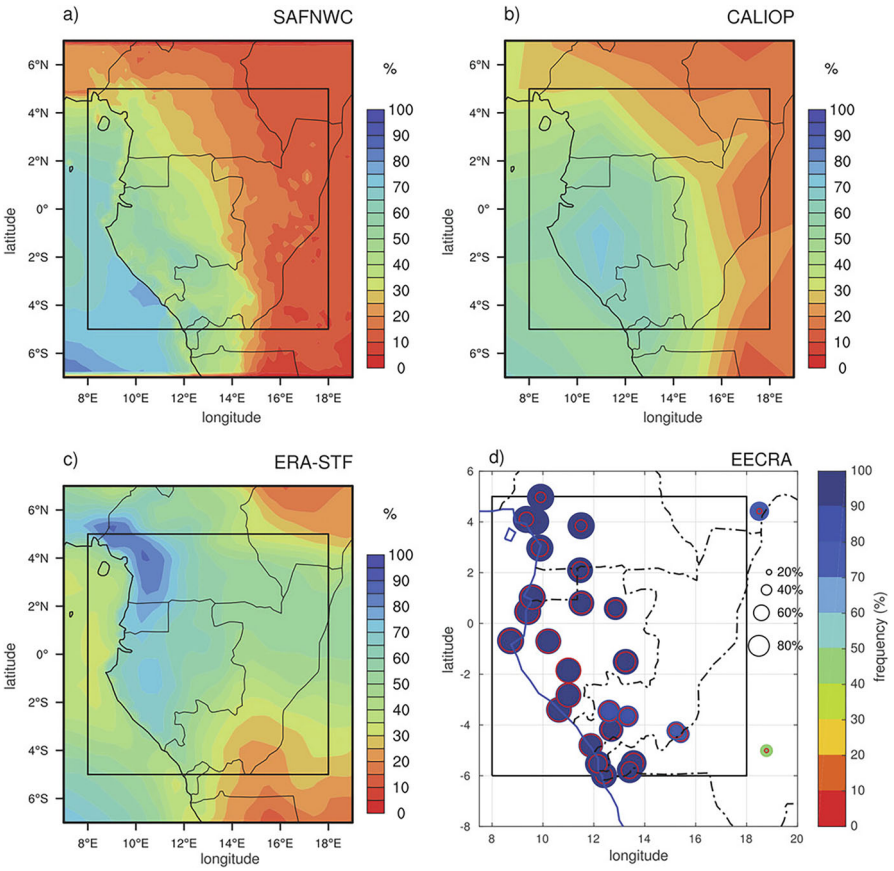



**Fig. 7** Low-level cloud frequency (%) in June–September for nighttime and daytime, from the (**a**) Satellite Application Facility for Supporting Nowcasting and very short-range forecasting (SAFNWC) (2009–14), (**b**) global climate model-oriented *Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observations* (CALIOP) (2007–15), (**c**) European Centre for Medium-Range Weather Forecasts interim reanalysis (ERASTF) (2009–14), and (**d**) the Extended Edited Synoptic Cloud Reports Archive (EECRA) (1971–2009). In (**d**), the circle size is proportional to the frequency. The total low clouds (blue disks) and the low stratiform clouds only (red circles) are marked (Dommo et al. 2018)

exhibit an east to west gradient with a high frequency of occurrence over the coastal region and a lower frequency inland (Dommo et al. 2018). Previous studies mentioned the influence of topography on the spatial distribution of the low clouds over WEA which exhibits a significant reduced low cloud frequency over the plateaus in the afternoon. Dynamic processes show that, during nighttime, the formation of low cloud over WEA is associated with moisture flux related to low level westerlies, strong convergence in the lower layer (below 1000 m, e.g. ~900 hPa) and turbulent upward mixing of moisture (Dommo et al. 2022). The reinforcement of the radiative cooling at the cloud top helps to maintain the cloud deck once it has been formed.

During daytime, latent and sensible heat flux from the surface, due to downward shortwave radiation, contributes to increase the vertical turbulence and deepen the boundary layer and thus, combined with decreasing relative humidity in low levels ~1000 m mostly due to the diurnal warming, acts to partly destroy the cloud deck and decrease the cloud fraction.

At the interannual scale, Moron et al. (2023, 2025) show that mechanisms driving low level clouds over WEA are associated to the meridional shallow overturning cell and a strong cold tongue over the equatorial Atlantic. Processes operating at intraseasonal cycle, involve tropical waves (Moron et al. 2025).

Although considerable progress has been made in understanding the structure of clouds, accurately representing them in climate models over WCA remains challenging, particularly for low clouds (Camberlin et al. 2023). This unrealistic representation contributes to the large uncertainties noted in regional and global climate projection (Dufresne and Bony 2008).

## Nature of the Precipitation Regimes

The rainfall data available for the Congo are inadequate for assessing the mean spatial pattern of rainfall. Figure 8 shows the spatial pattern based on NIC131 and based on the CHIRPS satellite rainfall dataset. Both are in excellent agreement with each other and with a map produced by Bultot (1971) for 1930–1959, a time when over 100 stations were available.

Inland, three rainfall maxima are clearly apparent. The largest are over the Cuvette Centrale and just west of Lake Victoria, where in both maps, mean annual rainfall exceeds 2000 mm. As for the latter maximum, orography enhances rainfall as the easterlies flow over the Rwenzori and Mitumba Mountains in the Rift Valley highlands. In the former, rainfall appears to be enhanced by evaporation from the Congo River and the wet regions around it (Nicholson et al. 2021). The third maximum lies north of the one near Lake Victoria. It also appears to be related to orography, in particular the Blue Mountains. At the northern and southern extremes of the region, roughly 10°N and 10°S, rainfall is around 1000 mm. It increases steadily toward the central basin, being on the order of 1750–2000 mm over most of the region.

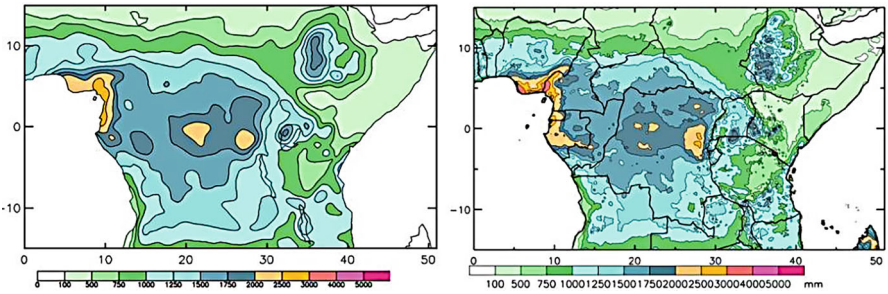



**Fig. 8** Mean annual rainfall (mm) based on gauge data (left) for the period 1945–1984 and CHIRPS data (right) for the period 1981–2019 (Nicholson 2022)

Figure 9 shows the seasonal cycle of rainfall in each five-degree grid cell. To the north, from 5 to 10°N, rainfall has a unimodal seasonal cycle with maximum rainfall in June-to-August or July-to-September. In the northern Congo Basin, from the equator to 5°N, two peaks are generally evident, but in most grid cells rainfall is also high in summer, mainly off the coast. Thus, the bimodal nature is not well developed. It is better developed in the southern Congo (equator to 5°S), but even there the dry season between the two maxima is not very dry, so the two rainy seasons are not extremely distinct. Over these two latitudinal bands, the bimodal cycle is more pronounced over the coastal region. Therefore, this bimodal character of annual rainfall is not obvious when averaging rainfall along each latitudinal band (Longandjo and Rouault 2024). In general, September–November seems to be the wetter period of the year. Farther south, most grid cells have a clear summer rainy season, although in some two peaks are evident.

The month of maximum rainfall (Fig. 10) changes progressively from March in the far south, around 10°S to August in the far north at roughly 7°N. The driest month shifts abruptly from June or July south of 0 to 2°N to January in northern hemisphere sections.

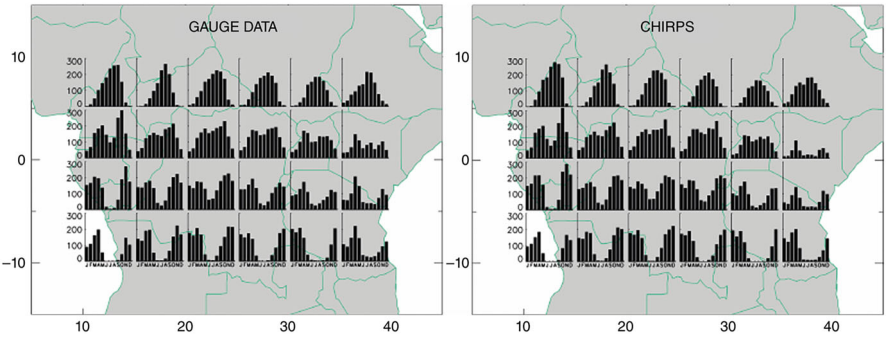



**Fig. 9** The seasonal cycle of rainfall, with bar graphs indicating mean rainfall in each month (Nicholson 2022). Based on gauge data averaged for the period 1945–1984

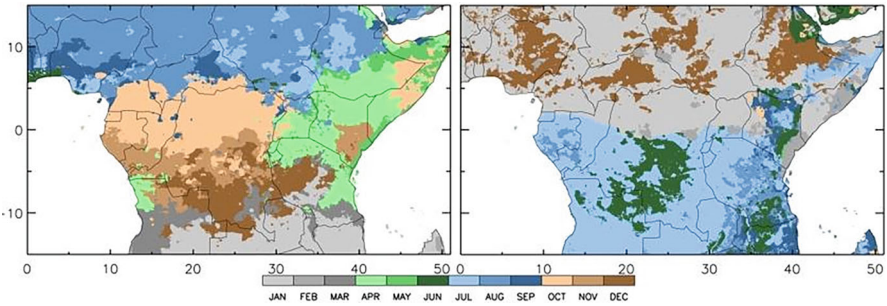



**Fig. 10** Months of maximum rainfall (left) and minimum rainfall (right), based on CHIRPS data for the period 1981–2019 (Nicholson 2022)

Most of the rainfall in the Congo Basin (70–80%) is associated with mesoscale convective systems (Feng et al. 2021). These tend to form in the late afternoon but persist through the night, producing short-lived convective rainfall in the afternoon but long-lived stratiform rainfall at night. Consequently, there is a nocturnal rainfall maximum in many areas. Consequently, the diurnal cycle of precipitation exhibits two peaks due to MCSs (the first peak in the afternoon and the second at night) compared to a single peak for days with no mesoscale convective systems (only one peak in the afternoon) (Tikeng et al. 2024).

The Congo Basin experiences the highest frequency of lightning in the world. Within the region there are two very pronounced maxima, co-located with the two regions of maximum rainfall: just west of the highlands and over the central basin. The small village of Kifuka experiences the absolute highest number of flashes per year, 158/km$^2$ (Kalair et al. 2013). Mesoscale Convective Systems are responsible for the intensity of lightning activity in the region, mainly close to the equator (Jackson et al. 2009).

An unusual characteristic of Congo Basin rainfall is the lack of spatial coherence of rainfall variability and spatial teleconnections. Throughout most of Africa both characteristics are strong, and teleconnections extend across the continent. However, studies based on 90 climatic regions (e.g., Nicholson et al. 2012a, b) show that both characteristics are lacking over the Congo Basin, with very low correlation among station for the Congo during both rainy season clearly evident in Fig. 11.

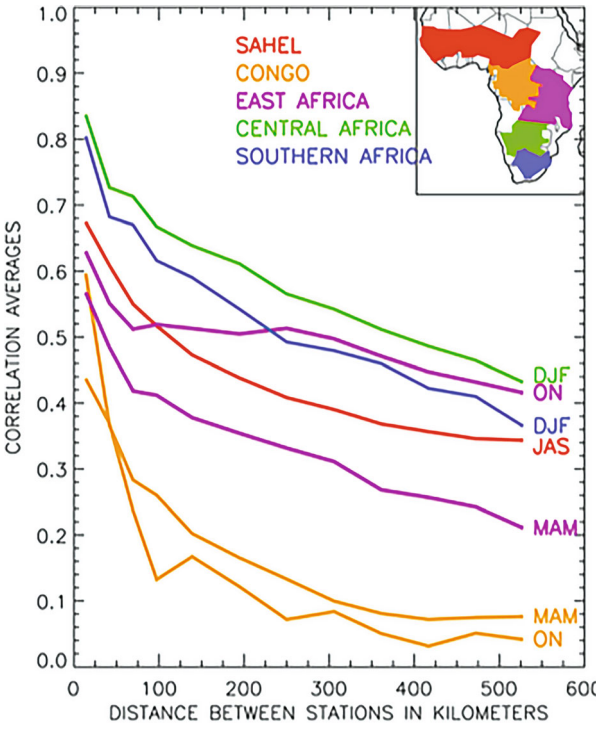



**Fig. 11** Inter-station correlation during the period 1930–1989 as a function of distance between stations in five geographical sectors in Africa (Jackson et al. 2009)

## Regional Drivers of Climate Variability

Establishing the long-term interannual variability of rainfall over the Congo Basin is difficult because of the decline of the station network since the 1970s. Precipitation from various datasets for the Congo Basin tends to disagree with each other, which can be attributed to the various interpolation approaches used by the observations, temporal availability, and satellite-only to blended data (Dallmann 2023). This makes it difficult to establish the relevant forcings. Conclusions of various studies are to some extent contradictory.

Interannual variability was examined by several studies. Balas et al. (2007) concluded that the large-scale factors controlling interannual rainfall variability vary greatly from region to region and from season to season. They also concluded that links to global SSTs and ENSO were quite weak. In some areas/seasons a weak link to El Niño but not La Niña was evident; in others the reverse was true. Dallmann (2023) likewise concluded that ENSO and large-scale SSTs were not factors in interannual variability in the Congo Basin.

In contrast, Hua et al. (2016, 2018) found linkages with the Indo-Pacific SSTs. They concluded that the principal factors associated with the long-term drying trend in April–June (Fig. 12) were an enhanced and westward extension of the tropical

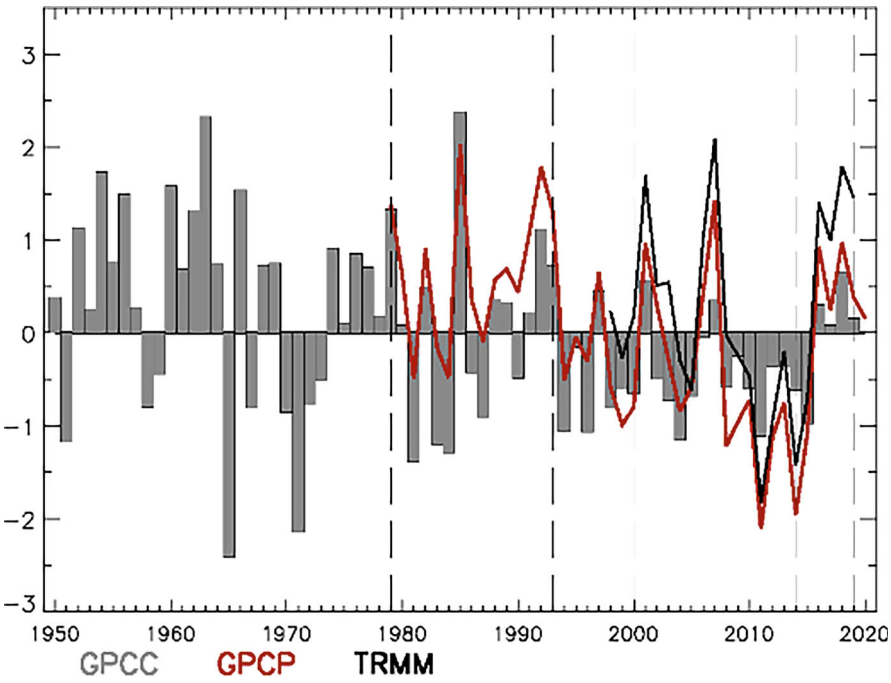



**Fig. 12** Time series of April–May–June areal averaged (10°S–8°N, 14–32°E) rainfall 1950–2019 based on GPCC (bars), GPCP (red dashed line), and TRMM 3B43 (black dashed line). (From Nicholson et al. 2022b). Rainfall is expressed as a standardized departure. Vertical lines delineate recent wet and dry periods

Walker circulation, an anomalous anticyclonic circulation in the lower troposphere over southern Africa, weakened ascent over Central Africa, and reduced low-level moisture transport. These appear to have been triggered by changes in SSTs in the Indo-Pacific sector, in particular decreasing temperatures in the equatorial Pacific but increasing temperatures over the tropical Atlantic and Indian Oceans and the western Pacific.

Nicholson et al. (2022b) examined two wet periods during the AMJ season, 1979–1993 and 2016–2020 (Fig. 12). They concluded the first wet period was related to a warmer central and eastern pacific and a cooler western Pacific, compared to the dry phase between 2000 and 2014. Changes in moisture flux and the Walker circulation were also involved. In contrast, during the second wet period, warming was more pronounced in the central and eastern Pacific compared to the western Pacific, which decreased the trans-Pacific SST gradient in the 2016–2020 period compared to either prior period. For this episode, the major factors appear to be an increase in Convective Available Potential Energy and in total column water vapor.

The Indian Ocean provides a significant amount of atmospheric moisture for rainfall to the Congo Basin (Dyer et al. 2017). Dezfuli and Nicholson (2013) and Nicholson and Dezfuli (2013) found only weak associations but found a tendency for dry/wet conditions over Congo Basin to be associated with abnormally warm/cold Indian ocean temperatures. However, in recent decades, the influence of the Indian Ocean Dipole on the Congo Basin rainfall during September–December has increased (Jiang et al. 2021). Positive/negative Indian Ocean Dipole events are associated with enhanced/reduced moisture transport and wet/dry conditions over the Congo Basin. This influence is more pronounced south of the equator (Moihamette et al. 2024).

The western part of the Congo Basin is the region most sensitive to SST variations in the tropical Atlantic Ocean. Warmer/colder than normal SSTs in the equatorial and southern Atlantic together are associated with wet/dry conditions in the region along the coast during the AMJ season (Nicholson and Dezfuli 2013). However, Congo Basin's coastal rainfall strongly connects with the local SST along the Benguela coast, resulting in rainfall increases under the effect of warm SST anomalies on the Benguela coast (Nicholson and Dezfuli 2013). Wetter years also tended to be associated with strongly developed westerlies in the lower troposphere (Pokam et al. 2014). During the JJA/SON seasons, the Atlantic Niño causes increased rainfall, leading to wet conditions over the Democratic Republic of the Congo (DRC), Congo, and north Angola, whereas Cameroon and the Central African Republic experience dry conditions. This pattern is reversed when stronger upwelling in the equatorial Atlantic produces cold SST anomalies in these regions (Balas et al. 2007). The South Atlantic Ocean Dipole (Nnamchi et al. 2011) also influences Congo Basin rainfall. A colder-than-normal SST off the coast of South America, but warmer-than-normal SST along the west/central coast of Africa causes a convergence (divergence) of moisture flows over the southern Atlantic coast (inland the Congo Basin) resulting in increased (decreased) rainfall in these regions of the Congo Basin in the JJA season. An inverse pattern results in opposite rainfall

variability (Nana et al. 2023). The Madden-Julian Oscillation also has an impact on rainfall in the Congo Basin (Raghavendra et al. 2020).

## Extreme Weather and Climate Events

### Extreme Rainfall

Extreme rainfall is an event that is of very high magnitude with a very rare occurrence at a particular place (IPCC 2021). Extreme rainfall is one of the most frequent and widespread severe weather hazards to affect Congo Basin countries (Igri et al. 2015; Tanessong et al. 2017; Kenfack et al. 2024). Often, a significant amount of precipitation occurs in only a few hours, leading to severe flooding and risk of landslides.

The interannual variability of precipitation during October and November reveals recent precipitation extremes, particularly in 2019 and 2023. (Fig. 13). From the spatio-temporal variability of the southern Congo (10°S–0°) in October 2019 and 2023 (Figs. 14a, c), two very wet years over Equatorial Africa (Nicholson et al. 2022a; Nana et al. 2025), rainfall extremes are primarily over the western region. In November 2019 and 2023, rainfall extremes are over all regions. Spatio-temporal variability of the northern Congo (0–10°N) in October 2019 (Fig. 14b) shows more extreme rainfall and in a greater longitudinal extent than October 2023 (Fig. 14d). November 2019 shows larger rainfall extremes only in the eastern Congo and only for half of the month. November 2019 shows more rainfall extremes across latitudes

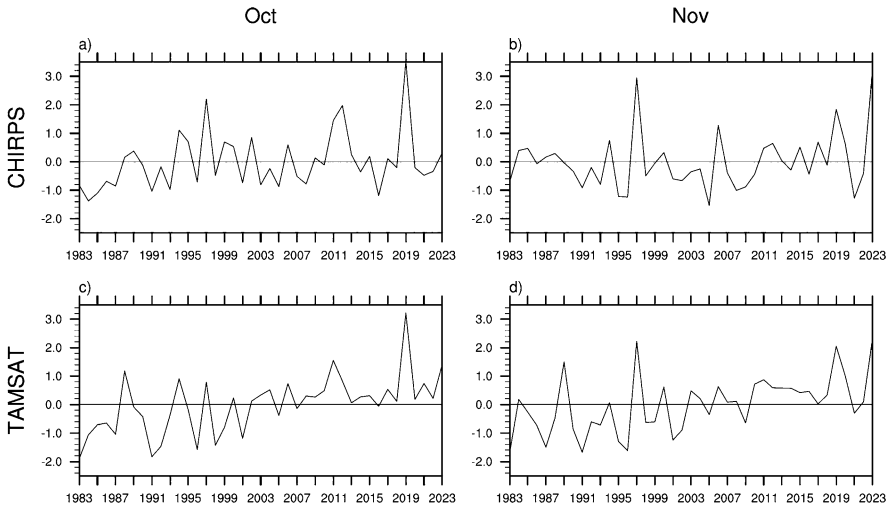



**Fig. 13** Time series of monthly rainfall over the Congo Basin (10°S–10°N, 10°E–40°E) for the standardized anomalies (1983–2023) during October and November from (**a** and **b**) CHIRPS and (**c** and **d**) TAMSAT

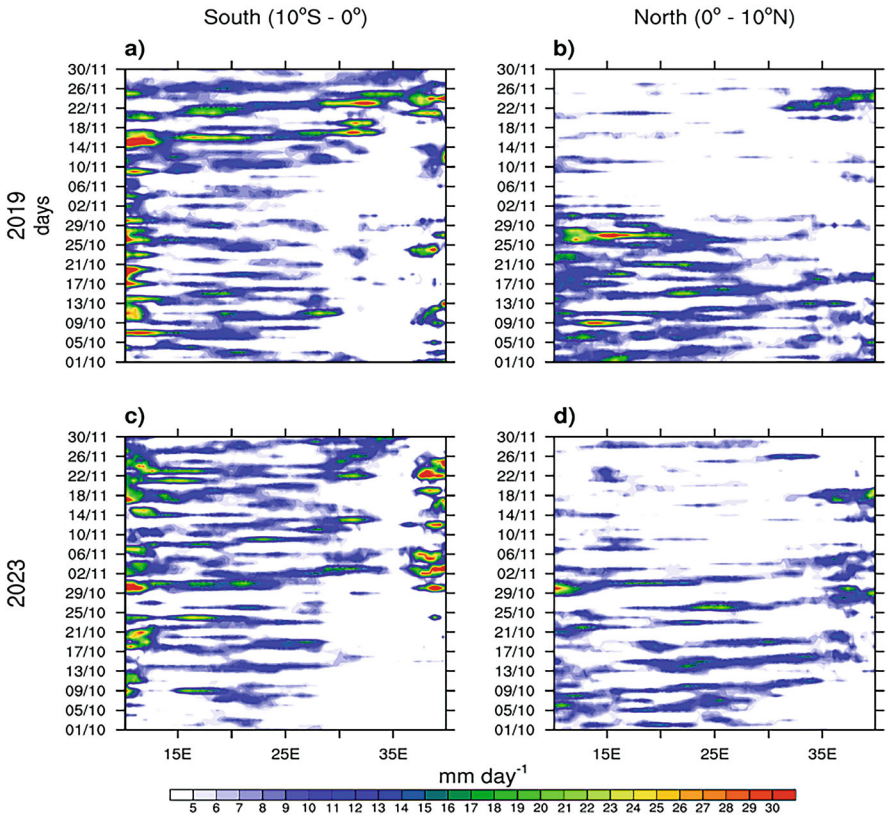



**Fig. 14** Daily rainfall from CHIRPS, averaged over 10°S–0° (first column) and 0°–10°N (second column), for (**a** and **b**) 2019 and (**c** and **d**) 2023

compared to November 2023. Figure 14 shows that the southern Congo rainfall extremes are more consistent with each other in both months compared to the northern Congo rainfall extremes.

Nicholson et al. (2022a) investigate the unprecedented October and November 2019 rainfall extremes in equatorial Africa, putting them in their historical context and analyzing the juxtaposition of forcings needed to explain them. The mechanisms underlying these extremes of rainfall are not straightforward. The Indian Ocean Dipole and the associated moisture provision to equatorial Africa contribute to wetter conditions over the Congo Basin (Moihamette et al. 2022). SST variability of the Atlantic Ocean may also contribute. However, over the Congo Basin, the lack of a homogeneous response of rainfall variability suggests that local factors may play a significant role in extreme rainfall. The prevalence of low wind shear over the Congo Basin prevents random convective outbreaks in the region from organizing into large-scale propagation systems, leading to this heterogeneous response in rainfall patterns. Then, Convective Available Potential Energy and total column

water vapor appear to be the main factors for the occurrence of extremes over the Congo Basin (Nicholson et al. 2022b).

## Meteorological Drought

Meteorological drought is defined as a period when precipitation is significantly below the long-term average. Few studies are based on improving mathematical tools to accurately determine meteorological drought in the areas of the Congo Basin. The Standardized Precipitation Index (SPI) remains the most used because it has the most advantages, such as being flexible, depending on a single variable (precipitation which is the most easily accessible), and can describe drought at several time scales (Batool et al. 2025). However, it requires modeling the distribution of data by a statistical function, which is generally assigned to the gamma distribution. Recent studies have shown that such an assumption induces errors in the characterization of drought (Guenang et al. 2019) and propose selection by decision test, the most appropriate distribution in a sample of functions. Very few studies have looked into solving this problem. In the particular case of Central Africa, improvements in the calculation of this index may be found in Fotse et al. (2024).

Mabrouk et al. (2022) shows an increase in drought risk in the Congo River Basin. The reasons are awarded to the vulnerability and population rise in that region (Ahmadalipour et al. 2019). This drought can affect Congo Basin by reducing forest photosynthetic as shown by Zhou et al. (2014). Other studies focused on particular countries. Kapiri et al. (2023) focused on the study of drought from the 1970s to the 1990s and its influence in the Tropical City of Beni, Eastern DR Congo. Results show that the city of Beni has suffered from drought during the years 1970 to 1990. Guenang and Kamga (2014) also found that many localities in Cameroon recorded severe to extreme drought during the 1980s. Some agroecological zones of the country are expected to suffer from these drought categories in the future decades of the end of the twenty-first century (Guenang et al. 2024).

Possible mechanisms for drought in Central Equatorial African were examined by analyzing the circulation changes related to sea surface temperature (SST) variation (Hua et al. 2016). It was found that drought for the season April–May–June was correlated to atmospheric circulation and SST variation. This finding was confirmed by Nicholson et al. (2022b) studying rainfall conditions in the Congo Basin. Ndehedehe et al. (2019) also examined the impacts of global multi-scale climatic drivers on hydro-climatic extremes over the Congo Basin and found that drought was correlated to the phenomena of ENSO, QBO, MJO, and AMO. Additionally, increases in evapotranspiration will offset increases in precipitation where rainfall amounts are expected to increase and exacerbate drought severity in regions where precipitation is expected to decrease (Karam et al. 2022). Nicholson (2022) suggested that lower moisture flux convergence and lower relative humidity are responsible for drier conditions over the Congo Basin as compared to other tropical rainforests. It was observed that the occurrence of drought over the Congo Basin

coincide with flood over the Amazon and vice versa (Eltahir et al. 2004); this phenomenon is defined as a see-saw oscillation was observed at a decadal scale between the Amazon and Congo Basin (1945–1955, 1960s, and 1970s).

### Heat Waves

Recent trend of surface temperature over northern Congo Basin have shown an increase greater than average global warming (Engelbrecht et al. 2015), as a result of anthropogenic global warming. As a consequence, the Congo Basin experiences increases in extremes of heat and in turn heat waves, mainly in the northern and western part of the region (Kaissassou et al. 2023). This presents a growing challenge for the region. Strong heat stress is experienced over the region from November to February. Moderate heat stress is observed from April to June. The average length of heat waves in northern Congo Basin varies between 4.8 and 5.2 days, growing longer with time and associated with an increased trend of maximum temperature (Hu et al. 2019).

The synoptic feature driving these heat wave events involves the occurrence of an anomalous convergence center in the upper troposphere and a divergence center in the lower troposphere, inducing strong subsidence anomalies, which leads to warming through greater solar insolation. This enhancement of the solar radiation induced by strong subsidence anomalies is the major contribution to the occurrences of HW events over northern Congo Basin.

## Issues, Gaps, and Challenges

A serious limitation in developing an understanding of the mean climate of the Congo and its interannual variability is a dearth of recent observational data. During much of the twentieth century, rainfall records for the Congo were plentiful. Some 500 stations were operative in the Democratic Republic of the Congo (DRC) during the 1940s through 1960s (Bultot 1971). When economic conditions worsened and political conditions changed, the number of stations rapidly declined, especially during the 1970s. By the early twenty-first century, only 12 gauges were operative in the DRC.

This decline is illustrated in Fig. 15 (left), which shows the total number of months with rainfall records in each grid box in the NIC131 dataset (Nicholson et al. 2019) during the period 1995–2012. Clearly there are few records available in the Democratic of the Congo during that period. The results are similar for GPCC, but with fewer station months in almost every grid point with available data. Figure 15 (right) shows the stations available in four multi-year periods.

Gridded datasets have been produced to cover the recent years. However, these are not independent datasets because all contain more or less the same records until about 1998. These include NIC131 (Nicholson et al. 2018), NIC131-gridded (Nicholson et al. 2019), GPCC of the Global Precipitation Centre in Offenbach, Germany

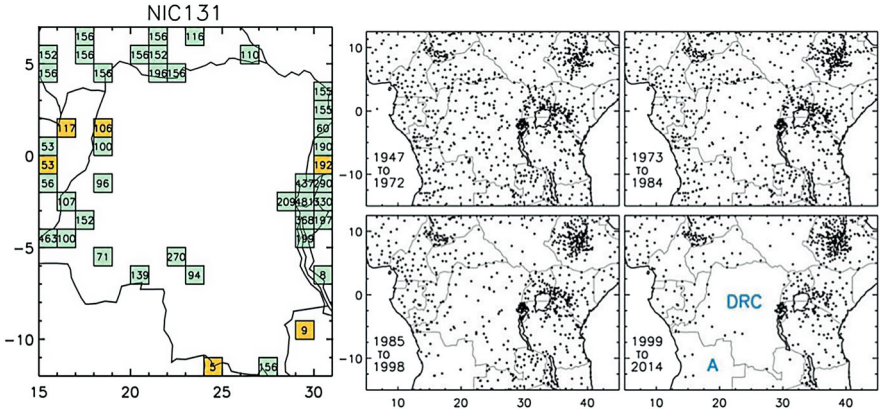



**Fig. 15** Left: Total number of months with available rainfall records during the period 1995–2012 for any grid box with data in NIC131 (Nicholson et al. 2019). Grid boxes in orange are those with a greater number of records in GPCC. Right: Station network around the Congo Basin in four time periods. (From Nicholson et al. 2018). Country boundaries are shown. In the map for 1999–2014, the letters DRC and A, respectively, identify the Democratic Republic of the Congo and Angola

(Schneider et al. 2015); CRU of the University of East Anglia (Harris et al. 2014); and the University of Delaware (Willmott and Matsura 2000). It should be noted that the decline in station records affects all of these sources. Many of the sources continued providing records post-1998 by using the data available through the Global Telecommunications System (GTS), but the GTS provides very little data.

Numerous satellite precipitation datasets cover the Congo region. While, in principle, satellite data provide the needed spatial detail, their reliability is dependent on the quality and density of ground station records. Several validations found large discrepancies between gauge and satellite data over the Congo. Nicholson et al. (2019) found that the various available satellite datasets differed greatly in their ability to accurately estimate rainfall over the Congo. They concluded that the most reliable satellite products over the Congo region are CHIRPS2, GPCP2.3, and PERSIAN-CDR. Meanwhile, reanalysis datasets are inconsistent with each other in their spatio-temporal rainfall estimates and likely do not adequately represent rainfall within the Congo Basin (Nicholson and Klotter 2021; Hua et al. 2019).

The dearth of rainfall data is matched by an absence of upper air data from radiosondes, which are necessary to capture the thermodynamics associated with key rainfall systems, notably MCSs. Key metrics such as CAPE have been shown to contain misleading trends in reanalysis data (Benestad et al. 2022).

The unreliability of observation data hampered efforts to constrain climate model results, which directly impacted the ability of the model to represent regional climate. There is significant variation in the representation of rainfall climatology among global climate models (Creese and Washington 2016). In some months the difference is up to a factor of 5. Although the coarse resolution and the parametrization of these models contribute to these biases, the poor skill of those models in

representing the strength of LLWs or the location of AEJ components lead to rainfall biases over the Congo Basin (Creese and Washington 2018; Kuete et al. 2023). To overcome this issue of coarse resolution, the ability of regional climate models to represent regional climate processes has been assessed (Tamoffo et al. 2023, 2024). Increasing model resolution does not always lead to improved climate simulation (Vondou and Haensler 2017; Wu et al. 2020) with reasons behind finer scale model biases similar to those of global climate models, including misrepresentation of regional teleconnection, land–sea thermal atmospheric circulation, and land–atmosphere feedback leading to error in the regional hydrological cycle (Mba et al., 2022; Akinsanola et al. 2025). The direct consequence is the lack of agreement between climate models on the sign and magnitude of future change in the Congo Basin (Creese and Washington 2018).

In recent years, significant pan-African (TAHMO) and regional (WASCAL, SASSCAL) investments have been made to bridge the gap in ground-based meteorological data availability. However, the Congo Basin remains data defficient with sparse network coverage.

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# The Evolution of Congo Basin Ecosystem Diversity

4

Nicola Mary Anthony, Clay Archange Boupoya, Adam Freedman, Olivier Hardy, Bila-Isia Inogwabini, Simon Lewis, Jacob Heen Lowenstein, Anne-Marie Lezine, Sassan Saatchi, Tom Smith, Nicolas Texier, and Gretchen Walters

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N. M. Anthony (✉)
University of New Orleans, New Orleans, LA, USA
e-mail: nanthony@uno.edu

C. A. Boupoya
Herbier National du Gabon, Libreville, BP, Gabon

A. Freedman
Harvard University, Cambridge, MA, USA

O. Hardy · N. Texier
Université Libre de Bruxelles, Brussels, Belgium

B.-I. Inogwabini
Swedish University of Agricultural Sciences, Uppsala (Sweden) and School of Management, Catholic University of Congo, Kinshasa, Democratic Republic of Congo

S. Lewis
University of Leeds, Leeds, UK

J. H. Lowenstein
Dogen Institute, Gyobutsuji, AR, USA

A.-M. Lezine
Université Sorbonne, Paris, France

S. Saatchi
California Institute of Technology, Pasadena, CA, USA

T. Smith
University of California Los Angeles, Los Angeles, CA, USA

G. Walters
University of Lausanne, Lausanne, Switzerland

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**Abstract**

The Congo Basin is a biologically diverse and dynamic terrestrial region composed of a central rainforest block flanked by savanna-forest ecotone. Embedded within this region are the Congo, Ogooué, and Sanaga which constitute the most biodiverse river systems in Africa. Although the Congo Basin is dominated by lowland forest, it also harbors a variety of terrestrial and freshwater ecosystems. Forests and associated savannas have been shaped by both abiotic and anthropogenic influences and differ in terms of their hydrology, elevation, and soil type. Current species distributions are complex and are thought to have been shaped by both historical and ecological factors. Major drivers of speciation are thought to have resulted from either geographic isolation through past refugia, riverine barriers or divergence across environmental gradients. Both genetic and genomic tools can help to refine taxonomy, identify unique evolutionary lineages, and understand the historical and ecological factors that have led to the rich biodiversity that we see today. Genetic tools are increasingly being applied to conservation efforts, including tracking and curbing the illegal wildlife trade. Genomic techniques also offer powerful means to preserve biodiversity in the face of climate change and identify populations with the greatest potential to adapt. This approach can inform placement of new protected areas to enhance species resilience and reduce extinction risk. Despite the potential of genomic tools, their integration into conservation planning remains in its infancy and will require expertise and long-term investment. Future efforts should focus on developing a road map for incorporating genomic data into conservation strategies along with fostering stronger communication between researchers and practitioners. Lastly, many species in the Congo Basin await discovery and for most groups, there is a backlog of species awaiting description. Developing regional expertise is needed to address this taxonomic impediment.

**Keywords**

Rainforest · Ecosystem · Congo basin · Biodiversity · Speciation · Genomics

## Biogeographical History of the Congo Basin

### Forest Ecosystems

Lowland rainforest constitutes the main ecosystem of the Congo Basin, covering approximately 1.7 to 1.8 million km$^2$ (Hansen et al. 2000; Mayaux et al. 2013; Verhegghen et al. 2012a) (Fig. 1) and a high density of aboveground carbon (Fig. 2). It is generally characterized by a tall, closed canopy, with a complex multi-layered vertical structure, so that the understory is usually dark, except in forest gaps. An estimated 8.5% of its area has been lost between 1990 and 2020 (Yuh et al. 2024).

Renowned for their high biodiversity, central African rainforests vary in their floristic composition at different spatial scales, leading to different classification schemes. From a phytogeographic perspective, White (1983) distinguished three regional centers of endemism: Upper Guinea (West Africa), Lower Guinea (western Congo Basin), and Congolia (eastern Congo Basin; Fig. 3). This subdivision is supported by quantitative analysis of the whole flora of the region (Droissart et al. 2018), although other analyses have distinguished moist and wet forest, based on the amount and seasonality of rainfall (Fayolle et al. 2014). Forests are also classified according to the relative dominance of deciduous tree species (i.e., trees shedding

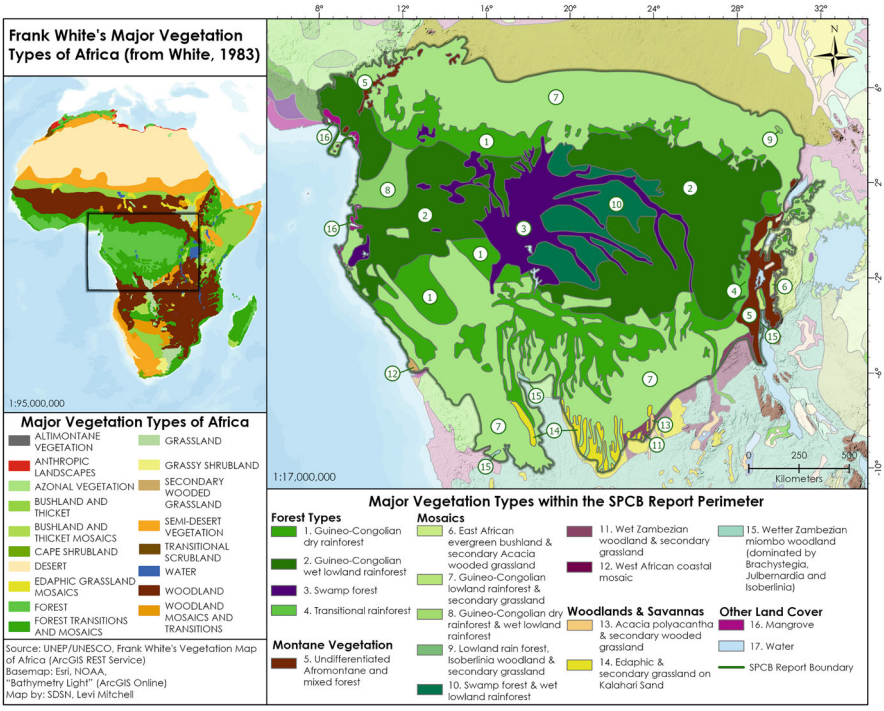



**Fig. 1** Major Congo basin vegetation types. (Adapted from Verhegghen et al. (2012b))

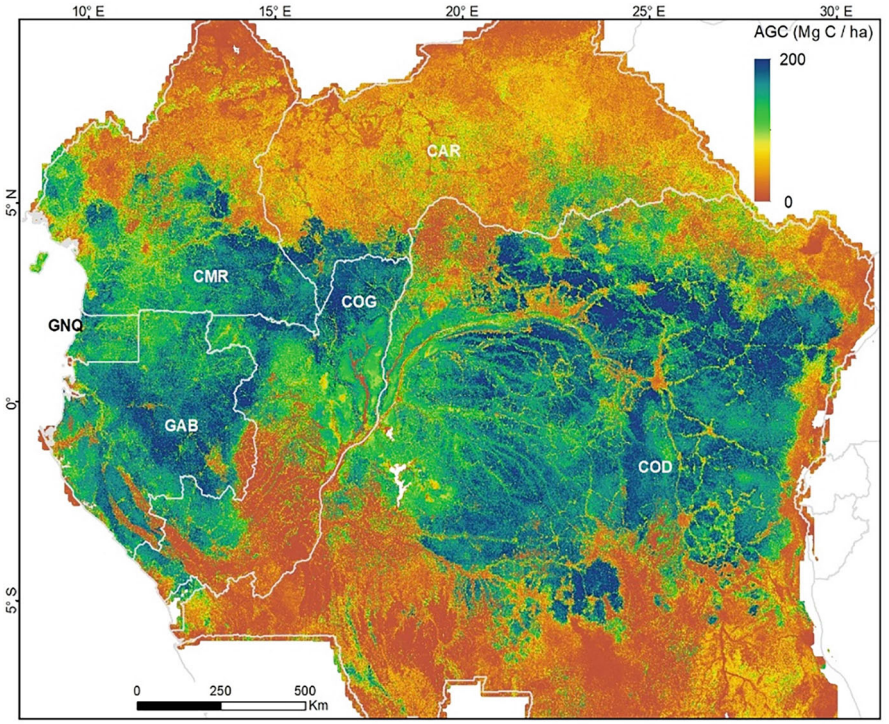



**Fig. 2** Spatial distribution of the aboveground carbon density (AGC, Mg C/ha) of the Congo basin rainforest at 1 ha resolution for the year circa 2020 obtained by combing air- and space-borne remote sensing data and the-state-of-the-art gradient boosted regression trees. Key: *CMR* Cameroon, *GNQ* Equatorial Guinea, *GAB* Gabon, *COG* Republic of the Congo, *CAR* Central African Republic, *COD* Democratic Republic of the Congo. (Adapted from Xu et al. (2017), (2021); Sagang et al. (2024))

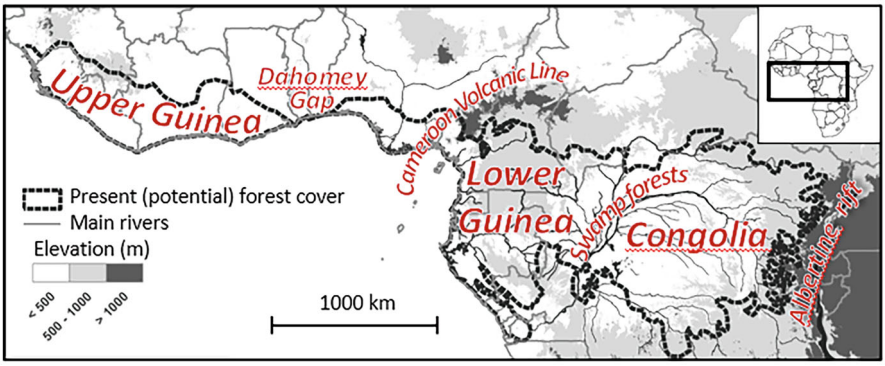



**Fig. 3** Major biogeographical regions and patterns of elevation in West and Central Africa. (Adapted from Hardy et al. (2013))

their leaves during the dry season), distinguishing deciduous, semi-deciduous, and evergreen forests, whose distribution is closely related to the total amount of rainfall, cloud cover, as well as the duration and severity of the dry season (Philippon et al. 2019). One of the most recent broad-scale classifications based on forest inventories in the Congo Basin distinguish ten forest types (Réjou-Méchain et al. 2011), which differ in the relative dominance of key functional traits (wood density, deciduousness, and maximum diameter). Satellite images are also used to produce vegetation maps distinguishing different forest types (Gond et al. 2013; Verhegghen et al. 2012a), notably 20 m resolution images from Sentinel-2 satellites allowed a regionally harmonized typology of 15 forest types (Dalimier et al. 2021).

At a more local scale, forest types are distinguished according to (i) species dominance (monodominant versus mixed forest); (ii) water table depth (swamp forest, temporally inundated forest, *terra firme* forest), which is closely related to the topographic position; and (iii) the degree of disturbance (primary versus secondary forest). Previously, scientists often assumed that primary forests were devoid of human influence. However, scientists now recognize that humans have influenced the floristic composition of African forest for about three millennia through slash and burn agriculture and other cultural practices (Morin-Rivat et al. 2017; Oslisly et al. 2013; Yasuoka 2013). In some regions, extensive slash and burn farming centuries ago still has profound impacts on dominant canopy trees today, such as in the mahogany forests of Northern Congo (White and Oates 2001), the forests of the Ntem Valley in Cameroon (Carrière 2003), the *Aucoumea klaineana* stands in Gabon (Engone Obiang et al. 2014), and Cameroon's coastal forests (Morin-Rivat et al. 2017).

The existence of monodominant forests (forests where at least 60% of the canopy is made of a single species) is unusual, since tropical rainforests are usually characterized by a large number of tree species at relatively low density. Some monodominant forests are made up of pioneer tree species and are considered to be a transient state. One example are the *Sacoglottis gabonensis* and *Aucoumea klaineana* forests of coastal Gabon and the Republic of the Congo which emerged 500 to 1000 years ago. These forests are thought to be a product of recolonization following coastal deforestation in response to swidden agriculture (Delègue et al. 2001), the slave trade (White et al. 2000), or salt production from boiled seawater, an extensive practice along the Atlantic coast of Gabon in the sixteenth century (Hymas 2016). *A. klaineana* is endemic to Gabon and Equatorial Guinea and is by far the most important timber species exploited in Gabon. This species colonizes savannas and abandoned fields, forming a dense high forest after one or two centuries. These dense stands are scattered throughout Gabon near village sites that were forcibly abandoned during the colonial policy of regroupment, which forced villages to relocate to roadsides (Walters et al. 2025). However, *A. klaineana* is unable to regenerate by itself and is replaced by mixed forest in the long term (Engone Obiang et al. 2014). Only a handful of tree species can form stable (climax) monodominant stands, which can be as small as 0.1 ha or cover several $km^2$ as is the case for the timber species *Gilbertiodendron dewevrei* (Tovar et al. 2019). The high density of their foliage seems to inhibit establishment of seedlings by most other species except *G. dewevrei* seedlings which are particularly shade-tolerant (Peh et al. 2014).

The limit of lowland rainforest can be gradual, as is the case for the transition toward submontane forest, which occurs around 700–900 m (Cheek et al. 2000; Senterre 2005), or abrupt, as seen in the transition to savanna, which tends to occur when annual rainfall falls below about 1580 mm (Staal et al. 2016), but sometimes less (1300 mm in Lopé, Gabon). In fact, forest and savanna ecosystems can coexist over a broad climatic envelope (900–1900 mm), even up to 3000 mm on well-drained deep sandy soils, such as in the Plateaux Batéké, but exclude each other on a local scale, leading to alternative stable states (Aleman et al. 2020). Where climatic and soil conditions allow both ecosystems to persist, it is common to find a mosaic landscape where forest occupies humid areas like valleys, and savanna the drier ones, like elevated plateaus. Rainfall, herbivory, or fire can then shift the spatial distribution of the forest-savanna transition zone. However, in many cases in the forest-savanna mosaic, fire is unable to maintain the boundary and forest encroaches savanna (Jeffery et al. 2014).

The extent of rainforest in Africa has continuously changed over geological time, depending on orbital processes, plate tectonics, and climatic conditions (Kissling et al. 2012; Zachos et al. 2001). Six major "geo-climatic" periods have impacted the biodiversity of tropical Africa since the extinction of dinosaurs, 66 million years ago (Couvreur et al. 2021). Rainforest may have dominated Africa during the mid-Eocene (c. 55 million years ago), possibly covering c. 22 million km$^2$ according to a paleogeographic vegetation reconstruction (Kissling et al. 2012), but its extent globally declined, with an abrupt reduction during the last ten million years (Couvreur et al. 2021; Kissling et al. 2012). The last two million years (Quaternary) have been marked by glacial-interglacial cycles at higher latitudes. Fossil pollen records from marine sediments from the Gulf of Guinea show a decay of lowland forest pollen taxa concomitant with glacial episodes, especially during the last 1.1 million years. Therefore, forest cover during glacial maxima might have been much more reduced and probably fragmented than today (Maley and Brenac 1998). However, Pleistocene paleo-vegetation data is generally lacking from the Congo Basin. This hinders estimates of the past distribution of lowland rainforests (Elenga et al. 2004), making it difficult to tease apart the different hypotheses proposed for the distribution of Pleistocene forest refugia (Anhuf et al. 2006; Aubreville 1949; Hamilton and Taylor 1991; Kingdon 1980; Maley and Brenac 1998). Although precipitation was higher in tropical Africa during the Holocene, (deMenocal et al. 2000), two climatic crises affected the Congo basin about 4300 and 2500 years ago, the latter coinciding with the expansion of slash-and-burn agriculture (Maley et al. 2018), probably mediated by Bantu populations (Bostoen et al. 2015; Grollemund et al. 2015).

## Peat Ecosystems

Forested wetlands are an important habitat within the Congo Basin. Also known as swamp forests, these have been estimated to cover 360,000 km$^2$ of the "central depression" or Cuvette Centrale of the Congo Basin (Bwangoy et al. 2010); see Fig. 1.

This habitat spans the northern-eastern Republic of the Congo (ROC) and western Democratic Republic (DRC) of the Congo Basin. Swamp forests occur across large interfluvial basins between rivers, such as between the Ubangi and Likouala-aux-herbes Rivers in the Republic of the Congo (ROC) and in the river valleys of the middle reaches of the Congo River and various left-bank tributaries, including the Ikelemba and Ruki Rivers in the Democratic Republic of the Congo (DRC) (Bwangoy et al. 2010; Crezee et al. 2022). Other sizeable wetlands in the Congo Basin region include near the Lomami River in central DRC, and the Minkébé wetlands in northwest Gabon, plus various coastal wetlands, such as those associated with the Ogooué River in Gabon (Fluet-Chouinard et al. 2015). Small areas of wetland also occur elsewhere, typically close to rivers, streams, lakes, or in small depressions (Gond et al. 2013).

Compared to *terra firme* forest, forested wetlands tend to be composed of shorter stature trees and have lower tree biomass and lower tree biodiversity (Bouillenne et al. 1955; Dargie et al. 2017; Évrard 1968; Gond et al. 2013). In all these regions, animal diversity is largely unexplored, except charismatic megafauna. Central African forested wetlands are known to have dense populations of forest elephants and western lowland gorillas in the large interfluvial basins of the ROC (Fay and Agnagna 1991; Rainey et al. 2010). However, the once thriving Minkébé elephant population has been reduced by ~25,000 individuals due to poaching (Poulsen et al. 2017).

The most striking recent finding is that the Congo Basin contains the world's largest tropical peatland complex (Dargie et al. 2017). Approximately half of the Cuvette Centrale wetland area forms peat. In many locations, the high organic matter input from the forest into the soil, coupled with waterlogging impeding decomposition, has led to peat deposits slowly building up over thousands of years, forming peat soil beneath the forest (Dargie et al. 2017). These peat swamp forests are exceptionally high-carbon storage ecosystems. They are also vulnerable to a loss of this carbon if the peat dries, since decomposition processes accelerate and the carbon in the peat is released to the atmosphere (Dargie et al. 2017; Garcin et al. 2022).

The most recent ground-verified estimate indicates that there are 167,600 $km^2$ of peat swamp forest in the central Congo Basin, representing 36% of the world's tropical peatland area (Crezee et al. 2022). Peat is found in both interfluvial basins (Dargie et al. 2017), which form peat-domes (Davenport et al. 2020), and in river valleys in the Cuvette Centrale (Crezee et al. 2022). The interfluvial peatlands appear to be waterlogged due solely to topography and rainwater, while the river valley peatlands include water from adjacent rivers, and run-off from adjacent higher ground (Georgiou et al. 2023). Peat depth is shallow at the edges, becoming consistently deeper with distance from the peatland edge (Crezee et al. 2022). The maximum peat thickness was 5.9 m, found in the center of a large interfluvial peatland (Dargie et al. 2017). Peat has been accumulating for at least 20,000 years in places (Garcin et al. 2022; Hawthorne et al. 2023), with ages of more than 10,000 years documented in several locations across the region (Dargie et al. 2017). These findings have transformed scientific understanding of central Congo

Basin wetlands and reveal that DRC and ROC are now the second and third most important countries in the tropics for peatland area, respectively, after Indonesia (Xu et al. 2018).

The forest overlying the peatlands is of three types. The most widespread is the hardwood swamp forest, in which *Uapaca paludosa*, *Carapa procera*, and *Xylopia rubescens* are often common, covering ~55% of the peatland area. The second is another common palm-dominated peat swamp forest dominated by *Raphia laurentii*, a trunkless palm with fronds that reach the canopy, covering ~44% of the peatlands. Finally, there is a much rarer (<1%) palm-dominated peat swamp forest, dominated by *Raphia hookeri* that occupies abandoned river channels (Dargie et al. 2017).

The newly mapped central Congo peatlands are estimated to store an average of $1712 \pm 634$ Mg C $ha^{-1}$ in the peat (1 Mg = 1 metric ton), when extrapolating to the whole region, making the peatlands some of the most carbon-dense ecosystems on Earth (Crezee et al. 2022). The maximum estimate was 3970 Mg C $ha^{-1}$, which is approximately 20 times the carbon storage of the trees in a typical African humid tropical forest. In total, the peatlands are estimated to store 29.0 billion metric tons of carbon (Crezee et al. 2022). This is approximately 28% of the world's tropical peat carbon.

Peatlands have a long history of vegetation change. The first analyses of preserved pollen from peat cores show that peat began accumulating at the center of the interfluvial peatland ~19,600 calibrated years BP (Hawthorne et al. 2023). The peatland margins were much younger, initiating between ~9500 and 10,500 BP, suggesting that the peatland expanded over time. The peatland first formed in a grass- and sedge-dominated floodplain environment, with frequent fires, followed some seven thousand years later by a forest dominated by the genus *Manilkara* (~12,640 cal. yrs BP), then after a further three thousand years a transition to a more mixed swamp forest (~9670 cal. yrs BP), which stayed until the present day. Rainfall and/or its seasonality correlated with change in the species composition of the forest over this time. Thus, the peatland vegetation seen today is influenced by both succession and the annual extent and level of waterlogging (Hawthorne et al. 2023).

The globally important stock of carbon in peat is more vulnerable to release into the atmosphere because the region is only just sufficiently wet to accumulate peat, unlike, for example, the peatlands in the Peruvian Amazon or in Southeast Asia which occur under much wetter climates (Garcin et al. 2022). Therefore, environmental changes that reduce rainfall, increase rainfall seasonality, or increase temperatures could reduce the water table allowing the peat to dry out (Young et al. 2023). Such drying would result in an increase in the decomposition rate of the peat, with oxidation occurring and carbon being released to the atmosphere. This has happened in the past. The hydroclimate history of the region has been determined using preserved plant waxes from peat cores from the central Congo Basin. The hydrogen isotopes of plant waxes indicate whether they were formed during wetter or drier conditions. These analyses indicate a drying trend from ~5000 cal. yrs BP until about 2000 cal. yrs BP (Garcin et al. 2022). This occurred at the same time as evidence of a major loss of peat, documented as only very decomposed peat remaining, and a lack of peat thickness remaining at the site at that time (Garcin et al. 2022). There was

also a switch from the dominance of swamp forest species to forest species associated with drier conditions (Garcin et al. 2022; Hawthorne et al. 2023). The authors suggest that as the climate dried, there was a regional drop in the water table, resulting in a near-complete mineralization of several meters of previously accumulated peat. Subsequently, the drier conditions abated, at ~2000 BP, and the peatland stabilized, with peat accumulation resuming and typical swamp forest species becoming abundant again, all conditions that continue to the present day (Garcin et al. 2022; Hawthorne et al. 2023; Young et al. 2023). The drought event and peat carbon loss, likely related to Earth axial precession, shows the ecosystem's high sensitivity to changes in precipitation and/or its seasonality.

## Savanna Ecosystems

The largest savanna systems in Central Africa occur at the margins or as large incursions into the forest block (Fig. 1). Savannas to the north of the forest block are part of the Guinea-Congolia/Sudania Regional Transition Zone, while those to the south are classified as Guinea-Congolia/Zambezia Regional Transition Zone (White 1983). This vegetation has been shaped over time by both climatic and anthropogenic factors (e.g., fire). Savannas provide important ecosystem services, from livelihoods to cultural values and biodiversity. However, they remain poorly understood as they were previously considered as degraded areas rather than the ancient and biodiverse savannas (Bond 2016).

Savannas vary in age and have responded to many human and climatic processes (Oslisly et al. 2013). While those of the Plateaux Batéké (stretching from Gabon, across ROC to DRC) are estimated to have first formed 30,000 to 70,000 years BP (Schwartz 1988), other savannas are younger. The savannas in the Mouila-Ndende (Gabon) area are thought to have been present 20,000 years BP, then converted to forest, only to reappear 6000 years BP (Schwartz and Lanfranchi 1991). Those of Lopé and Mouila-Ndendé (Gabon) likely reformed about 2500 years BP during a dry climatic period (De Foresta 1990; Maley et al. 2018). However, those of Lopé's savanna marshes (Gabon) could be as old as 9000 years (Bremond et al. 2021) and represent a large enclave of savanna contained within the forest block. Coastal savannas of Gabon originated approximately 3000 years ago and were colonized by *A. klaineana* and *Sacoglottis gabonensis* over large areas (Delègue et al. 2001). The littoral savannas situated directly behind the beach are also in part formed by changing sea levels, with former beaches now located just inland in long dunes, parallel to the sea (Giresse and Kouyoumontzakis 1990).

Recent research on African savannas provides evidence of their ancient origins (Bond 2016). These biomes often have species compositions that are influenced by anthropogenic and natural fire regimes (Demichelis et al. 2020). These old-growth savannas are characterized by high herbaceous species richness, high endemism, and unique communities (Veldman et al. 2015) and can be distinguished by the presence of endemic pyrogenic geoxylic suffrutices that form underground forests and/or forbs with underground storage organs or flowering stimulated by fire (Bond and

Zaloumis 2016). These indicators have been found in the Plateaux Batéké savannas (Walters et al. 2022), but other Central African savannas remain to be studied.

Forests and savannas co-exist as alternative stable states in Central Africa even under the same rainfall regime (Aleman et al. 2020). In general, climate fluctuation between arid and moist periods favored savanna and forest expansion at different times. An arid period favored savanna formation 40,000–70,000 years BP, followed by a wet period of "forest revival" around 30,000 years BP, then by an arid period until 18,000 years BP where savanna resurged, and finally by a wetter period 3000 years BP (Giresse 1978). Overall, for the past 1000 years, savannas in southern ROC and northwestern and central Cameroon have largely been stable while others have shown changes in forest island density with a few converting from savannas with forest islands to forests with savanna islands (Giresse et al. 2023).

Encroachment of the forest into savanna is active in southern and central Cameroon (Sagang et al. 2022), in the coastal forest of ROC (Favier et al. 2004) and at the forest edge of the Plateaux Batéké in Gabon (Walters 2010). Forest advances into Congolese Mayombe savanna have occurred at a rate as high as 50 m per century (Schwartz et al. 1996). Fire slows forest progression but does not stop it and active protection of the forest edge can speed up forest colonization (King et al. 1997). Management fires in humid savannas are not able to stop forest colonization in the Lopé (Jeffery et al. 2014) and ecotonal forests stop fire spreading from the savanna into the forest (Cardoso et al. 2021).

Despite the presence of large savanna kingdoms along coastal Central Africa, including large urban centers of the Loango Kingdom, and the associated smelting processes which required wood, Giresse et al. (2023) found no evidence that human presence led to changes in vegetation. Their synthesis further shows that over the past 1000 years, Central African forests and savannas have been long inhabited and have undergone local disturbance, except for the forest crisis of 2600 years BP (White and Oates 2001).

Beyond climate, fire is an important factor shaping savannas. Fire structures the savanna woody vegetation including recurrent fires creating cooler fire regimes which favor increased tree growth, maintaining its open habitat, and dominant, fire-dependent tree species, such as *Hymenocardia acida* in the Batéké Plateaux (Walters 2012). Savannas contain species with fire-related traits such as fire-resistant tree bark and underground storage organs that release leaves post-fire (Menaut 1983; White 1993) and post-fire resprouting (Lamont and Downes 2011). Forb diversity varies across savannas (Walters 2012) with some being fire dependent (Walters et al. 2022). Herbivory by native and domesticated browsers also plays a role in shaping many savannas. Cattle densities can be high in some areas of Central Africa, where people such as the Fulani have high stocking rates (Boutrais 1994). In other savannas of Central Africa, buffalo (Taylor et al. 2023), duikers, and elephants play stronger roles.

### Riparian and Freshwater Ecosystems

During the Cenozoic Era (66 Ma, i.e., million years ago), the evolution of the Congo Basin was significantly marked by tectonic uplift and climatic changes that

influenced its landscape and hydrology. The Early Miocene epoch (23–16 Ma) was marked by warm and humid conditions favorable for extensive wetlands, shaded rivers, and a much more cosmopolitan continental ichthyofauna. During this time, the hydrological systems were predominantly stable, with rivers and lakes maintaining relatively consistent water levels due to abundant precipitation, which supported various aquatic habitats.

The Middle Miocene Epoch (16–11 Ma) saw profound changes, particularly with the Congo River's headwaters shifting southward, which reorganized existing drainage patterns and diverted river systems such as the Fwa and Inkisi (Flügel et al. 2015). This period also corresponded with increasing sedimentation rates driven by climatic fluctuations, enhancing erosion and reshaping the geological configuration of the basin (Guillocheau et al. 2015). There was a marked retraction of rainforests and emergence of more open savanna landscapes, indicative of increasing aridity (Couvreur et al. 2021; deMenocal 2004; Plana 2004). This transition influenced hydrology by altering river flow patterns and lake levels, potentially leading to the abandonment or rerouting of certain river courses and changes in wetland extents, thereby impacting the habitats available for aquatic species (Lévêque 1997). In approximately the Middle Miocene, the Central African Atlantic Swell formed a low mountain range stretching from South Cameroon to South ROC (Guillocheau et al. 2015; Schefuß et al. 2016) contributing to the divergence of Lower Guinea and Congo freshwater fauna (Lévêque and Paugy 2017).

Simultaneously, the Albertine Rift, located along the western margin of the East African Rift System, played a critical role during this period (Guillocheau et al. 2015). The ongoing tectonic activity caused notable uplift and volcanic activity in the region, which directly influenced the hydrography of the Congo Basin and surrounding areas (Guillocheau et al. 2015). Initially, by the Late Miocene (11–5 Ma), the area that would become Lake Tanganyika was characterized by a mosaic of shallow, temporary lakes, and wetlands instead of a singular, large lake basin (Cohen et al. 1997). Global cooling began to take hold, contributing to further aridification. Precipitation patterns became more erratic, leading to lower water levels in rivers and lakes, which may have resulted in seasonal wetlands and increased isolation of aquatic environments (Cohen et al. 1997). This drying trend would have introduced new ecological dynamics, as species adapted to fluctuating water availability, shifting the evolutionary pressure on aquatic organisms.

Transitioning into the Pliocene (5.3–2.6 Ma), the uplift of the Congo and Angolan margins accelerated, facilitating extensive geomorphic transformations (Savoye et al. 2009). Tectonic uplifting activities in the Albertine rift (Lezzar et al. 2002) severed an east-west river linking the eastern Congo basin from the Tanzania plateau, the remnants of which can be seen in the Lukuga and Malagarasi rivers, respectively West and East of lake Tanganika (Cohen et al. 1997; Goodier et al. 2011). The favorable conditions of this era supported the expansion of tropical rainforests, which likely contributed to a rise in water levels across various lakes and rivers (Runge 2022; Weiss et al. 2015). The enhanced rainfall conditions resulted in more substantial hydrological connectivity among various water bodies, facilitating the movement of aquatic species and likely reducing isolation among populations (Van Steenberge et al. 2020).

By the Late Pliocene, the region's uplift had caused approximately 500 m of elevation changes (Goodier et al. 2011). This uplift contributed further to the intricate topography of the basin, altered precipitation patterns leading to the establishment of incised valleys and a more complex network of river systems reflecting both dendritic and linear characteristics. The Pliocene-Pleistocene transition introduced increased climatic variability characterized by glacial and interglacial cycles (deMenocal 1995; Plana 2004). The consequent fluctuations in climate had significant effects on the hydrology of the Congo Basin, leading to oscillating lake levels and changing river flows over time. During wetter periods, rivers could expand and create extensive floodplains and wetlands whereas during drier phases, lakes and rivers might have receded or fragmented, resulting in isolated pockets of water that acted as refuges for various freshwater species (Bragança and Costa 2019). The Pleistocene (2.6–0.012 Mya) witnessed ongoing adjustments to river channels due to tectonic influences associated with the East African Rift system, enhancing the sensitivity of these systems to geological disruptions (Guillocheau et al. 2015). By the Late Pleistocene, the three main basins that had existed since the Miocene had coalesced to the modern single basin of Lake Tanganyika (Weiss et al. 2015).

The origins of the Congo River can be traced back to earlier configurations, which were defined during periods when the basin was shaped by both tectonic activity and climatic regimes conducive to sediment deposition and erosion (Guillocheau et al. 2015). Importantly, for reconstruction of historical biogeography there is considerable ambiguity concerning the events and chronology forming today's main channel of the Congo River (Stankiewicz and de Wit 2006; Takemoto 2023). A vast body of literature, much outside the public domain, supports unequivocally the existence of a river flowing into the Atlantic at or near the present-day outlet for the past 30 mya (Burke et al. 2008). There is some disagreement of whether the antecedent river emptied into the sea 200 km North (Karner and Driscoll 1999; Uenzelmann-Neben 1998) prior to the Pliocene. The turbite sediment transport path of the Congo Fan attests that the Congo River fed into the Atlantic at its present course by the Early Pliocene (Anka et al. 2009).

Palynological records from the Congo fan provide further insights into the river's history and climate in the Congo Basin. These records indicate that the Congo River had assumed its present course by the Middle Pleistocene. The pollen data also reveal fluctuations in forest cover, with *Podocarpus* (Afromontane) forests expanding during cool, humid glacial stages (1.05–0.6 Ma) and swamp assemblages dominating during warmer inter-glacial periods. Megadroughts occurred at 135 and 75 kya that exceeded the aridity of the Last Glacial Maximum and a major rise in rivers at 70 kya (Dupont et al. 2001; Scholz et al. 2007). The blackwaters of the Cuvette Centrale formed only around 17.5 kya, highlighting the millennial-scale dynamics of landscape evolution that remain obscured for most of the Congo Basin.

## Montane Ecosystems

Submontane and montane forest ecosystems represent about 2.8% and 0.8% of the forested area of the Congo Basin, respectively. They are found essentially in two

regions separated by about 2000 km at the western and eastern limits of the Congo Basin: (1) the Cameroonian Volcanic Line (CVL) stretching from the islands of the Gulf of Guinea to the Adamawa plateau in northern Cameroon and (2) the Albertine Rift situated across the border between DRC, Uganda, Rwanda, Burundi, and Tanzania (Fig. 3, areas above 1000 m elevation).

Montane forests of Cameroon are part of the West Africa Biodiversity Hotspot (Myers et al. 2000). These forests are not only exceptional for their plant richness and endemism, but also for their faunal diversity (Denys et al. 1999; Muafor et al. 2011). In addition, they provide a wide range of ecological services, vital for local populations as a source of water, and offer many forest products such as firewood, timber, medicinal plants, and fruits (Fogwe and Kwei 2015). Afromontane forests are patchily distributed, bounded at higher elevation by Afroalpine grasslands and an ericaceous belt, and at lower elevation by sub-montane forests and savannas, which form the transition between lowland rain and seasonal forests. *Podocarpus latifolius*, the emblematic tree of these Afromontane forests, is found between 850 and 2900 m altitude on the CVL, where it can form large monospecific stands, as on Mount Oku (the Kilum-Ijim forest). It is also found on isolated massifs and inselbergs all along the west coast of Africa, from Angola to Cameroon/Nigeria, in populations rarely exceeding a few dozen individuals. Located within or on the fringes of densely populated regions, Afromontane forests are at serious risk from anthropogenic pressure. For example, in Cameroon the Kilum-Ijim forest which covered 20,000 hectares has lost 62% of its area, which was converted into cropland and became increasingly fragmented between 1978 and 2001 (Solefack et al. 2012).

Montane forests of Cameroon have long been considered as contemporary relicts occupying refugial areas in response to an exceptionally favorable climate in the recent past (White 1993). Based on the presence of distant populations of *Podocarpus*, White (1981) postulated a connection between East, South, and West African Afromontane forests. Recent genetic studies confirm past connections between East and West Africa (Migliore et al. 2022) but also show a barrier to gene flow across the Equator in western Central Africa.

The vegetation history of the montane forests is better known than that of the lowland forest of the Congo Basin because many montane forests are found in regions where volcanic crater lakes offer ideal conditions to accumulate pollen in their sediments, providing continuous pollen records up to about 90,000 years (Lézine et al. 2019). Late Quaternary pollen data (Lézine et al. 2019, 2023) in the northern sector of the CVL point to the long-term persistence of montane populations with fluctuating sizes according to climate change: expansion during interglacial periods and reduction during glacial maxima. They show that the upper tree line was particularly unstable, shifting substantially in response to climate change, whereas the transition between the montane and lowland forests remained remarkably stable. In the southernmost sector of the CVL (Lézine et al. 2025), a slightly different scenario emerges with *Podocarpus* populations comparatively slightly more developed during the last glacial and dramatically reduced during the Holocene. Interestingly, *Podocarpus* is today absent from the Manengouba Massif and Mount Cameroon. Only relict, poorly developed, populations persist in

this sector such as in Mount Kupé and the Ebo forest of Cameroon. A similar evolution seems to have occurred in some areas of the Congo Basin, such as in the Bois de Bilanko in Congo (Elenga and Vincens 1990), where forest trees (*Podocarpus*, *Olea*, *Ilex*) may have spread to low elevations during the last glacial and then disappeared during the Holocene. However, no such environmental change is recorded in the glacial sequences of Ngamakala in Congo (Elenga et al. 1994), showing that the biodiversity of the central forest massif was far from homogeneous at that time. Marine cores (Dupont et al. 2000) also note the presence of *Podocarpus* populations during the last climatic cycle in equatorial West Africa but point to strong regional disparities. While a remarkable and continuous expansion of *Podocarpus* populations is recorded in Gabon except for the Holocene (core GIK 16876), successive phases of development/contraction of *Podocarpus* populations are recorded in Congo (core GeoB 1008).

All these cores show that, despite major changes in diversity, the Central African forest has not undergone major phases of retraction during the last climatic cycle. It is only at the edge of the forest massif to the north (lakes Bosumtwi in Ghana (Talbot et al. 1984) and Barombi Mbo in Cameroon (Maley and Brenac 1998) that the massive expansion of grasslands at the expense of the forest during the last glacial is recorded. These results partly confirm the hypothesis (Aubreville 1949) that the northern limit of the Guineo-Congolian forest may have shifted southward during the last Ice Age.

In response to the abrupt increase in rainfall at the last glacial-interglacial transition (Weldeab et al. 2007), montane forests gradually developed to reach an optimum between 9.5 and 8.5 ka (Lézine et al. 2025). The Holocene forest expansion lasted until 3.3–3.0 ka, depending on altitude, when montane forests collapsed (Lézine et al. 2013). This collapse most certainly originated in the Middle Holocene, when rainfall seasonality was established (Vincens et al. 2010), resulting in the gradual destabilization of the forest block. While montane forest has partially recovered from the 3.3 ka environmental crisis at higher altitudes, this is not the case on the Adamawa plateaus, where montane forest has massively retreated. In the lowlands, the impact of this crisis was more a change in forest composition and density than the replacement of forests by a grass-dominated landscape (Vincens et al. 1999). This conclusion was recently confirmed by isotopic studies on soil profiles from Cameroon (Desjardins et al. 2020) and in the Congo basin (Bremond et al. 2017).

During the last few millennia, the forest cover remained roughly unchanged in the lowlands of the central forest massif (Lézine et al. 2023). In contrast, both high- and low-elevation sites from the western sector of the equatorial forest show a marked forest recovery that began in the early years of the little ice age and accelerated around 1450 CE. The forest expansion in this region occurred despite increased human presence. In the absence of sufficient archaeological and paleo-botanical data, the impact of neolithic populations on the natural environment is still the subject of intense debate. It is however probable that rather than a massive destruction of forest, people have used periods of climate-induced clearance events to develop agriculture (Ngomanda et al. 2009; Lézine et al. 2013).

### Bais and Other Rare Ecosystems

In addition to major ecosystems, the Congo Basin hosts relatively rare ecosystems stretching over narrow areas but hosting a unique flora and/or fauna, such as inselbergs (Parmentier et al. 2005), cave systems (Labadie et al. 2025), mangroves (Ajonina et al. 2008), and swampy forest clearings or baïs. Generally in Central Africa, the term "baï" is used by indigenous peoples of the region to describe this environment. This term bai is now widely used to describe these forest clearings.

These botanically remarkable azonal biotopes are a real magnet for forest fauna. For example, at Langoué in the south of the Ivindo National Park (Gabon), the Wildlife Conservation Society has recorded nearly 1080 elephants and 52 gorillas that regularly visit the clearing. One of the largest and best known bais is Dzanga Bai (CAR) has been the site of long-term elephant studies spanning several decades. These clearings thus offer the opportunity to study large mammal behavior and represent a vital asset for the development of ecotourism.

Deuse (1960) carried out the first ecological and phyto-sociological study of the esobe vegetation in the eastern region of Lake Tumba. This study distinguished a number of groups and associations. An open-water aquatic grouping, with a depth of between 10 cm and 1 m and a bottom composed of muddy peat. A semi-aquatic group characteristic of the lower parts of the esobe that are periodically flooded. An exundated peaty grouping that develops at the head of springs and in the beds of the streams that flow from them. A *Rhynchospora corymbosa* association that is established on waterlogged peat of around 50 cm and forms tight clumps. An association between *Bulbostylis laniceps* and *Xyris vanderystii*, which is established on firm peat, 10–50 cm thick. An association between *Stipularia africana* and *Syzygium* aff. *cordatum*, a shrubby formation scattered along the small watercourses of the baï.

More recently in ROC, Lejoly and Lisowski (1997) carried out a study of the vegetation of clearings on hydromorphic soil in Odzala National Park and described three new associations and one grouping. In Gabon, no in-depth botanical study had yet been carried out on these particular biotopes until Temgoua (2006) carried out a detailed characterization of marshy clearings in the Ivindo National Park. More recently, Boupoya (2010) completed his thesis on the flora and vegetation of these environments in Ivindo National Park, identifying 229 species in 175 genera and 72 families across 133 phyto-sociological surveys. The overall flora of the clearings is dominated by Cyperaceae, Rubiaceae, and Fabaceae.

## Biodiversity Patterns

### Species Distribution Models

The Congo Basin contains more than 10,000 plant species, among which at least 2264 are tree species, 1966 shrub species, 1384 liana species, and 3510 herb species (Sosef et al. 2017). About 30% of those species are endemic to the Congo Basin.

Although plants and vertebrates are the best studied organisms, the degree of botanical exploration shows many geographical gaps, in particular in some countries like ROC, CAR, and large areas within DRC (Sosef et al. 2017). Therefore, new species are regularly described (Lachenaud et al. 2018), and genetic markers can greatly help to delimit closely related species, for example, in trees (Bouka et al. 2024; Dainou et al. 2014). It is likely that the majority of extant species in the Congo Basin have been formally described for groups like plants, birds, and mammals. However, this is probably not the case for arthropods (Stork 2018). Therefore, huge efforts are still needed to describe existing species of the Congo Basin.

The geographic distribution of species varies widely from widespread species to narrow endemic species. For example, Texier et al. (2022) have shown that about 15% of the endemic flora of western central Africa has a known range size of less than 10 $km^2$. Species distributions depend on numerous factors, but a few interlinked factors are particularly important: (i) the distribution of the habitat(s) to which the species is adapted, (ii) the species dispersal ability in relation to potential barriers to dispersal (oceans, mountains, rivers, savannas), (iii) species interactions (e.g., prey-predator relationships, diseases, parasitic relationships but also mutualisms like plant-pollinator, plant-seed disperser, or plant-mycorrhizal relationships, which can be more or less specific and obligatory), and (iv) the history of environmental and biotic factors affecting the distribution of a species.

In the Congo Basin, many species are adapted to only one of its constituent ecosystems (e.g., lowland forest, montane forest, savannas, etc.), and sometimes to a particular component of an ecosystem (e.g., periodically inundated forest). The distribution of species with good dispersal and competitive abilities tends to follow quite closely the distribution of habitats to which they are well adapted and can be modeled reliably using gridded environmental layer data like Climate Research Unit (Harris et al. 2020) or WorldClim (Fick and Hijmans 2017). However, species with poor dispersal abilities, or adapted to a highly fragmented habitat type (e.g., montane ecosystems), may only occupy a subset of their potential habitats. The distribution of forest species with limited dispersal ability, such as *Begonia* plants, can potentially reveal the position of Pleistocene forest refugia (Sosef 1994). Even within the relatively continuously distributed lowland forest of the Congo Basin, barriers like major rivers can delimit the range of some species including many primates and artiodactyls (Anthony et al. 2007; Colyn et al. 2001; Fonteyn et al. 2023; Kingdon 1989). By contrast, rivers usually do not represent major barriers for plant species. Finally, given that environmental conditions are always changing, though at varying paces, species ranges are not explained by the current distribution of habitats or barriers but by past environmental and biotic conditions so that their current ranges reflect just a moment in their slow colonization or retreat. For such cases, species distribution models must be interpreted cautiously as they can miss the actual drivers of a species' range.

## Community Patterns of Diversity

Species assemble in communities whose composition depends on different ecological and evolutionary processes (Chesson 2000; Thompson et al. 2020;

Vellend 2010). Among the main drivers of species assemblages are (i) selection through habitat filtering, (ii) biotic interactions (competition, predation, parasitism, mutualism), (iii) dispersal, and (iv) ecological drift (stochastic fluctuations of population sizes due to their finite size). At deep temporal scales, speciation and adaptive evolution also matter, constituting the ultimate sources of diversity. The development of large public databases of species occurrences (e.g., GBIF, https://www.gbif.or) has benefitted from better quality controls (Brooks et al. 2001) for African vertebrates (Dauby et al. 2016) for African plants and has greatly facilitated large-scale community ecology studies (Silva de Miranda et al. 2022). A big challenge to addressing the ecology of species-rich communities is that there is little knowledge of species' individual ecology, making it difficult to understand the proximal mechanisms underlying species assembly. Functional ecology and the analysis of phylogenetic structure of communities can circumvent this challenge to some extent.

Studies in the Congo Basin generally highlighted the importance of environmental filtering, for example, in fishes (Walsh et al. 2022). The analysis of functional traits and their inter-correlation can also reveal a continuum of opposing strategies favoring coexistence through niche partitioning. For example, in rainforest trees, large-statured, light-demanding, deciduous and wind-dispersed species dominating the canopy coexist with small-statured, shade-tolerant, evergreen and animal-dispersed species found in the understory (Loubota Panzou et al. 2018). Tree species with the most original functional traits tend also to be the rarest so that the analysis of functional traits can guide conservation priorities to favor functional originality rather than redundancy (Kearsley et al. 2019).

Community phylogenetics integrates phylogenetic relationships among species into the analysis of communities. When species assemblages are mostly driven by environmental filtering, we expect that related species will tend to occur in the same habitats, a pattern known as phylogenetic clustering, while if competitive exclusion dominates, we expect the most related species to exclude each other, leading to a pattern known as phylogenetic overdispersion (Hardy and Senterre 2007). Species phylogenies are much easier to obtain thanks to advances in DNA sequencing tools and access to public DNA databases (e.g., GenBank) and large DNA-based phylogenies for some broad taxonomic groups, like angiosperms (Janssens et al. 2020). The most often encountered pattern in the Congo Basin is a phylogenetic clustering of species in local communities, suggesting that habitat filtering is more important than competitive exclusion, at least in plants (Hardy and Senterre 2007; Parmentier and Hardy 2009; Parmentier et al. 2014). Broad-scale patterns of phylogenetic diversity can also identify areas where paleo- or neo-endemism occurs. For plants, the Guineo-Congolian lowland rainforest region is characterized by widespread and old lineages while mountainous areas are centers of both neo- and paleo-endemism (Dagallier et al. 2020), highlighting the importance of conserving their unique biodiversity where evolutionary processes are very active. Finally, community phylogenetics reveals the legacy of evolutionary constraints: studying tropical African woody species, Gorel et al. (2022) showed that most forest and savanna species were adapted to one of six bioclimatic subgroups, wet forest, moist forest, dry forest, cold savanna, hot savanna, and a coastal group intermediate between

forest and savanna groups. Despite a general trend of climate niche conservatism during speciation over the last 50 mya, biome shifts occurred from forest to savanna in about 5.2% of cases and from savanna to forest in about 1.8% of cases, indicating that most woody lineages originate from the forest biome, probably because the rainforest was much more widespread in Africa for most of the Cenozoic before the Pleistocene (Kissling et al. 2012). Furthermore, climate niche was much more labile in some families (e.g., Fabaceae and Rubiaceae) and some genera (e.g., *Combretum*, *Ficus*, *Cola*) and highly conserved in some large clades, like the order Magnoliales, which rarely adapted to savanna (Gorel et al. 2022).

## Drivers of Diversity Patterns: Pleistocene Refugia, Riverine/Landscape Barriers, and Environmental Gradients

In an era of unprecedented anthropogenic environmental change, informing conservation strategies with an understanding of the mechanisms that drive population structure and the formation of new species is vital. Conservation strategies should aim to preserve the evolutionary processes that generate and maintain this genetic variation. The hope is that some of the genetic variation those processes have produced will enhance species' "evolvability," i.e., ability to mount an *in situ* evolutionary response to threats like climate warming and habitat disturbance.

The evolutionary processes responsible for speciation in African rainforests have continued to engender debate (Moritz et al. 2000b). Typically, these discussions have centered on the importance of geographic isolation versus ecological gradients. Historically, emphasis was focused on isolation driven by lowland glacial refugia (Haffer 1969; Mayr and O'Hara 1986). Notably, the role of Pleistocene glacial refugia (Fig. 4) in isolating previously contiguous rainforest populations and driving rainforest diversification (Haffer 1997). Other allopatric speciation models included isolation on mountains during glacial periods (Fjeldsa and Lovett 1997; Moreau 1966; Roy 1997) or major riverine barriers to gene flow (Moritz et al. 2000b).

Lacking, however, are attempts to distinguish the actual mechanism(s) of divergence and speciation. Typically, if divergence was found in allopatry, genetic drift was assumed to be the likely cause (Roy 1997), though selection might be an equally parsimonious explanation. Moritz et al. (2000a) emphasized the importance of testing alternative mechanisms, including measuring the relative roles of selection and drift in promoting divergence and speciation.

In addition to the role of geographic isolation in allopatric speciation, there is mounting evidence for the role of natural selection along environmental gradients in driving ecological speciation. Early studies (Endler 1982a, b; Gentry 1989) emphasized the dominant role of natural selection in parapatry—in which adjacent populations inhabit different environmental regimes—might play in rainforest speciation. Empirical studies that followed showed evidence in a wide array of taxa (Ogden and Thorpe 2002; Orr and Smith 1998; Schluter 2009). Studies suggesting that parapatric speciation along environmental gradients may be common are further bolstered by theoretical models showing that this mode of speciation can readily

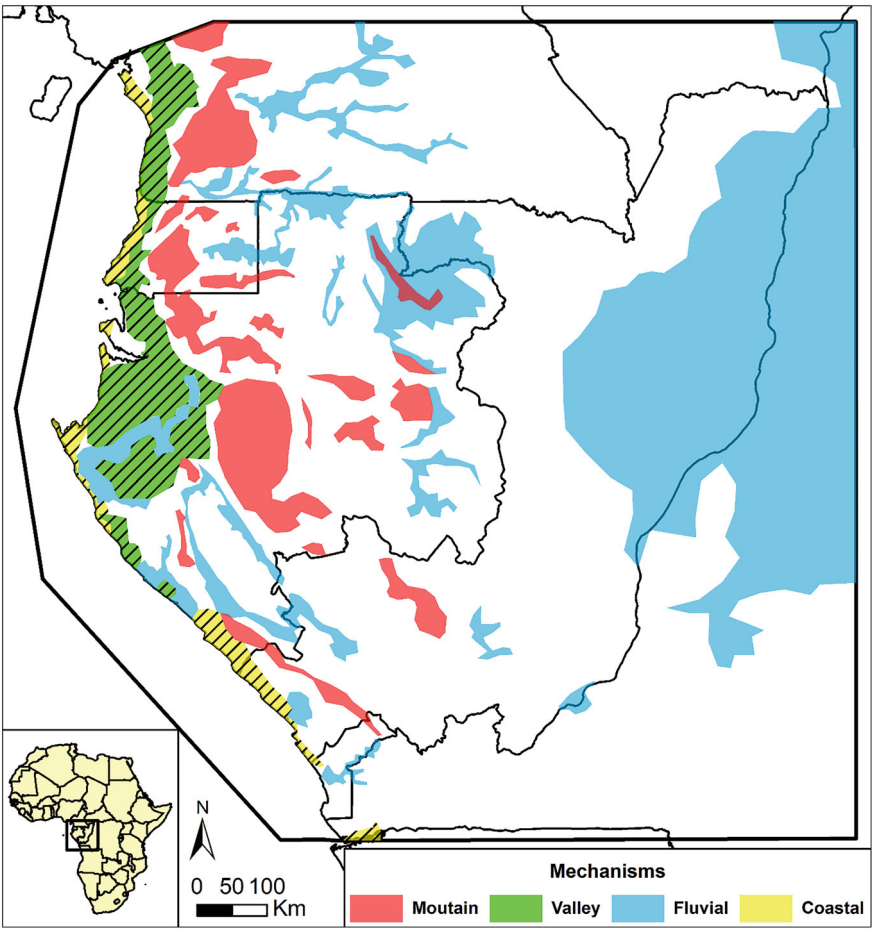



**Fig. 4** Putative schematic locations of forest refugia in western Central Africa during the Last Glacial Maximum. The four colors indicate the main hydrological mechanism on which the existence of putative forest refugia is based and the hatched parts symbolize territories where only microrefugia would have persisted over a small surface of the colored part. (Adapted from Texier (2021))

occur (Doebeli and Dieckmann 2003; Gavrilets et al. 2000). Hindering progress is a lack of robust tests of these competing hypotheses. The importance of allopatric and parapatric speciation may depend on time scales and the type of organisms. Moreover, geographic isolation and selection can act together, such as in the "vanishing refuge model" (Barratt et al. 2018; Couvreur et al. 2021), where climate change would firstly isolate a population in a temporary micro-refugium and then force adaptation to new environmental conditions, eventually leading to speciation.

African rainforests are severely at risk due to a myriad of anthropogenic threats, including climate change. This makes addressing this long-standing debate critical

for making informed conservation decisions. Genetic studies of diverse African rainforest species, including birds (Smith et al. 2000; Zhen et al. 2017), mammals (Anthony et al. 2007; Gonder et al. 2011; Ntie et al. 2017), reptiles (Allen et al. 2021; Freedman et al. 2023), amphibians, and plants (Hardy et al. 2013; Jongsma et al. 2018), have revealed varying degrees of population structure. Rough geographic concordance between patterns of genetic differentiation and hypothesized rainforest refugia are used to support arguments for allopatric isolation in ancient forest refugia as the primary generator of rainforest biodiversity. However, only a few studies have attempted to test the refugial model's fit to genome-scale data (Barratt et al. 2018; Jaynes et al. 2022; Pineiro et al. 2017). Moreover, molecular clock estimation of population divergence are often much more ancient than the last glacial cycle and can vary greatly (Matvijev et al. 2022; Migliore et al. 2020; Pineiro et al. 2021), even among species displaying similar phylogeographic structures (Demenou et al. 2020), so that it is usually not possible to assess whether populations diverged in response to glacial cycles or other drivers. At the inter-specific level, dated species phylogenies of plant and animal taxa indicate that diversification occurred mostly from the Late Miocene to Pliocene (Couvreur et al. 2021), so that the contribution of Pleistocene climate change to the species diversity today would be restricted to a few clades, for example, in some mammals, e.g., fruit bats (Nesi et al. 2021), forest duikers (Johnston and Anthony 2012), cercopithecine monkeys (Guschanski et al. 2013), and a few plants, e.g., *Begonia* (Plana 2004).

Although there is direct pollen evidence from oceanic cores that major vegetation changes in the Congo Basin followed the glacial-interglacial rhythm, at least since 1.05 million years (Dupont et al. 2001), the hypothesis that the lowland forest of the Congo Basin was fragmented during the Pleistocene glacial periods has been mainly supported by indirect evidence. Moreover, the impact of low atmospheric $CO_2$ concentration during the glacial peaks is also difficult to establish due to the absence of similar conditions in today's vegetation (Dupont et al. 2001). There is some support for the periodic fragmentation of rainforest into refugia from palaeoecological studies (Anhuf et al. 2006; Maley 1996; Maley and Brenac 1998), detailed plant genetic investigations, and current distribution patterns of areas of endemism of forest plant taxa (Sosef 1994; Texier 2021). Texier (2021) explored different mechanisms maintaining rain or moist forests during glacial periods based on the accessibility of water to plants through shallow water tables and low stratiform clouds in drier climates, suggesting that in addition to some permanent forest blocks such as those proposed by Maley (1996, 2001), many areas in Lower Guinea could have remained suitable for forest species, possibly within forest-savanna mosaic landscapes. It should be stressed however that claims for the importance of refugia in the diversification of forest taxa have often been made despite few efforts to examine possible roles of environmental gradients, genetic divergence by environmental variation, or analyses of adaptative phenotypic variation. An alternative hypothesis, namely, parapatric speciation (Smith et al. 1997), cannot be adequately tested without such data. Consequently, the refugia hypothesis can become an implicit null model without the evidence to justify it. For speciation along the African rainforest-savanna gradient, evidence has been indirect and often

many decades old and based on data such as the frequency of contact zones between forest and savanna habitats versus those between refugia (Endler 1982a, b).

In contrast, many recent studies have found that divergent natural selection across environmental gradients may be an essential generator of African rainforest biodiversity (Freedman et al. 2023; Smith et al. 1997; Zhen et al. 2017). These studies rely on either differentiation in phenotypic traits involved in local adaptation or evidence for isolation-by-environment or IBE (Wang and Bradburd 2014), in which allele frequency-environment correlations cannot be explained solely by geographic distance alone. While these studies indicate diversifying natural selection may contribute to an ongoing process of genomic divergence, none of them have demonstrated that speciation across the gradient has occurred. However, a recent study that employed a panel of tens of thousands of SNPs found evidence for speciation along the rainforest-savanna gradient in a rainforest lizard that was likely driven by local adaptation (Freedman et al. 2023). More integrative investigations across multiple species are needed to elucidate general patterns concerning the role of local adaptation via diversifying selection and to disentangle adaptation from isolation such as that which might arise in putative refugia. General patterns concerning the relative contribution of adaptation, isolation via refugia, and divergent selection among refugial represent a gap in our knowledge of the mechanisms that generate and maintain biodiversity in African tropical forests.

Several other alternative historical scenarios of diversification and speciation of rainforest and savanna taxa have received relatively little attention but should be the focus of future studies. For example, there is limited evidence to suggest that the isolation of savanna remnants during warmer interglacial periods may have played a role in driving intra-specific diversification in central African grassland rodents (Mboumba et al. 2011). Similarly, the role of the seasonal inversion in rainfall patterns either side of the equator in driving species diversification has been documented in plants but has received little attention in other central African taxa (Hardy et al. 2013; Helmstetter et al. 2020; but see Blatrix et al. 2017). There is also a general lack of knowledge of the role that riparian areas could have played in providing microrefugia during drier glacial periods (Leal 2001, 2004) and deserves further attention.

## Evolutionary-Informed Approaches to Conservation Decision-Making

### Phylogenetics and Phylogenomics

Phylogenetic systematics is the study of evolutionary relationships between organisms and has been applied to a wide range of issues such as resolving taxonomic issues, estimating phylogenetic diversity, dating species radiations and inferring evolutionary specific units or ESUs (Avise 2000; Ksepka et al. 2015; Pellens and Grandcolas 2016). Phylogenetic methods have also been used extensively to map the geographical distribution of evolutionary lineages (phylogeography) and infer

biogeographical history (Avise 2008; Matvijev et al. 2022). Although molecular phylogenies have traditionally been based on a handful of markers, there is increasing interest in using genome-wide approaches (phylogenomics) to more accurately estimate phylogenies. Lastly, DNA sequence data has been used in DNA barcoding approaches to identify species from reference databases and in DNA-based surveys of environmental samples (DeSalle and Goldstein 2019).

Phylogenetic analyses of species radiations within the Congo basin have been carried out in a wide range of taxa. Africa was an island continent from the mid-Cretaceous to early Miocene leading to approximately 75 million years of isolation and a complex migration history (Gheerbrant and Rage 2006). A number of groups that either originated or are endemic to the Congo Basin region include mammals within the superorder Afrotheria (Springer et al. 1997; Stanhope et al. 1998), artiodactyls (Johnston and Anthony 2012; Rakotoarivelo et al. 2024), birds (Huntley et al. 2018; Huntley and Voelker 2016; Nana et al. 2014), rodents (Nicolas et al. 2005; Pradhan et al. 2021), crocodilians (Shirley et al. 2014), and amphibians (Blackburn 2008; Zimkus et al. 2010). Despite its lower plant diversity compared to the Neotropics or South-East Asia, tropical Africa also hosts many plant lineages that diversified locally (Couvreur et al. 2021; de la Estrella et al. 2020; Ojeda et al. 2019).

Species radiations associated with CVL, Albertine Rift, and Eastern Arc mountains have also been documented and are associated with high levels of endemicity (Cable and Cheek 1998; Cheek et al. 2000; Dolinay et al. 2021; Greenbaum et al. 2015; Voelker et al. 2009). All of these areas are considered to be biodiversity hotspots based on their high levels of endemicity and degree of threat (Myers et al. 2000). Phylogenetic studies have also been used to trace patterns of diversification across the oceanic islands of the Gulf of Guinea (Bell et al. 2014; D'Haijère et al. 2022). Indices of phylogenetic diversity have also been used to rank sites for biodiversity (McGoogan et al. 2007; Smith et al. 2000). These approaches have also been applied to plant communities to infer ecological and evolutionary processes in the Congo Basin at local (Hardy and Senterre 2007; Parmentier et al. 2014) and continental (Dagallier et al. 2020) scales.

Previous studies have shown that divergence times of many species predate the Pleistocene (Hassanin et al. 2018; Migliore et al. 2018; Rakotoarivelo et al. 2024; Shirley et al. 2014) and in plants may be associated with shifts in karyotype (Farminhão et al. 2021). However, climate oscillations within this epoch have most likely played an important role in recent speciation and/or intra-specific diversification (Duminil et al. 2013; Gaubert et al. 2016; Huntley et al. 2018). Similarly, intra-specific diversification across the CVL has been documented in a number of species groups (Demenou et al. 2020; Migliore et al. 2020).

Phylogenetic systematics and DNA barcoding have also helped document biodiversity, reveal cryptic lineages, and resolve taxonomic relationships (Decru et al. 2016; Delabye et al. 2019; Ntie et al. 2010; Sonet et al. 2019). However, the lack of robust reference databases and resolution of individual species can hamper DNA barcoding efforts (Johnston et al. 2011; Parmentier et al. 2013). Lastly, DNA barcoding tools have been applied to wildlife forensics and the tracking of the timber trade (Mascarello et al. 2023; Mwale et al. 2017), providing promising avenues for international regulation of illegal trafficking.

## Population Genetics, Single Nucleotide Polymorphisms (SNPs), and Genomics

Population genetics is the study of patterns of population genetic variation and evolutionary diversification at the intraspecific level (Riddle and Jezkova 2019). In Congo basin animals, hypervariable mitochondrial DNA sequences and nuclear microsatellite analyses have been traditionally used to quantify genetic variation, assess genetic structure, infer demographic history, and interpret phylogeographic patterns (Anthony et al. 2007; Gonder et al. 2011; Mitchell et al. 2015a; Nicolas et al. 2011; Ntie et al. 2017). Chloroplast DNA sequences, nuclear loci, and microsatellites have been typically used in plants (Hardy et al. 2013; Ley et al. 2017; Matvijev et al. 2022; Vanden Abeele et al. 2023). Generally, these studies point to the importance of Pleistocene refugia and/or riverine barriers in intraspecific diversification. However, competing models of diversification resulting from selection across environmental gradients or isolation in riparian refugia have received relatively little attention.

More recently, population genetic studies have been refined to include the development of single nucleotide polymorphisms (SNP) arrays, restriction-associated DNA or RAD sequencing, and whole plastome or mitochondrial DNA sequencing (Faye et al. 2016; Jones et al. 2018). For example, whole chloroplast genome sequencing revealed signatures of large-scale range expansion starting 200,000–300,000 years ago for three tree species characteristic of different vegetation types: *Staudtia* in the Congolian rainforest (Matvijev et al. 2022), *Brachystegia* in Miombo savannas (Boom et al. 2021), and *Podocarpus* in montane forests (Migliore et al. 2020). Whether these range expansions were truly synchronous and resulted from a period of major vegetation changes throughout tropical Africa remains to be tested. Generally, genome-wide studies have revealed the underappreciated role of ecological gradients in driving intraspecific diversification and highlight the importance of using rigorous statistical approaches to differentiate between competing models of diversification (Freedman et al. 2023; Miller et al. 2024). Gene-environmental associations (GEAs) have also been explored in several studies using RAD sequence data to identify candidate loci that might be targets of selection (Morgan et al. 2020; Smith et al. 2021). These studies and others (Miller et al. 2024) also point to the potential use of indices of "genomic vulnerability" or "genomic offset" that measure the degree to which populations will have to adapt to future climate change.

In general, most studies of medium- to large-sized animals have been based on non-invasive genetics using hair, feces, or museum specimens to generate mitochondrial, nuclear microsatellite, or major histocompatibility complex data (Mitchell et al. 2015a, b; Ntie et al. 2017; Weber et al. 2023). However, few studies have been able to tackle genome-wide studies without access to tissue or blood samples. Genomic analyses of non-invasively sampled species are still undergoing development, but approaches based on SNP arrays (Bourgeois et al. 2018; Laguardia et al. 2021) or targeted exon capture of non-model organisms (Jones and Good 2016) are developing rapidly and provide promising avenues for future work.

Population genetic approaches can also be used to differentiate patterns of gene flow between the two sexes. In animals, these studies have generally relied on comparing data from mitochondrial data (maternal) and either Y chromosomal (paternal) or nuclear microsatellite (biparental) markers. In plants, these questions have been addressed by comparing chloroplast DNA (maternal) to pollen (paternal) data (Petit et al. 2005). Population genetic approaches have also been used to delineate evolutionary significant units (ESUs) for conservation or in recommendations for the translocation and maintenance of evolutionary lineages of animals in captivity (Soto-Calderon et al. 2015). Forensic genetics have also been used to understand the geographic origin of confiscated samples and patterns of illegal trade (Tinsman et al. 2023; Wasser et al. 2015; Yeo et al. 2024). Lastly, species distribution models have been used to identify patterns of niche differentiation and its role in species evolution (Sesink Clee et al. 2015). Hind-cast modeling can also be used to predict the location of hypothesized refugia and help disentangle the effects of Pleistocene-era refugial dynamics from other potential drivers of genetic differentiation (Miller et al. 2024; Morgan et al. 2020).

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# The Hydrology of the Congo Basin

5

Raphaël M. Tshimanga, Mark A. Trigg, Michel Bechtold, Venkataramana Sridhar, Phillip Negrel, Benjamin Kitambo, Gode Bola, Catherine Awidi Mushi, Kechnit Djamel, Guy Moukandi, Cyriaque Nguimalet, Sebastian Apers, Adrien Paris, Sly Wongchuig, Ayan Santos Fleischmann, Fabrice Papa, and Paul Bates

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R. M. Tshimanga (✉) · G. Bola · K. Djamel
Congo Basin Water Resources Research Center (CRREBaC) & the Regional School of Water (ERE), University of Kinshasa (UNIKIN), Kinshasa, Democratic Republic of the Congo

M. A. Trigg
School of Civil Engineering, University of Leeds, Leeds, UK

M. Bechtold
Department of Earth and Environmental Sciences, KU Leuven, Belgium

V. Sridhar
Department of Biological Systems Engineering, Virginia Polytechnic Institute and State University, Blacksburg, VA, USA

P. Negrel
BRGM, Orléans, France

B. Kitambo
Congo Basin Water Resources Research Center (CRREBaC) & the Regional School of Water (ERE), University of Kinshasa (UNIKIN), Kinshasa, Democratic Republic of the Congo

Institute of Geodesy, University of Stuttgart, Stuttgart, Germany

Department of Geology, Faculty of Sciences, University of Lubumbashi (UNILU), Lubumbashi, Democratic Republic of the Congo

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**Abstract**

The chapter provides a comprehensive review of the hydrology of the Congo River Basin (CRB), emphasizing its physical features, current data and models, hydrological processes, environmental pressures, and the evolving scientific understanding. Water resources of the CRB support vital ecosystem and societal services that include agriculture, fisheries, hydropower, navigation, water supply, biodiversity conservation, and maintenance of vulnerable ecosystems such as peatlands and flooded forests that are crucial for carbon storage and climate resilience. The CRB hydrology is shaped by its diverse physiographical and geomorphological features, linked through a complex river network encompassing wetlands, lakes, and groundwater systems. Connectivity between headwaters, the Cuvette Centrale, and major tributaries (Kasai, Lualaba, Oubangui, and Sangha) plays a central regulatory role. Our current understanding of these processes remains very limited, which restricts our ability to implement policies for water security and address the impacts of change on physical systems

C. A. Mushi
Department of Civil and Environmental Engineering, Ardhi University, Dar es Salaam, Tanzania

G. Moukandi
LMEI/CUSI/ENSP, Marien N'gouabi University, Brazzaville, Congo

C. Nguimalet
Département de Géographie, Faculté des Lettres et Sciences Humaines, Bangui, République Centrafricaine

S. Apers
Soil Service of Belgium (BDB), Willem de Croylaan, Leuven, Belgium

A. Paris
Hydro Matters, 1 chemin de la Pousaraque, Le Faget, France

S. Wongchuig · F. Papa
Université de Toulouse, LEGOS, CNES/CNRS/IRD/UT, Toulouse, France

A. S. Fleischmann
Mamirauá Institute for Sustainable Development, Tefé, Brazil

P. Bates
School of Geographical Sciences, University of Bristol, Bristol, UK

and society. Increasing pressures from deforestation, mining, land use, and climate change threaten hydrological stability, livelihoods, and ecosystem resilience. Heightened vulnerability to hydro-climatic extremes, such as floods, droughts, and landslides, and biological risks like Ebola outbreaks raises concerns of an approaching hydro-ecological tipping point. The chapter calls for urgent investment in monitoring networks, remote sensing, data integration, and predictive modeling to support sustainable water resources management and development. **Fifteen major hydrological research challenges are identified**, underscoring the need for robust scientific investment. Beyond the CRB, findings will enhance global understanding of tropical forest hydrology and reinforce the basin's critical role in the Earth System.

**Keywords**

Congo River Basin · Hydrological processes · Environmental pressures · Data and models · Scientific challenges

## Introduction

The contemporary history of the Congo River Basin (CRB) that we know to date includes the expedition of Henry Morton Stanley in early 1875 for the exploration of the great Congo River (Stanley 1890; Baker 1894; Wack 1905). It also includes the role of the Congo River in the transaction of goods between Arabs and the inhabitants of the Congo Basin in the nineteenth century, the slave trade, and the colonialism by western powers. The history is also shaped by early migrations of peoples who colonized the river banks of the basin (Vansina 1990; Tshimanga 2009). In February 1885, the General Act of the Berlin Conference provided the status of the Congo Basin in terms of its geographical extent, but also the freedom for trade and shipping across the Congo River to its mouth in the Atlantic Ocean and the ban on the slave trade. "This basin is bounded by the watersheds (or mountain ridges) of the adjacent basins, namely, in particular, those of the Niari, the Ogowé, the Chari, and the Nile, on the north; by the eastern watershed line of the affluents of Lake Tanganyika on the east; and by the watersheds of the basins of the Zambesi and the Logé on the south. It therefore comprises all the regions watered by the Congo and its affluents, including Lake Tanganyika, with its eastern tributaries."

The Congo River rises from the tributaries of the Lualaba and Lufira Rivers, in the southeast of the Katanga in the Democratic Republic of Congo (DRC), and flows 4700 km before emptying its average annual flow rate of about 41,000 $m^3/s$ into the Atlantic Ocean, covering a drainage area of 3.7 million $km^2$. The riparian countries of the CRB include DRC (62%), Central African Republic (11%), Angola (8%), Republic of Congo (7%), Zambia (5%), Tanzania (4%), Burundi, and Rwanda (0.49%). The tropical forest of the Congo Basin extends to the northwestern part of the topographic hydrographic boundary of the CRB, encompassing six riparian countries: Cameroon, Central African Republic, DRC, Gabon, Guinea Equatorial,

and the Republic of the Congo. This review focuses on the topographic hydrographic boundary of the CRB.

Historically, the Congo River served as the artery of colonial economic networks, enabling the export of minerals, timber, rubber, and other goods. Hydrological studies of the Congo Basin evolved largely to support these economic needs, particularly ensuring safe navigation for exports and assessing rainfall variability critical to agriculture.

A landmark in hydrological monitoring was the establishment of the Kinshasa gauging station in 1903 (4.30°S, 15.31°E), followed by over 400 flow gauges, 150 climate stations, and 1000 rainfall gauges between 1903 and the 1960s (Tshimanga 2022). This network provided robust hydrological data. However, after independence in the 1960s, monitoring networks declined due to limited state capacity and shifting political priorities. The implication is that there is a good coverage of hydrological records for the period before 1960, which are not sufficient to represent the current conditions of environmental changes in the basin.

The challenge of data quality necessary to foster adequate understanding of the hydrological functioning of the CRB and enable predictive capacities prompted large-scale experiments to collect new field data (Borges et al. 2019; Tshimanga 2022; Bates et al. 2023) and application of new robust approaches for hydrological predictions in the basin or validation of satellite missions (Alsdorf et al. 2016; Papa et al. 2022). There have also been efforts toward the use of global datasets, including global climate (both reanalysis and satellite-based) and physical basin properties datasets as well as satellite altimetry for prediction of water level and discharge (Kitambo et al. 2022; Paris et al. 2022). However, there are several challenges for performing such studies, including the uncertainty in modeling approaches and satellite estimates (Washington et al. 2013) and the lack of adequate in situ data to validate satellite-based information. Jointly, they pose difficulties to develop locally relevant predictive approaches that can effectively support water resources development in the basin.

The hydrology of the Congo Basin remains poorly understood, limiting effective water resource management and forecasting of environmental change impacts. Meanwhile, the basin faces escalating pressures from pollution (mining, industry, plastics, urban waste), river fragmentation, and deforestation, disrupting hydrological regimes and degrading aquatic habitats. Recent years have seen more frequent and intense extreme hydro-climatic events, including floods and landslides, signaling major shifts in basin dynamics (Tshimanga et al. 2016; Bola et al. 2022a). Research highlights a growing trend of hydrological drought in the Cuvette Centrale, threatening biodiversity and the survival of sensitive ecosystems like peatlands and permanently inundated forests, with profound ecological and socio-economic consequences Ndehedehe et al. (2022).

All these extreme events and the emergence of infectious diseases (Ebola, monkey pox) translate a disruption in the functioning of the Congo Basin ecosystem. What are the causes? Are we close to a tipping point in the Congo Basin? Demands for water resources are expected to increase from the other drought-plagued countries of Africa, which need the availability of information to establish sustainable

water resources management strategies. As human pressures grow, these ecosystems are at risk, and all the potential economic and environmental benefits they provide, including fluvial navigation and the blue economy, hydropower and renewable clean energy, agriculture for food security, and maintenance of endemic species and vulnerable ecosystems such as peatlands (Trigg and Tshimanga 2020).

There are major challenges for hydrological research and water resources management in the CRB (Alsdorf et al. 2016; Tshimanga 2022), which necessitate urgent attention in terms of investment for new data collection with experimental field work, remote sensing, and robust process based and predictive models, including artificial intelligence. This chapter provides a review of what we know to date on the hydrology of the CRB, current and future impacts, and it identifies possible knowledge gaps to inform future investment for hydrological science research and water resources management strategies in the Congo Basin and the region of central Africa.

## Dominant Features of the Hydrology of the Congo Basin and Connectivity

### Congo River Catchment and Its Evolution

The CRB is located within 10°N, 12°E to 14°S, 34°E (Fig. 1) and shares its drainage divides with other large river and lake basins of Africa, including the Zambezi basin in the south, the Nile basin in the east, and the Lake Chad basin (through the Chari River) in the north, all of which drain in opposite directions, thus emphasizing the complexity of regional drainage patterns. The extent of the Congo Basin tropical forest encompasses a number of other watersheds that include Kouilou-Niari, Ogoué, and Sanaga and drain their water into the Atlantic Ocean. Within the CRB itself, there is no single classical mode of drainage pattern which emphasizes the heterogeneous nature of the underlying geology. The CRB is approximately circular, ringed by topographic highs, also called "Swells" (Kadima et al. 2011) or "Rises" (Runge 2008), with a large central depression, an internal drainage basin known as the *Cuvette Centrale* (Bwangoy et al. 2010). These topographic highs include the Atlantic Rise on the western ridge of the basin, the Asante Rise on the northern ridge, the Mitumba Mountains on the eastern ridge, and the Lunda Rise (Shaba and Angola swells) in the southern ridge. The main rivers generated from the Atlantic Rise are known as the Sangha, Likouala Mossaka, Likouala Aux Herbes, Kouyou, Alima, Lefini, Nkeni, Foulakari, Mponzo, Luozi, and Inkisi. The Asante Rise encompasses the streams that drain the CRB starting from its drainage divides with the Chari (Lake Chad) and Nile Basins to the main trunk of the Congo River. This drainage unit is known as the Oubangui basin, the name of the main stream that connects all the upstream north-eastern tributaries to the main trunk of the Congo River (Nguimalet 2022). The Mitumba Mountains mark a clear drainage divide between the Congo and the Nile basins and constitute the source of the main rivers that provide substantial flow contributions to the Congo River at Kisangani and the lower

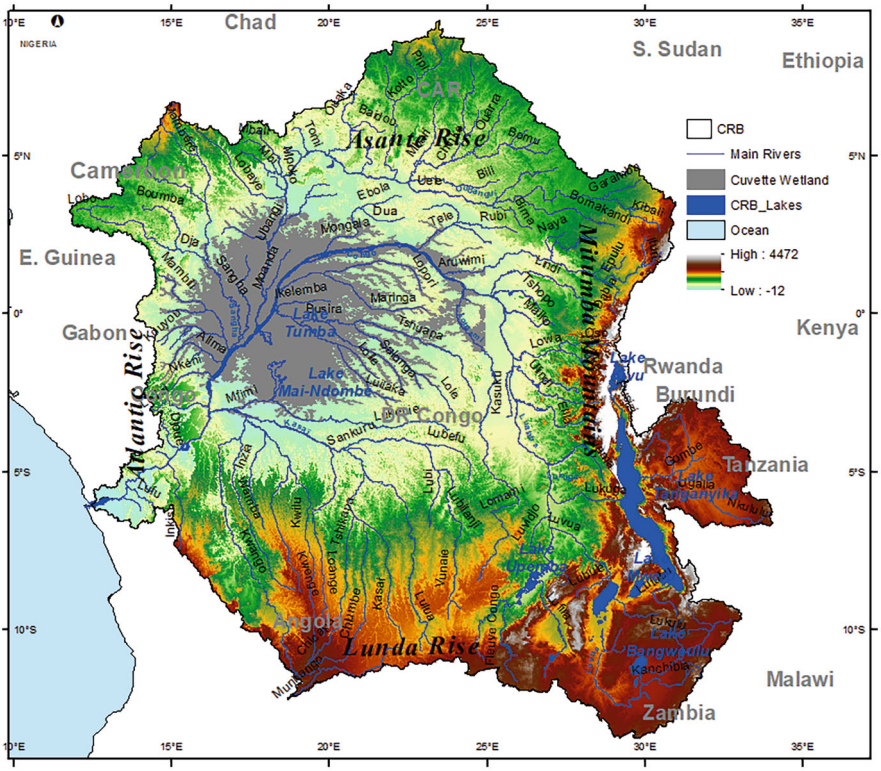



**Fig. 1** Physiographic setting of the Congo River Basin

part of Lualaba. The southern rim of the CRB is flanked by the Lunda Rise, which is shaped by the Angolan highlands in the south-west and the Shaba, or north Zambian swell in the south-east. The main rivers of the southern CRB, notably the Kasai and Lualaba Rivers, rise in the highlands of the Angolan and Shaba Swells (Lunda Rise), respectively.

The Congo River's unique arc-shaped course is a result of the basin's ancient geological and tectonic history, combined with its location across the Equator. This distinctive path is largely influenced by the Congo Craton, an ancient, stable continental crust in central Africa, which creates a bowl-shaped depression (the Cuvette Centrale) that directs the river in a sweeping arc across the region (Flugel 2014). This unusual course allows the river to cross the Equator twice, leading to its bimodal flood pattern and relatively stable year-round discharge with relatively small amplitude range for such a large river (Kitambo et al. 2022). The Congo's path also contributes to its extensive drainage network, which includes many large tributaries from both north and south of the Equator. This complex network results in consistent water flow, as the alternating wet and dry seasons in different parts of the basin integrate into the main channel to provide a continuous source of water to the river

throughout the year. Further west, the Congo passes through regions with varied topographies, including the Malebo Pool (formerly Stanley Pool), a wide, lake-like section where Kinshasa and Brazzaville sit on opposing banks (Kechnit et al. 2024). As the river approaches the Atlantic, it descends rapidly through the Livingstone Falls, a series of rapids that present a dramatic drop in elevation at the of its journey from the interior of Central Africa to the coast, where the river has no delta and instead carves a canyon into the sea floor (Talling et al. 2022).

Two main theories explain the Congo River's geomorphology and flow direction (Tshimanga 2012). The first posits a southeastward flow into the Indian Ocean during the Late Cretaceous–Paleogene, redirected by East African highlands uplift in the Oligocene/Eocene (Stankiewicz and de Wit 2006). Marine deposits in southeastern valleys support this, though some argue they reflect northern marine intrusions (Giresse 2005). Alternatively, Giresse suggests initial northward drainage via the Chari Basin into Lake Chad. Despite differing views, both theories agree the basin was once landlocked or a deep-sea fan, with current Atlantic drainage being recent, shaped by long-term channel modifications (Runge 2008).

## Large River Channels Morphology

The Congo River ranks second largest in the world after the Amazon, and first in the African continent, in terms of discharge and drainage area. Meanwhile, within the CRB itself, there are tributaries of second and third order which surpass all other African major rivers in terms of their area and discharge. Table 1 shows some comparative characteristics for the major river basins of Africa.

The hydrographic network of the CRB features a complex geomorphology that is vital for understanding ecosystems' distribution. The Congo River's course is characterized by significant hydrographic features, including expansive lakes, floodplains, wetlands, peatlands, and islands. Tshimanga et al. (2022a) identify three major reaches of the Congo River's course. The upper reach begins at the Katanga Plateaus and flows north to Boyoma Falls at Kisangani. This segment, known as the Lualaba, is followed by the middle reach, which extends approximately 1740 km from the city of Kisangani to the city of Kinshasa. The middle reach ends at the Pool Malebo, a significant fluvial-lacustrine system (Kichnit et al. 2024a) before the Congo River advances downstream toward the Atlantic Ocean (see Fig. 2). There are major tributaries, including Kasai River in the southern hemisphere, and Oubangui and Sangha Rivers in the northern hemisphere that join the Congo River in its middle course. The influx of water from these tributaries influences flow dynamics, leading to variations in river velocity and sediment transport patterns. This interaction fosters diverse habitats that support a wide range of aquatic species, enhancing the overall biodiversity of the Congo River system. Understanding the interactions of these tributaries is crucial for effective management and conservation strategies, particularly in the face of environmental changes and human activities.

The hydrodynamics of the Congo River are shaped by bathymetry and morphology, with stark contrasts between the Chenal and multithreaded reaches. The Chenal

**Table 1** Major river basins of Africa and their drainage area and discharge characteristics

| No. | River Basin | Drainage area (*1000 km$^2$) | Discharge (m$^3$/s) |
|---|---|---|---|
| 1 | Congo | 3700 | 41,000 |
| 1.1 | *Kasai* | 900 | 11,020 |
| 1.2 | *Lualaba* | 970 | 8940 |
| 1.3 | *Oubangui* | 604 | 5320 |
| 1.4 | *Sangha* | 220 | 2570 |
| 2 | Niger | 2300 | 5589 |
| 3 | Zambezi | 1330 | 3500 |
| 4 | Nile | 3400 | 2830 |
| 5 | Chari | 600 | 1059 |
| 6 | Senegal | 337 | 650 |
| 7 | Okavango | 721.258 | 475 |
| 8 | Orange | 973 | 365 |
| 9 | Limpopo | 413 | 170 |

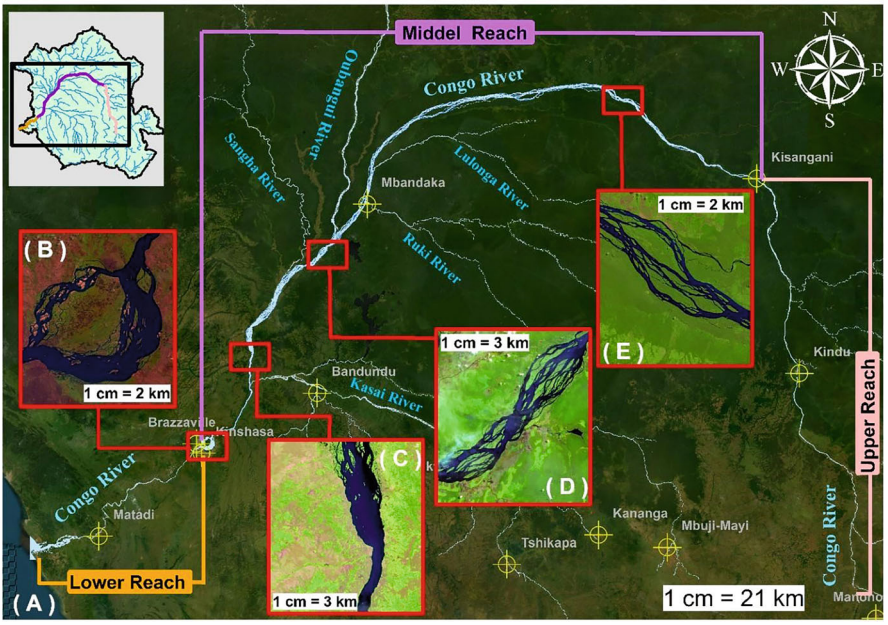



**Fig. 2** Overview of the Congo River Reaches, including (**a**) various reaches, (**b**) Pool Malebo, (**c**) the Chenal reach at Tshumbiri, and multithreaded reaches in (**d**) Lukolela and (**e**) Bumba. (River course from Landsat 8_9. Source: https://earthexplorer.usgs.gov/)

reach, with greater depths, supports higher velocities due to reduced friction and better hydraulic efficiency. In contrast, the multithreaded reaches between Kisangani and Kinshasa feature numerous islands that split the channel, disrupting flow and

causing turbulence and sediment deposition. As only 20% of the middle reach maintains a single channel (Alsdorf et al. 2016), flow velocities are markedly lower. These dynamics critically influence sediment transport and ecological processes, highlighting the strong link between river morphology and hydrodynamic behavior.

## Headwater Catchments

The CRB is structured around four dominant headwater catchments, namely, the Oubangui (Northeast), Sangha (Northwest), Kasai (Southwest), and Lualaba (Southeast), with the Plateaux Batékés extending the Cuvette Centrale in the west (Moukandi N'kaya et al. 2022). These upstream units are large, varying from 212,400 km$^2$ (Sangha) to 961,648 km$^2$ (Lualaba), drain steep topographies, and form the Congo River's major tributaries (Fig. 3). A catchment classification system is required in this area to help synthesize our understanding of the interaction between climate variability, catchment characteristics (e.g., vegetation, soils, topography), and the resulting hydrological responses (Sivakumar et al. 2015).

Tshimanga et al. (2022b) developed a framework delineating 1740 catchment units, based on topography (199), socio-economic and anthropogenic factors (204),

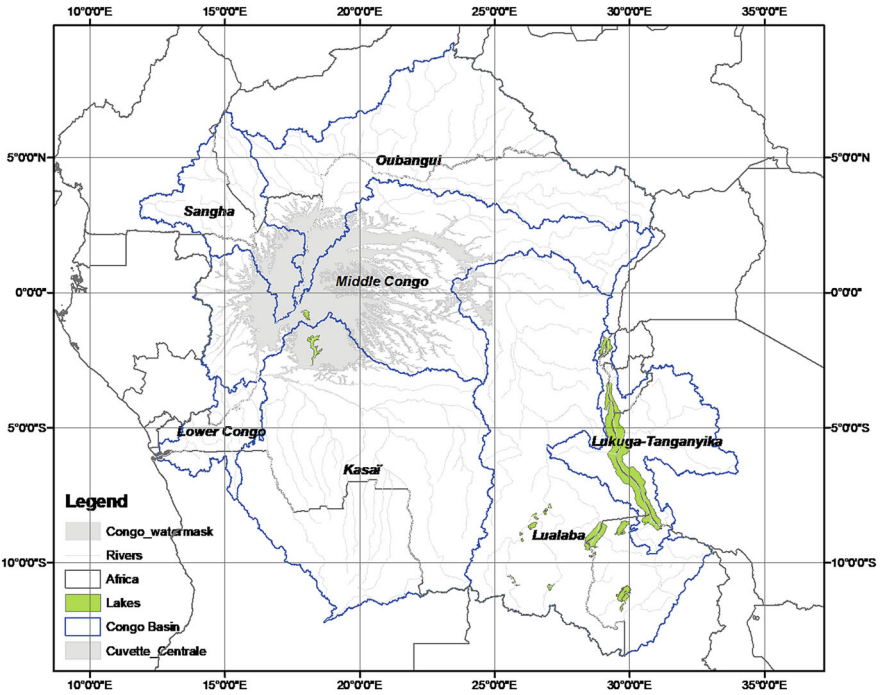



**Fig. 3** Major drainage units and headwater catchments of the CRB

and traditional hydrological nomenclature (1337). These units provide standardized descriptors of physical and socio-environmental attributes. This framework underpins the Congo Basin Catchment Information System (CB-CIS, www.cbcis.info), offering 128 attributes across seven management themes: governance, climate, physiography, hydrology, risks, water uses, and external linkages. CB-CIS enhances data availability and scalability, supporting integrated water resource management, policy decisions, and transboundary cooperation.

## Wetlands, Peatlands, and Lakes

The CRB hosts several wetlands, peatlands, and natural lakes of global significance, including various Ramsar sites (wetlands of international importance; see section "Wetland, Peatland, and Lake Dynamics and Functions" for details). These water bodies are predominantly distributed across the south-eastern rim of the basin, in the Lualaba drainage system; in the central part of the basin characterized by the Cuvette Centrale; and in the coastal region of the basin with a large extent of mangroves (Hughes and Hughes 1987; Bwangoy et al. 2011; Hughes et al. 2013; Kabuya et al. 2020; Dargie et al. 2017; CRREBaC 2022). Figure 4 shows the geographical distribution of what we know to date in terms of wetlands, peatlands, and natural lakes of the Congo Basin. It should be stressed that there is quite a good number of water bodies of great relevance in terms of the storage volume and aquatic ecosystem services in the Congo Basin, but which remain unclassified due to a lack of adequate studies (Tshimanga et al. 2022b).

## Groundwater

The CRB holds significant groundwater resources (Tourian et al. 2023), distributed in four major hydrogeological units, which influence significantly the spatial variability in groundwater storage anomalies (GWSA) (Kitambo et al., 2025). These include the unconsolidated sedimentary aquifer composed of coarse alluvial sediments reaching up to 120 m thick, the cretaceous consolidated sedimentary intergranular aquifer consisting mainly of semi-continuous sandy loam and soft sandstone, the consolidated sedimentary one dominated by fracture flow composed mainly of sandstone and calcareous rocks, and the Precambrian basement aquifer often consisting of basalt and granite (UNEP 2011; Africa Groundwater Atlas 2019).

Currently, little is known and understood about the characteristics (i.e., the size of the aquifers, recharge rates, or interactions between groundwater and surface water), the spatiotemporal variability of groundwater resources, and the way they link to climate variations within the basin, leading to a significant gap in the scientific knowledge of the Congo Basin's groundwater resources. Despite the recent advances in characterizing groundwater storage anomaly changes (Crowley et al. (2006), Richey et al. (2015), Becker et al. (2018), Tourian et al. (2023),

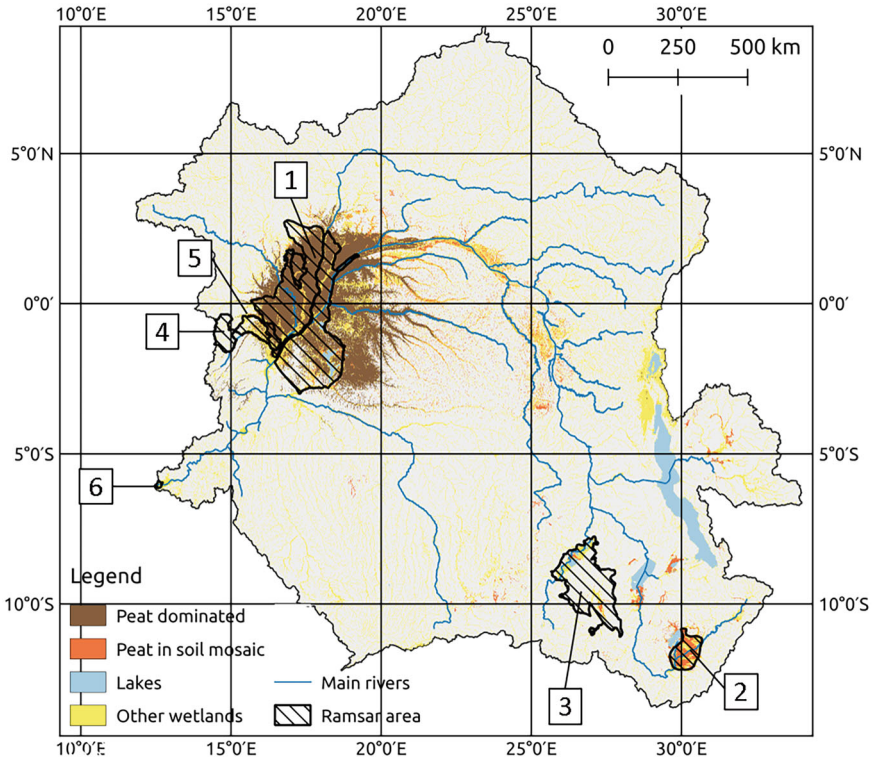



**Fig. 4** Distribution of wetlands, including peatlands, with areas declared as Ramsar sites (1) flooded Cuvette Centrale; (2) Bangweulu Wetlands; (3) Basin de la Lufira; (4) Leketi-Mbama; (5) Tchikapika-Owando; (6) Parc national des Mangroves). (Data sources: Global Peatland Map 2.0, Ramsar sites (https://rsis.ramsar.org), Global Lakes and Wetlands Database, Cuvette Centrale peat distribution from Crezee et al. (2022))

Mouakoumbat et al. (2022)), its knowledge at the large scale is still inadequate. A recent study performed by the Congo Basin Water Research Center (CRREBaC) and its international partners (i.e., Laboratoire d'Etudes en Géophysique et Océanographie Spatiales, University of Stuttgart) helped to characterize the dynamics of groundwater storage at the basin and subbasin scales (Kitambo et al., 2025). The study revealed that GWSA consists of 24%, 42%, 42%, 29%, 16%, and 19% of the total water storage anomaly from GRACE satellite, respectively, in Sangha, Oubangui, Kasaï, Middle Congo, Lower Congo, and Lualaba subbasins (Fig. 5) (Kitambo et al. 2025). This work enhanced our understanding of groundwater dynamics in the basin through Earth Observation and field integration. A groundwater storage database using GRACE, remote sensing, and monitoring networks are vital to assess climate impacts, understand groundwater–surface water interactions, identify recharge zones, and strengthen integrated resource management.

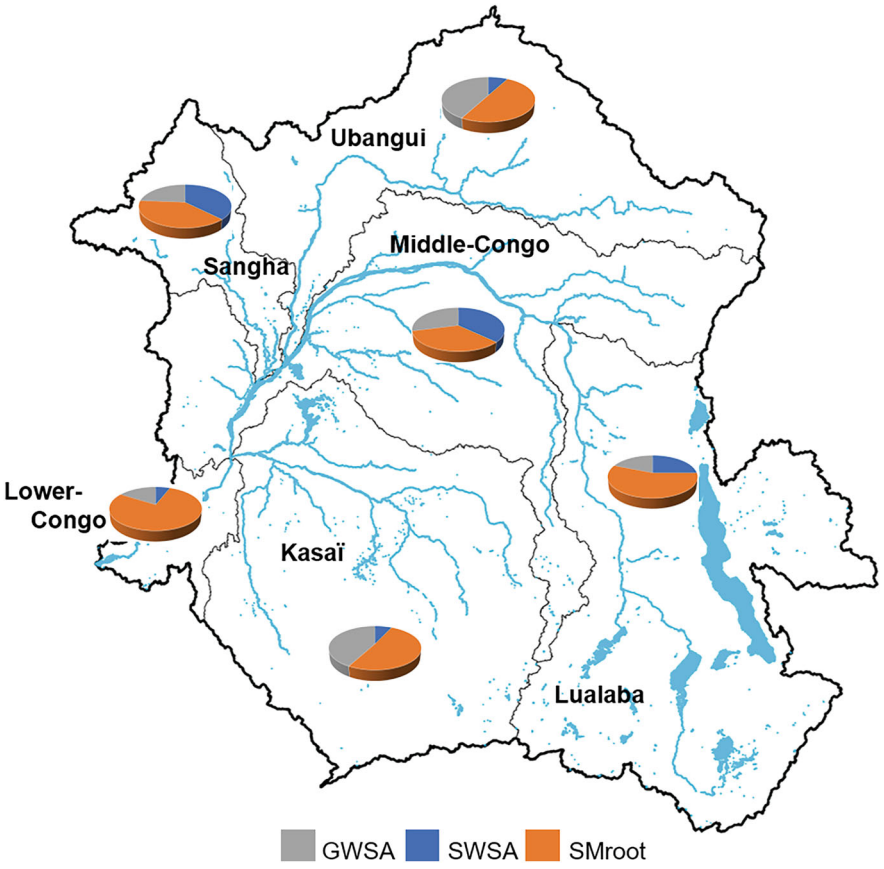



**Fig. 5** Contribution (%) from surface water storage anomaly (SWSA), root zone soil moisture (SMroot), and groundwater storage anomaly (GWSA) reservoirs to Total Water Storage Changes from GRACE for each subbasin in the CRB

## Measurements, Remote Sensing, Modeling, and Decision Support System

### In Situ Measurements

Since the 1960s, many riparian countries of the CRB have been marked by a drastic decline in the hydro-meteorological stations, so that, within the CRB, no more than 15 gauging in situ stations are considered operational today (Tshimanga 2022). Figure 6 shows the quality and distribution of the existing streamflow monitoring gauges in the Congo Basin that spans 3.7 million km$^2$. Comparatively, this is critically far beyond the hydrometric monitoring network of the United Kingdom, which encompasses more than 1400 gauges over 230,000 km$^2$ of the surface area.

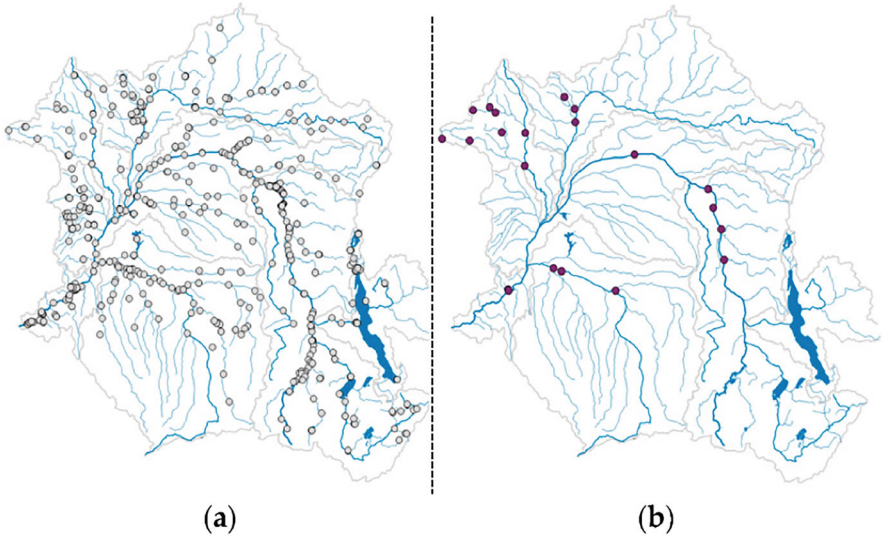



**Fig. 6** Decline in the hydrological monitoring stations of the Congo Basin, (**a**) before 1960s and (**b**) current situation

Also, as a comparison, the Brazilian portion of the Amazon River Basin currently has around 60 operational river gauges (Moreira et al. 2023). At present, and still in the absence of any real National Hydrological Service, it is the river navigation services of the Congo and CAR (GIE-SCEVN—Groupement d'Intérêt Economique—Service Commun d'Entretien des Voies Navigables) and then the DRC (Regie des Voies Fluviales) that have inherited part of the data from the former hydrometric networks.

During the last decade, scientists endeavored a number of meso- and large-scale field experiments aiming at enhancing the quality and availability of in situ data (Borges et al. 2019; Tshimanga et al. 2022a; Bates et al. 2023). One of these initiatives is the Congo River users Hydraulics and Morphology—CRuHM project (2016–2022, Bates et al. 2023), which focused on carrying out several cross sectional ADCP measurements over the main navigable reach of the Congo Basin (1700 km long), between the towns of Kisangani and Kinshasa, as well as the lower reach of the Kasai River from the town of Bandundu to its outlet in the Congo River (Fig. 7).

### ADCP Measurement

The first ADCP measurements in the Congo River were carried out in July 2008 (Oberg et al. 2009). RVF and GIE-SCEVN initiated other numerous ADCP measurements, which remain unpublished. Between 2017 and 2019, the CRuHM project conducted ADCP measurements over 29 cross sections along the middle reach of Congo River (Tshimanga et al. 2022a). The measurements targeted both single and multi-thread channel styles in the middle reach of the Congo River (Fig. 8).

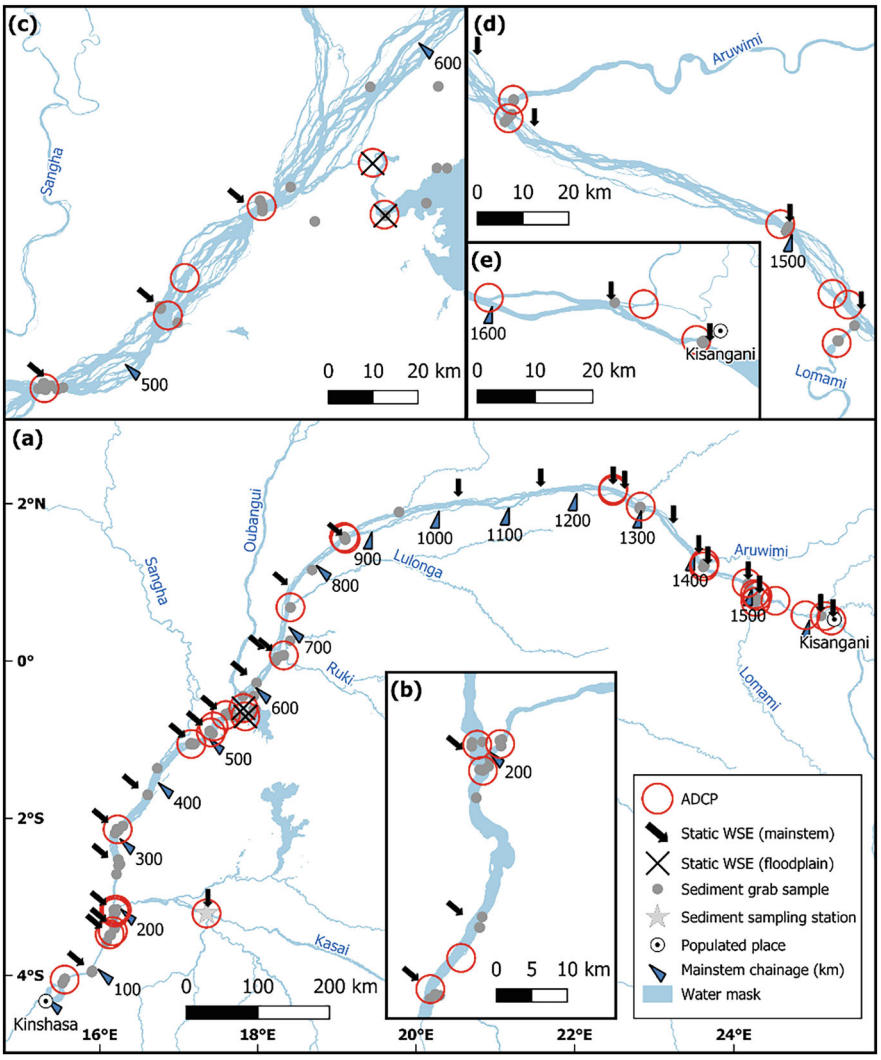



**Fig. 7** Study reach and locations of measurements (Chainage calculated from the navigation path used with the CRuHM boat)

## Water Surface Elevation and River Bathymetry

Measuring elevation in the Congo River Basin (CRB) is challenging due to sparse benchmarks and limited cellular networks. To address this, the CRuHM team used Precise Point Positioning (PPP) with GNSS equipment in 2019, collecting continuous Water Surface Elevation (WSE) data every 50 m along the Congo River between Kisangani and Kinshasa (Fig. 9). This dataset is indispensable for the determination of the longitudinal profile and the hydraulic gradient, which are important characteristics in the optimal use of a river. Taking into account the longitudinal profile, this allows the identification of locations with similar hydro-sedimentary characteristics.

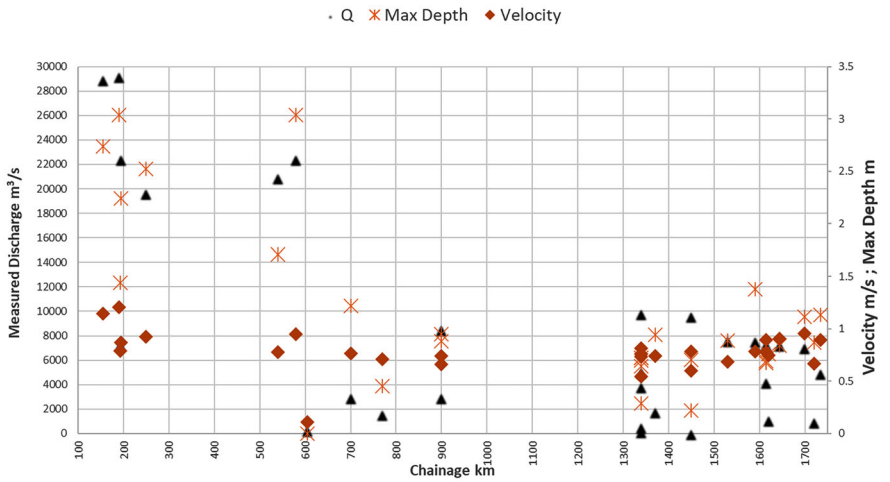



**Fig. 8** Measured discharge, channel hydraulic depth, and velocity for 29 cross sections along the Congo River main stem (max depth values divided by 10 to fit the scale) (Tshimanga et al. 2022a)

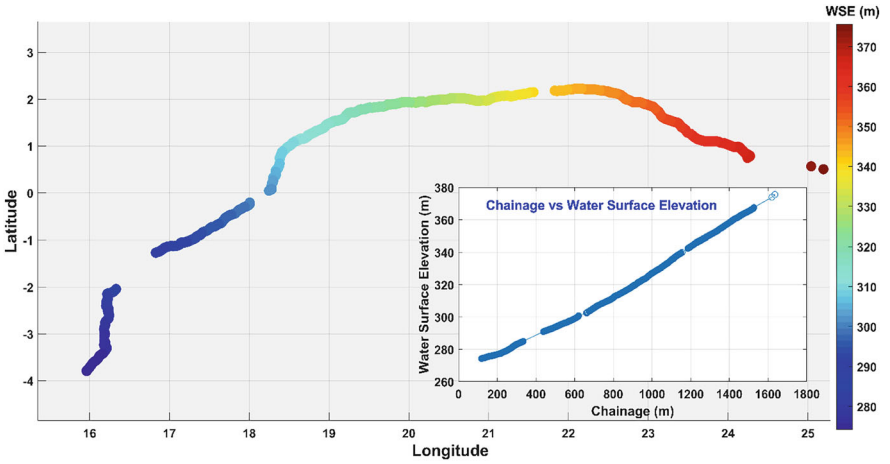



**Fig. 9** Continuous water surface elevation measurements along the middle reach of the Congo River using GNSS (Tshimanga et al. 2022a)

Through a longitudinal profile, slope variations can be observed that can indirectly provide information on past climates, structural controls, eroding and deposition sections, sediment transport capacity, and upstream-downstream flow dynamics.

Figure 9 illustrates the WSE data along the studied river reach and its relationship with chainage (distance along the river). The longitudinal profile of WSE reveals a clear and consistent increase in water levels from the upstream to the downstream end of the reach. This systematic downstream rise in WSE is attributed to the river's slope and flow characteristics, which influence the longitudinal variation in water surface elevation. Analysis of the data highlights a significant range in WSE within

the studied river reach, with maximum values reaching approximately 370 m and minimum values around 270 m. This variation is a critical parameter for establishing accurate boundary conditions in hydraulic models and informing effective water resource management decisions.

Several initiatives have been undertaken to measure the bathymetry of the middle reach of the Congo River, as highlighted in studies by Alsdorf et al. (2016), Carr et al. (2019), and Tshimanga et al. (2022a). While earlier measurements did not comprehensively cover the entire reach, data from the PANAV project has effectively encompassed the middle reach, particularly the Chenal reach, which extends from 50 km to 250 km along the river. In this segment, data were collected at 100-meter intervals between each cross-section, providing a detailed understanding of the river's depth and topography, which is crucial for navigation and environmental management. In contrast, the multithreaded reach, extending from 250 km to 1600 km, presents unique challenges that require a different measurement strategy. Here, data collection occurred at 1-km intervals due to the river's complex geomorphology, characterized by numerous islands and extensive cross-sectional areas. These geological features complicate the maintenance of consistent measurement intervals, thereby impacting the precision and reliability of the bathymetric data.

Figure 10 shows the map of the interpolated bathymetry for the main channel of the Congo River and its singularities (Ketchnit 2024). The in situ dataset for a 1740 km stretch of the river consists of cross sections spaced at 1 km intervals.

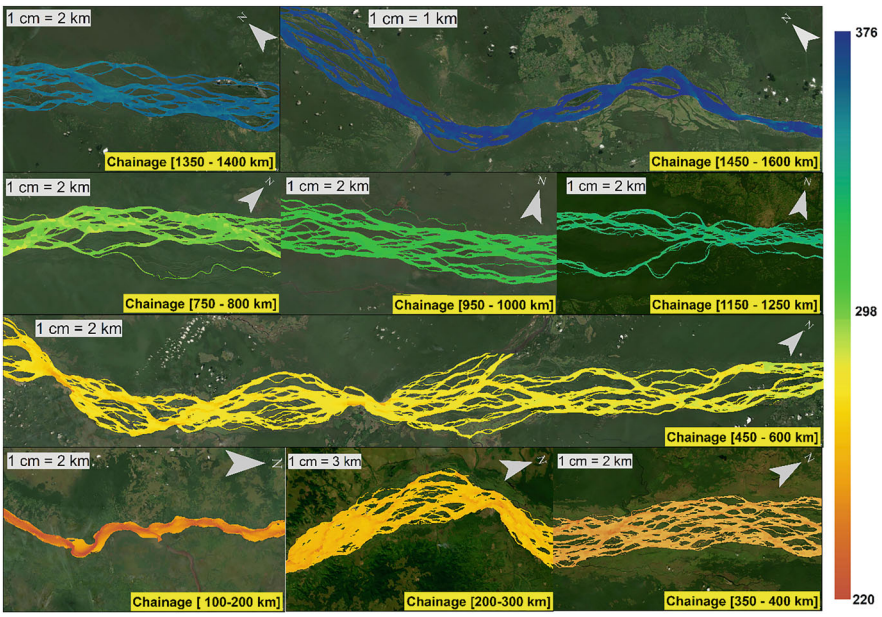



**Fig. 10** Interpolated bathymetry along the middle reach of the Congo River

Overall, the WSE and bathymetry measurements taken along the middle reach of the Congo River between 2017 and 2019 have revealed that the variability in water surface slope is greater than previously thought. Such variability is important for characterizing the hydraulic behavior of river reaches (Montazem et al. 2019). The variability appears to be the result of changes in bathymetry, especially as the Congo River enters the C*henal* and is joined by the Kasai tributary. Initially, the water surface slope becomes relatively steep (8 cm/km) as it approaches the entrance to the *Chenal*.

### Sediments and Carbon

Coynel et al. (2005) published the results of 6-year experiment, including TSS, particulate organic carbon (POC), and dissolved organic carbon (DOC), for the main stem of the Congo River near Brazzaville-Kinshasa station, and the Oubangui, Mpoko, and Ngoko-Sangha tributaries, where they noted a clockwise hysteresis pattern in relation to river discharge. The results obtained in this study are in the same order of magnitude, most specifically for TSS, although it is currently difficult with instantaneous samples taken over one low flow season to derive variability and establish a comprehensive pattern.

Alsdorf et al. (2016) and Richey et al. (2022) provide a comparative summary of the river discharge-controlled carbon fluxes in the Congo and Amazon basins. They identified that Congo River has an exceptionally low TSS yield, which however has a high POC content and ranks fifth in terms of annual POC flux to the oceans. With respect to DOC, the Congo River is a major global exporter with a total flux estimated at between 11.5 and 12.4 Tg C/yr. Combining the DOC and POC loads, the Congo River exports 14.4 Tg C/yr of organic carbon to the Atlantic Ocean and is the second major exporter of terrestrial organic carbon on Earth after the Amazon.

During 2019, the research team under the CRuHM project conducted a number of samplings together with ADCP cross sectional measurement (Tshimanga et al. 2022a). These data encompass total suspended sediment (TSS) and organic matter (OM) for the sections with ADCP measured discharge (MD). The results are representative of the low flow season during the month of August 2019 along the main channel of the Congo River between Kisangani and Kinshasa.

Basically, these observations, while highlighting the role of these major tropical river basins of the world in the dynamic of aquatic carbon fluxes, also lead to many hypotheses that should be investigated through a combined approach that include field measurements, laboratory analyses, and modeling to establish the geographic distributions and magnitude of the riverine carbon fluxes. To date, there is little knowledge of the spatial distribution of these fluxes across the hydrographic continuum of the Congo Basin, including wetlands and lakes, headwater catchments, and their small streams that currently undergo major land use changes. Furthermore, there is a lack of information on how the change in hydrological regime, including rainfall, streamflow, and sediment loads influences these dynamics.

## Remote Sensing

A number of satellite-based products necessary for assessing basin-wide water balance or improving hydrological predictions are now available at the global scale, encompassing the region of the CRB (Papa et al. 2022). These products have been used in many studies such as temporal changes in river water levels derived from radar imagery (Rosenqvist and Birkett 2002), seasonal and long-term trends of terrestrial water storage from Gravity Recovery and Climate Experiment (GRACE, Crowley et al. 2006), and temporal changes in water surface elevations and connectivity between the mainstem and floodplain channels evaluated from space-borne radar (Jung et al. 2010). Satellite altimetry has been used to infer hydrologic variables and evaluate water sources and sinks along wetlands using multiple remote sensing measurements such as GRACE, satellite radar altimetry, GPCP, JERS-1, SRTM, and MODIS (Lee et al. 2011; Becker et al. 2014; Kim et al. 2019; Carr et al. 2019). Landsat imagery has been used to characterize the hydraulics of the middle reach of the Congo River (O'Loughlin et al. 2013), and hydrologic modeling of the CRB has used various sources of satellite derived rainfall as input (Paris et al. 2022; Wongchuig et al. 2023). While the benefits of these satellite-based products are of no doubt, it is important however to recognize the difficulty of validation and associated uncertainties in some large areas of the CRB where there is a complete lack of ground-based historical observations (Washington et al. 2013).

Current efforts to leverage the use of these products and take into account uncertainty have led to the validation of a quite good coverage of satellite derived products, including ~2300 surface water level virtual stations, covering the period 1995 to 2020 and spatially distributed across the Congo Basin, with a total number of 323 VSs (Virtual Stations) from ERS-2; 364 and 342 VSs for ENV and ENV2 (new orbit of ENVISAT since late 2010), respectively; 146 and 98 VSs for Jason 2 and Jason 3, respectively; 358 VSs for SRL; 354 VSs for Sentinel 3A; and 326 VSs for Sentinel 3B. Figure 11 shows the map of the existing virtual stations with long-term time series of water level.

The current knowledge based on the use of these products reveals a persistent trend of drought over the central part of the Congo Basin, the distribution of the water availability throughout the basin, the quantification of the TDWS, and the spatial and temporal dynamics of the extent of episodic and seasonal inundation, wetlands, rivers, lakes, reservoirs, and floodplains (Kitambo et al. 2022, 2023; Wongchuig et al. 2023; Kechnit et al. 2024). However, the scientific community is still uncertain about the causes of the observed changes and how they would evolve in the future. Observed ground data are required to constrain predictive models to help improve our understanding of the processes, impacts, and causal relationships.

## Evaluation of Hydrologic Model Applications in the Congo Basin

The advent of hydrological modeling in the Congo Basin is relatively recent, given the need to address the many challenges of water resources management in the basin.

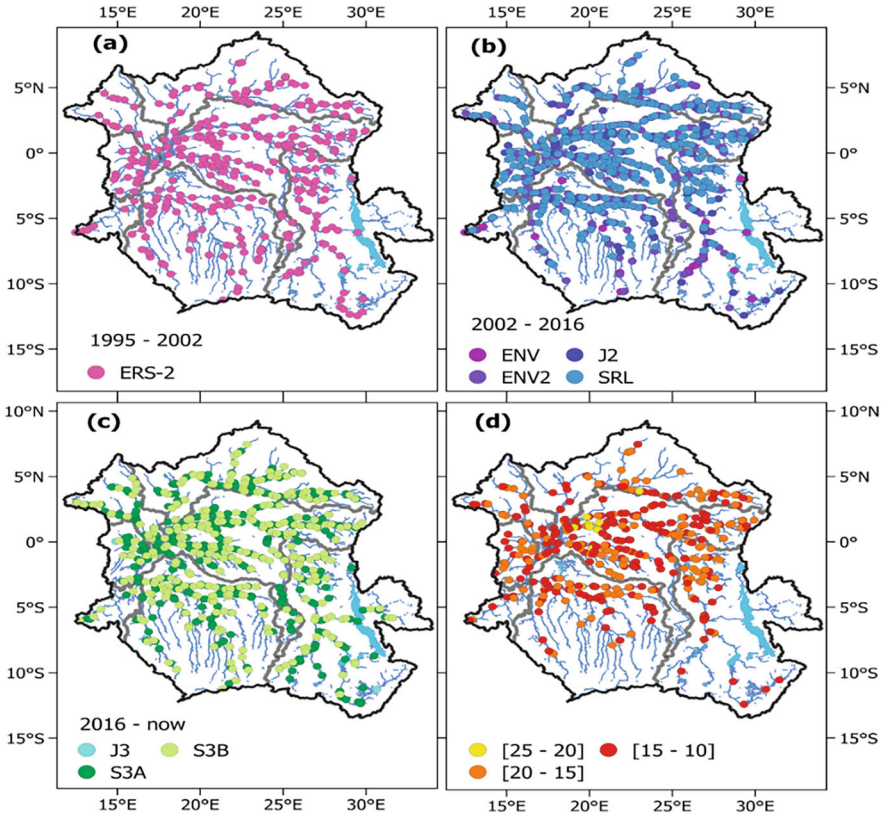



**Fig. 11** Locations of ~2311 Virtual Stations (VSs) from multi-satellite missions validated by Kitambo et al. (2022)

In a review of two decades of hydrological modeling in the Congo Basin, Tshimanga (2022) showed that there has been a great deal of efforts from the past modeling studies to address both data issues and process understanding and to establish models that represent the basin's hydrologic processes. The analysis also shows that there are still numerous issues and uncertainties that should attract the attention of future modeling studies—*right modeling for the right reason.* Modeling in the Congo Basin has evolved to encompass rainfall-runoff, hydrodynamic, and water allocation models. However, development has often focused on testing model viability rather than meeting operational needs of basin stakeholders. Key modeling systems include the following:

- Hydrologic Modeling System (HMS)—Source-to-sink approach for flow routing at continental scale. Applied to both the Congo and Nile Basins, but only Nile Basin gauging sites were used for validation (Asante 2000).

- River-Transfer Hydrologic Model (RiTHM)—Rainfall-runoff model applied to 11 major world basins, including the Congo. Successful elsewhere, but Congo calibration yielded a negative Nash Efficiency due to systematic overestimation of flows (Ducharne et al. 2003).
- PITMAN-GW—Semi-distributed rainfall-runoff model for the entire Congo Basin (99–403 sub-basins). Incorporation of storages (canopy, wetlands, lakes) and improved routing enhanced performance, calibrated with 31 gauging stations (Tshimanga et al. 2011; Hughes et al. 2013). Used for climate change impact studies, and informed WEAP, MIKE-HYDROBASIN, and later Lisflood-FP wetland parameterization (Kabuya et al. 2020).
- LISFLOOD-FP—4 km resolution hydraulic model combining in situ and modeled flows. Provided insights into Congo River discharge seasonality, floodplain interactions, and flood wave propagation (O'Loughlin et al. 2020).
- SWAT—Daily rainfall-runoff model for the whole basin, calibrated with 20 gauging sites. Successfully assessed water availability, climate change scenarios, and uncertainty from sparse hydrometric networks (Aloysius and Saiers 2017; Sridhar et al. 2022).
- Hillslope River Routing (HRR)—Daily model calibrated with four sites to simulate total water storage, validated against GRACE-derived storage changes (Beighley et al. 2011).
- Geospatial Streamflow Model (GeoSFM)—Daily rainfall-runoff model using satellite rainfall estimates. Initial results prompted model/data refinements, improving performance (Munzimi et al. 2019).
- Large Basins Model (MGB)—Hydrologic–hydrodynamic model calibrated with in situ and remote sensing data, with improved lake representation and assimilation of discharge/water level observations (Paris et al. 2022).

These modeling efforts are significant but still face structural and operational limitations. Many models are not directly usable by water managers due to lack of stakeholder integration and data input constraints. The absence of a catchment classification system has further limited model transferability and generalization (Tshimanga et al. 2022b).

## Understanding Hydrological Processes and Functions in the Congo Basin

The processes that take place at the Congo Basin scale are under the influence of many internal and external factors of the climate dynamics, land use and land cover, soil types, and the geology of the terrain. Figure 12 provides a schematic of our conceptual formulation of these processes. They include surface and sub-surface response to rainfall at the small scale but also include storage and attenuation effects of wetlands, floodplains, natural lakes, and the channel systems of large rivers. An adequate conceptual representation of storages such as forest canopy interception, soil moisture, groundwater, lakes, and wetlands as well as space-time variations in

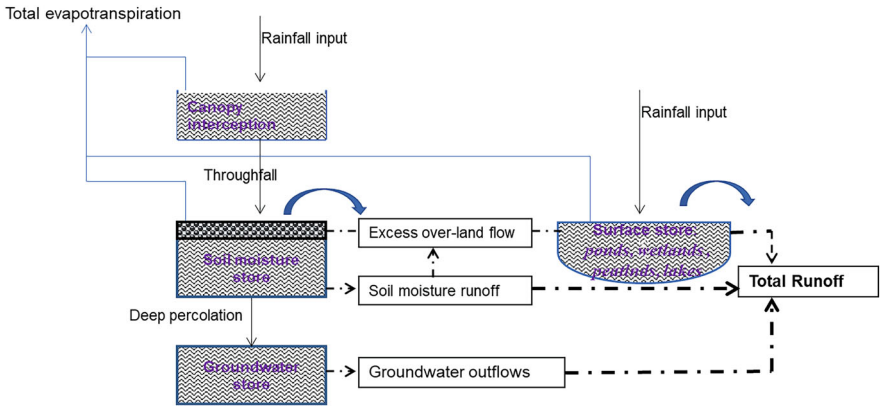



**Fig. 12** Conceptual dominant hydrologic processes for the CRB

quantities such as interflow, soil moisture flow, recharge, runoff, transmission losses, and evaporation would be a true representation of the hydrologic behavior of the CRB hydro-system.

## Rainfall Input

► Chapter 3, "Climate of the Congo Basin," of this book provides a comprehensive review of rainfall process over the Congo Basin. Mean Annual Precipitation over the Congo Basin is estimated to 1700 mm. Overall, there are three dominant modes of annual rainfall recycling over the Congo Basin (Worden et al. 2021):

- Transport of moisture flux from the Atlantic Ocean into the Congo Basin, which plays a critical role in determining the climate variability of the region throughout the year (Pokam et al. 2012).
- Transport of moisture flux from the Indian Ocean into the Congo Basin (Dyer et al. 2017).
- A significant part of rainfall recycling in the Congo Basin is vegetation-sourced, which accounts for up to 52% of the annual rainfall from local evapotranspiration (Smith et al. 2023). This process has been identified as a key modulator of the Congo Basin water recycling, suggesting that the Congo rainforest could be an important source of moisture for initiating the rainy season.

During the wet season, higher evapotranspiration rates are typically observed, which significantly contribute to local rainfall patterns and sustain the forest's hydrological cycle. In the dry season, reduced evapotranspiration levels result in a lower recycling rate, making the region more dependent on external moisture sources, such as the Atlantic and Indian Oceans. Part of the amount of the moisture recycled over the Congo Basin is transported to other regions of Africa, contributing

to rainwater supply to those regions. This has huge implications for livelihood of about 100 million of rural famers who depend direct on red-fed agriculture in the Congo Basin and a further 300 million of rural famers from the Sahel region and Ethiopian highlands who benefit from rainfall through atmospheric moisture recycling from the Congo Basin forests (Barimalala et al. 2023).

Analysis of historical ensemble precipitation data for the Congo Basin rainforest region shows a decreasing precipitation trend with about −90 mm per decade and an increasing dryness index of about 0.05 per decade (Wongchuig et al. 2025). This has also affected the trend in river flow. However, we are currently uncertain to whether this trend is induced by deforestation or change in the ocean sourced moisture flux to the Congo Basin. Deforestation in the Congo Basin affects not only the mean rainfall in the basin and neighboring countries, but also the spatial distribution and the temporal characteristics of the rain, such as the onset, cessation, and length of the rainy seasons. These have crucial implications in the agricultural sectors. The projected overall Congo Basin forest loss between 2015 and 2100 is estimated to induce a rainfall decline of 8% to 10% in the basin itself. The deforestation will also have large effects on neighboring regions as a result to its impact on rainfall patterns, which despite large uncertainties is believed to be potentially substantial. The indirect effect of deforestation on agriculture through the effect on rainfall is likely to be large, as there is a strong dependency on rain-fed agriculture in Africa.

## Forest Canopy Interception and Evaporative Losses

The tropical rainforest of the Congo Basin plays a key role in the hydrological cycle of the basin and the African continent. This role includes local rainfall recycling, but also regional moisture recycling, which further ensure rainfall supply to as far as the Sahel and Ethiopian highlands region. It is unfortunate that this role remains poorly understood to date, which undermines conservation efforts as well as promotion of the ecosystem services. It is understood that the massive forest canopy of the Congo Basin constitutes a major atmospheric storage that intercepts a significant amount of rainfall, which then undergo direct evaporative losses to the atmosphere without reaching the ground. Variability in land cover composition for the basin implies variability in surface canopy which will also affect the variability in rainfall interception storage across the basin. The type and structure of the forest canopy determine the amount of rain water that is captured and subsequently released to the atmosphere. Associated with the types of vegetation cover are litter depths and types, rooting depth, and densities, all of which have effects on the water balance and runoff generation mechanisms (Chappell et al. 2008). Some studies in the basin have been able to use proxy data to model the interception loss through forest canopy (Tshimanga and Hughes 2014). Adequate quantification of these processes could help understand the impact of the loss of forest canopy, through deforestation, on river runoff and

flooding, soil erosion, and sediment transport. Similarly, the forest cover plays a significant role in the infiltration processes, which remains understudied in the Congo Basin. In light of the heightened pressure from land use change in the basin, the findings of these studies are particularly pertinent.

## Evapotranspiration and Surface Air Temperature

There are relatively fewer studies that address Evapotranspiration (ET) and Surface Air Temperature in the Congo Basin, compared to precipitation (Alsdorf et al. 2016; Tshimanga 2022). An analysis based on 229 reference stations for the years 1950 to 1959 shows the annual average daily maximum, mean, and minimum temperatures for most of the Congo Basin are 30 °C to 31 °C, 23 °C to 25 °C, and 18 °C to 20 °C, respectively (Bultot 1972). The actual ET varies from region to region, from "a little more than 800 mm in Katanga to a little less than 1,200 mm in Uele" (Katanga is a region in the southernmost Lualaba Basin, and the Uele region occupies the eastern portion of the Oubangui Basin). For the entire Congo Basin, the actual ET "generally measures between 75% and 85% of the annual precipitation." Potential evapotranspiration (PET) peaks at about 1500 mm/yr near the equator, with lower values further north and south (Nicholson et al. 1997).

## Storage

Storage here refers to surface water stores such as lakes, wetlands and peatlands, and the subsurface stores in soil and groundwater. Our current understanding of these processes in the CRB is limited due to experimental challenges related to the measurement of these processes. However, the advent of satellite derived products such as total water storage variations from GRACE and inundation extent are enabling these measurements.

For instance, using satellite data, Tourian et al. (2023) show that currently the Congo Basin's Total Drainable Water Storage (TDWS) lies within a range of 476 $km^3$ to 502 $km^3$, unevenly distributed throughout the region, with 63% being stored in the southernmost sub-basins, Kasaï (220–228 $km^3$) and Lualaba (109–169 $km^3$), while the northern sub-basins contribute only 173 $\pm$ 8 $km^3$. The Kasaï sub-basin has the highest capacity, storing 220 $\pm$ 4 $km^3$ or about 43% of the total drainable water of the Congo Basin. Sangha, Oubangui, and Middle Congo contain in total 173 $\pm$ 8 $km^3$, equivalent to 63% of the Kasaï sub-basin. The Middle Congo, with its Cuvette Centrale, stores 90 $\pm$ 6 $km^3$ of TDWS, only 40% of the Kasaï estimates. Such a difference is expected, as both Kasaï and Middle Congo receive similar annual precipitation, but the latter is a shallow watershed with much larger discharge (498 $\pm$ 20 mm/yr) and evapotranspiration. The Lualaba sub-basin accounts for approximately 21% of the basin TDWS with 109 $\pm$ 4 $km^3$ (sum of its subbasins North, South and Lukuga), but most of the storage (61%) is concentrated

in the Lualaba-South (67 ± 2 $km^3$). Over the Lualaba-Lukuga the TDWS is 20 ± 1 $km^3$, for which the storage of Lake Tanganyika was subtracted from Total Water Storage Anomaly (TWSA).

Tourian et al. (2023) emphasize that the water amount of 476 ± 10 $km^3$ TDWS of the Congo Basin corresponds to 133 ± 3 mm of equivalent drainable water height, i.e., the level at which the discharge reaches zero. This means that when the Congo reaches its minimum drainable storage in August—40 mm (137 $km^3$), the basin could still be drained by about 339 $km^3$ (476–137 $km^3$). Conversely, when both the water storage and the discharge reach their maximum in December, the basin holds a water volume of 613 $km^3$.

Comparing the estimates over the Congo and Amazon basins, a ratio of about 25% between Congo's TDWS 476 ± 10 $km^3$ to Amazon's TDWS 1766 ± 47 $km^3$ is obtained. This is roughly equivalent to the ratio estimated between their mean annual discharge to the ocean (Congo 40,000 $m^3/s$, Amazon 209,000 $m^3/s$) and the ratio between the amplitude of their water storage anomaly (Congo 40 mm, Amazon 170 mm) as well as the ratio between their recharge (P-ET), e.g., Congo 300 mm/yr and Amazon 1100 mm/yr. Other attempts to characterize the surface water storage of the Congo Basin include the studies by Lee et al. (2011); Yuan et al. (2017); Becker et al. (2018); and Kitambo et al. (2023).

## River Discharge and Flow Variability

The Congo River is distinguished by its exceptional discharge characteristics, with an average annual flow rate of approximately 41,000 $m^3/s$ recorded at the Brazzaville-Kinshasa hydrological stations (Tshimanga et al. 2022a; Moukandi N'kaya et al. (2022). The river, situated at the equator, displays a weakly contrasting equatorial flow regime, exhibiting low seasonal discharge variability. The ratio between the highest monthly mean discharge of 75,500 $m^3/s$ and the lowest of 23,000 $m^3/s$ is only 3.3, indicating a relatively stable seasonal flow pattern. According to Laraque et al. (2020), Paris et al. (2022), the hydrological year starts in August and features two high-flow periods (October–January and April–May) alternating with two low-flow periods (February–March and June–September) (Fig. 13). A spatial analysis of discharge variability across the Congo River Basin reveals that local and regional factors exert a significant influence on the hydrological regime. For instance, discharge and rainfall patterns at specific locations such as Bangui, Ouesso, and Kisangani exhibit considerable variation, suggesting that discharge characteristics are not uniform throughout the basin (Bola et al. 2022b). Significant variations in river discharge have been observed over the years. Between 1960 and 1995, fluctuations were noted, with the river only recently returning to its long-term average. For Kinshasa/Brazzaville station, discharge increased by 21% between 1960 and 1970, 4.5% from 1971 to 1981, followed by a 5.3% decrease from 1982 to 1993, compared to the 1902–1959 average.

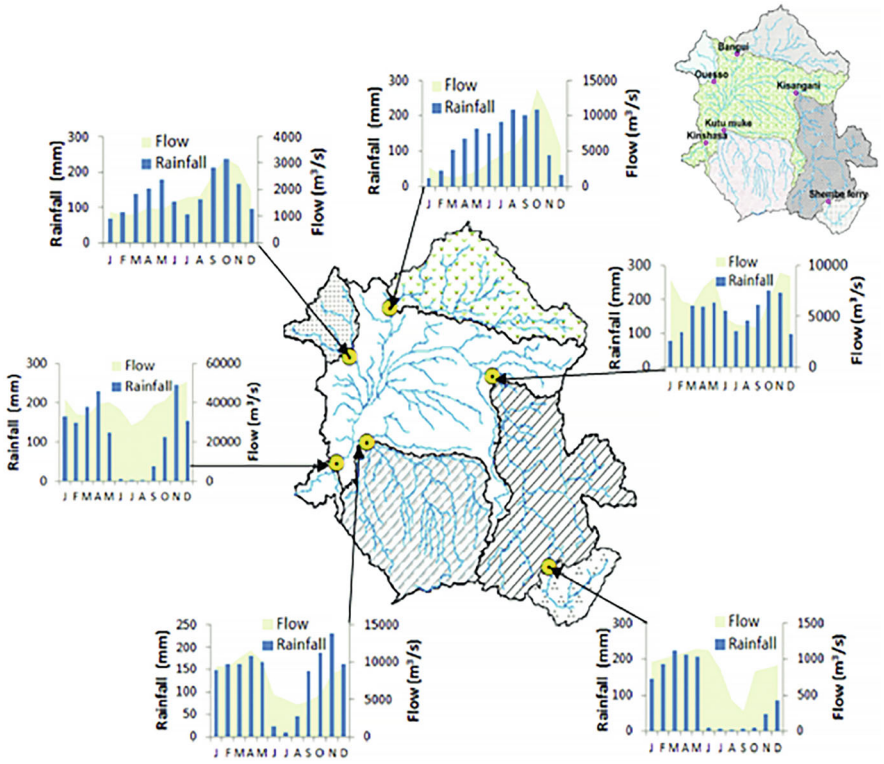



**Fig. 13** Rainfall-runoff relationship in specific stations of the Congo Basin (Bola et al. 2022b)

## Wetland, Peatland, and Lake Dynamics and Functions

A combination of available in situ measurements, hydrological modeling, and satellite observations is used to gain insights into these dynamics. A mass balance analysis by Yuan et al. (2022) estimated that river-wetland exchange accounts for less than 20% of the wetland inflow, while hydrological modeling by Datok et al. (2022) suggested a 69% contribution of the Congo River (33%) and tributaries (25% RoC and 11% DRC) to the wetland inflow, with remaining water input coming from precipitation. Georgiou et al. (2023) mapped the spatial distribution of the main water source for a subregion of the Cuvette Centrale. They found that 27.5% of the wetlands in the subregion received river or groundwater input. O'Loughlin et al. (2020) found that more than 16% of the river channel network actively exchanges water with wetlands and identified river-wetland exchange as a crucial feature in the propagation of Congo River flood waves. Interfluves co-occur with floodplains along the Likouala-Mossaka and Sangha Rivers, and floodplains are also found next to the Congo River, east/upriver along the left bank tributaries, and north and east of Lac Mai-Ndombe (Biddulph et al. 2021).

The dominant feature of the Bangweulu system is the seasonal flooding regime, which influences every aspect of the local environment and economy. By January each year, vast areas of the Bangweulu floodplains are inundated from local rainfall and runoff. Peak water levels occur in March when the inflow from the Chambeshi and other rivers draining the surrounding catchment spills across the seasonally flooded plains (6800 $km^2$) and into the permanent deepwater swamps (5000 $km^2$). Waters recede slowly during the dry season, reaching their lowest level in October/November, leaving only the central basin permanently under water. The mean annual outflow to the Luapula River is about 440 $m^3/s$. The extent of the floodwater inundation and the rate with which it rises and recedes varies from year to year. The climate is divided into three distinct seasons: a cool dry season from April to August, a hot dry season from August to October, and a warm wet season from November to April (Chundu et al. 2024). The wetland is fed by 17 major rivers from a catchment area of 190,000 $km^2$ but is only drained by one river, the Luapula River (Kamweneshe et al. 2003).

The wetlands associated with the Lufira River create extensive floodplains, papyrus, and other marshes, especially in the Upemba National Park region. The Lufira rises in the Shaba plateau south of Likasi. The river was dammed in 1926 at Mwadingusha near Likasi to form Lake Tshangalele, a reservoir for a hydroelectric generator supplying power for copper smelting. It flows northward through the Bia Mountains for about 500 km, joining the Lualaba in Lake Kisale. Its discharge at Kapolowe has been measured since 1920 (Devroey 1951, 1952). It is therefore fairly accurately known. Maximum discharge (between 150 and 250 $m^3/s$) coincides with flooding in the second half of the rainy season (February, March, or April). The minimum (between 7 and 2.5 $m^3/s$) occurs toward the end of November, i.e., after the start of the rainy season. The first rains serve mainly to provide the soil with moisture equivalent to field capacity. The heavy storms of November and December cause only minor, short-lived flooding. The peaks in the diagram represent a runoff of less than 1% of the water that fell. In the basin, only steep slopes with thinner weathering mantle are likely to favor runoff or hypodermic flow. In December, the latter rises, heralding the outcropping of the aquifer in the Dembos, flared-bottomed valleys with no organized linear flow. From January to April, the centimeter-thick sheet of runoff that appears in these valleys and sometimes lasts for several days after a period of heavy rain provides a significant proportion—around 40%—of the river's flow (Alexandre 1977). The Lufira basin is a wetland of worldwide importance, as the edapho-climatic factors prevailing in the area provide good conditions for the formation of various ecosystems and the development of a varied herbaceous and shrub flora. This ensures the maintenance of biological diversity, with the presence of numerous endemic species.

Lake Tanganyika partially drains into the Lukuga River at Kalemie and further feeds the Lualaba basin. This discharge contributes to 18% of the total annual water loss of the lake, while its water balance is mainly governed by evaporation, corresponding to 82% of its total annual water loss. Similarly, Lake Bangwelu and its surrounding wetlands ultimately discharge into the Luapula River, Lake

Mai-Ndombe and its wetlands contribute to the Fimi River, and Lake Mweru with its surrounding wetlands are drained by the Luvua River.

Leketi-Mbama is a unique inland wetland with a diverse mix of habitats including lakes, marshes, and floodplains. The main hydrological function of the Leketi-Bama zone is groundwater recharge: it retains around 35% of the direct rainfall over the region. The Kouyou is the main river feeding the area, receiving water from several tributaries including the Okeli Ambori stream and flowing into the Likouala Mossaka at Loboko village.

The Tchicapika-Owando is mainly made up of the Kouyou and Alima rivers, whose tributaries are the Lavouma and Diéle, respectively. The Kouyou flows into the Likouala-Mossaka, which in turn flows into the Congo River. The Alima flows directly into the Congo River. During high-water periods, all these rivers are connected in some places to floodplains and swampy forests. Floods are regular and of fairly long duration. Variations in river discharge regulate the intensity and duration of exchanges between the various geographical elements of the river-alluvial plain system. When the water level rises, water invades part of the alluvial plain, establishing connections and enabling exchanges with the minor bed. Conversely, when water levels fall, certain areas of the alluvial plain become isolated from the riverbed. Oscillations in the hydrological regime have an impact on the amplitude, duration, and frequency of floods. Whatever the period of high or low water, they exert a greater or lesser influence on the productivity of hydro systems (Fig. 14).

Most wetlands in the Congo Basin significantly contribute to dampening the flood risks downstream through many functions (Hooijer et al. 2005; Dommain et al. 2010; Acreman and Holden 2013; Gao et al. 2016; Crump et al. 2017). The Cuvette Centrale significantly extends the travel time of water from different regions of the Congo Basin before it reaches Kinshasa and Brazzaville and partly explains the long residence times of 2 months for the flow to move from the confluence of the Lualaba and Elila Rivers to Brazzaville, 1 month from the confluence of the Kotto and Oubangui Rivers, and approximately 15 days from the confluence of the Loange and Kasai Rivers (Sridhar et al. 2022). Besides taking up water, the Cuvette Centrale acts as a natural reservoir that traps sediment from upstream rivers thus reducing the amount of suspended particles flowing downstream. Reduced uptake of sediments would lead to a rise of the riverbed and impact flooding dynamics in downstream areas.

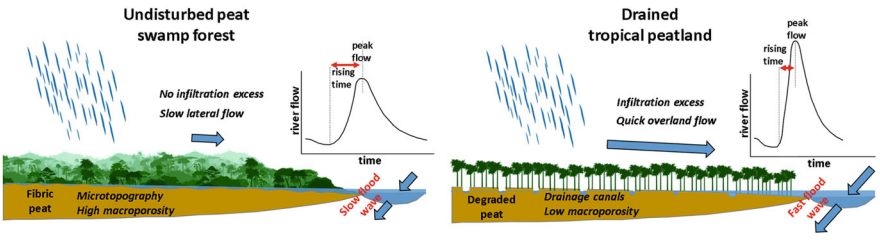



**Fig. 14** Schematic illustrating the buffering role of peatlands during rainy periods and high river stages, highlighting how human disturbance amplifies downstream flood risks

In the Cuvette Centrale, peat formation began at least 19,600 calibrated years before present (cal yr BP; taken as AD 1950; Garcin et al. 2022; Hawthorne et al. 2023), but mostly from about 10,500 cal yr BP (Dargie et al. 2017), coinciding with more humid conditions at the beginning of the Holocene (Schefuß et al. 2005). Peat accumulation is a good proxy for hydrological stability, as organic material will only accumulate under relatively stable hydrology (Dargie et al. 2017). Studies of cuvette centrale peat show that shifts in the hydrology have led to periods of peat accumulation, where the hydrology has been conducive, as well as hiatuses of that growth (Garcin et al. 2022).

The heterogeneous hydrology of the Congo Basin peatlands could indicate that various processes have initiated peat development at distinct times (Biddulph et al. 2021). A drying period between 5000 and 2000 yr bp implies a regional drop in the water table, causing peat decomposition, including some of that was already accumulated. There was no evidence of human impacts on the forest in that period. After 2000 yr bp, conditions stabilized and peat accumulation resumed. The authors conclude this may show that the stability of the carbon stocks in the peatlands may be sensitive to a climatic drought threshold (Garcin et al. 2022). Whenever the self-regulating hydrology of peatlands is disturbed by external factors such as artificial drainage, land use change, and climate change, their ecosystem functions and services are often lost. Future exploration of unexposed, remote peatland areas might strongly impact the peatland hydrology in the Cuvette Centrale (Dargie et al. 2019). The Congolese rainforest is relatively dry compared to tropical forests in Southeast Asia and Central and South America, receiving approximately 35–40% less precipitation (1700 mm $yr^{-1}$; Samba and Nganga 2012) than its Amazonian counterpart (Guan et al. 2015; Alsdorf et al. 2016). The limited precipitation and its bimodal pattern (Longandjo et al. 2024) make the Congolese rainforest and its peatlands water-limited during dry seasons and highly vulnerable to drought intensification or changes in the rainfall pattern (Jiang et al. 2019). Drought pressure poses a major threat to the peatlands of the central Congo Basin (Loisel et al. 2021), potentially leading to carbon emissions via oxidation or fires. Ongoing climate warming will likely increase drought severity, while possible intensification of El Niño could further prolong droughts (Rifai et al. 2019). Garcin et al. (2022) used paleo records from peat cores in the Cuvette Centrale and identified a long period (between 5000 and 2000 cal yr BP) of dry conditions, i.e., the "Ghost interval." Their research showed that environmental change could lead to a regional drop in peatland water levels with decreased peat accumulation or even peat decomposition, which might be a precedent of the impact of current and future drought pressure on these peatlands.

Most of the progress in our understanding of these historical conditions before traditional measurements has therefore been made by paleoenvironmental studies. We also see evidence of these significant changes in the hydrology from studies of Congo sediment in the Atlantic. A high aridity period during the last glacial maximum, an increase in precipitation and high river discharges from 15,200 yr BP, and around 9000–8000 cal ka BP, rainforest vegetation inhibited soil erosion and therefore sediment discharge (Marret et al. 2008).

While much remains to be done in this research area, including understanding how far back peat accumulation started, what we can take away is that changes in the hydrological regime can cause significant changes in the basin, such as loss of peat, and these can last thousands of years and potentially link to important carbon climate feedback mechanisms. The point here is that there have been significant changes in the magnitude and timing of the hydrology cycle induced by climate and vegetation changes in the past, showing that it may actually change substantially in the future if we perturb the current context.

## Biogeochemical Processes

Borges et al. (2019) carried out field measurements across the lowland part of the Congo River network to describe the spatial variations in fluvial dissolved carbon dioxide ($CO_2$), methane ($CH_4$), and nitrous oxide ($N_2O$) concentrations. Field measurements across the lowland regions of the Congo River network revealed a pronounced oversaturation of surface waters with carbon dioxide ($CO_2$) and methane ($CH_4$) relative to atmospheric equilibrium. Greenhouse gas dynamics in Congo Basin rivers showed extreme variability. $CO_2$ partial pressures (1087–22,899 ppm) and $CH_4$ concentrations (22–71,428 nmol/L) far exceeded equilibrium values (~400 ppm and ~2 nmol/L, respectively), while $N_2O$ varied less. Spatial variability, driven by stream size, stream order, and floodplain interactions, dominated over seasonal or diurnal changes. Larger streams had lower $CO_2$/$CH_4$ and higher oxygen. Rivers draining the Cuvette Centrale exhibited highest greenhouse gas levels, linked to flooded forests and wetland inputs. Elevated DOC (1.8–67.8 mg/L) and oxygen undersaturation (0.3–122.8%) highlighted strong organic matter decomposition.

In the Congo Basin, major and trace elements and Sr isotope ratios were investigated at the Pool Malebo for the 1989 and 2010 hydrological cycles (see for details Négrel 1993; Négrel and Dupré 1995; Henchiri et al. 2016). Additionally, the main tributaries were also investigated (Oubangui, Kasaï, Sangha, Likouala, and Lefini).

Figures 15 and 16 present the fluctuations of the $^{87}Sr/^{8}6Sr$ ratios and the discharge in the dissolved load obtained for the Congo River for the 1989 and 2010 surveys. Both figures showed that the $^{87}Sr/^{86}Sr$ ratios are highest during low flow and decrease with increasing discharge. This type of relationship can be interpreted as a mixing with two signatures (Grosbois et al. 2000; Négrel et al. 2003).

The $^{87}Sr/^{86}Sr$ isotope ratios exhibited strong seasonal patterns, peaking during low-flow periods and declining with increasing discharge. This inverse relationship suggested a dual-source mixing model, where Sr inputs during low flow likely derived from rock weathering and terrestrial sources, while during high flow, dilution from precipitation or other tributary inputs dominated (Fig. 17).

Further insight was gained from the relationship between Sr and sodium (Na) concentrations. A clear positive correlation existed between Na and Sr across seasons, with lowest concentrations during low water periods. Tributaries such as the Kasaï, Oubangui, and main Congo River channel displayed higher Na-Sr contents,

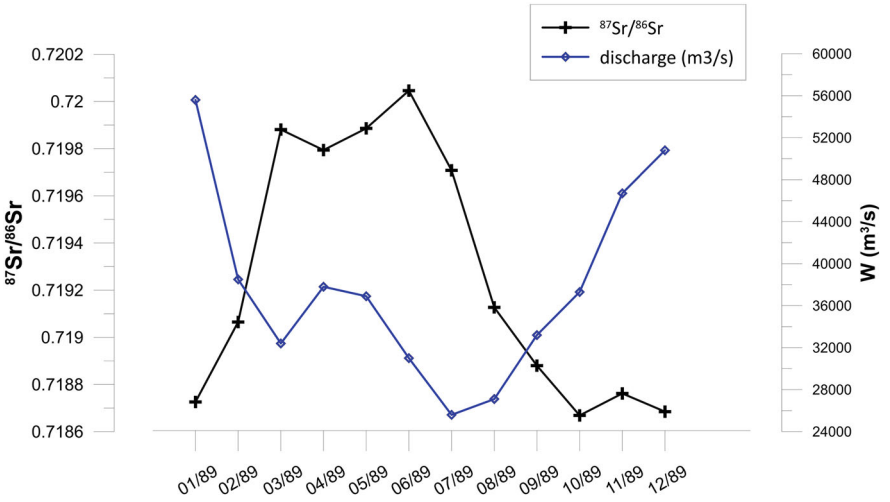



**Fig. 15** Mean monthly discharge of the Congo River at the Brazzaville station (W in $m^3/s$) and $^{87}Sr/^{86}Sr$ values for the samples collected each month at the Brazzaville station (Négrel and Dupré 1995)

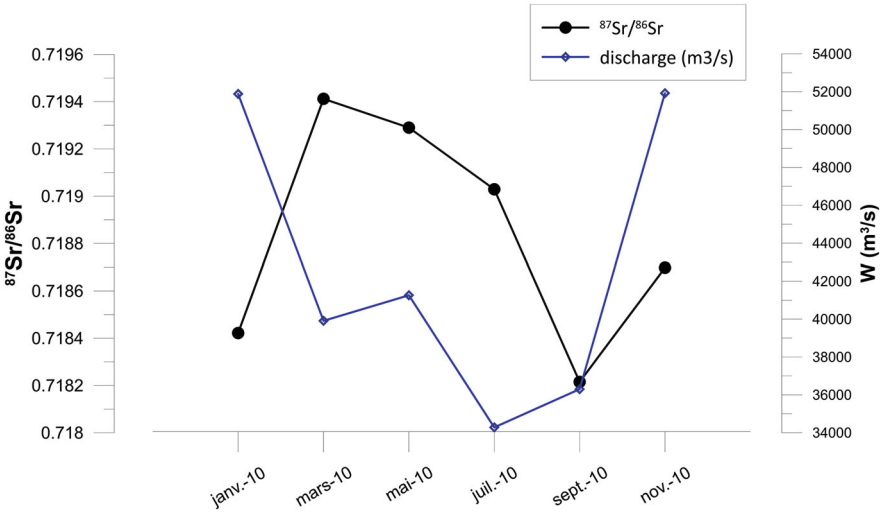



**Fig. 16** Mean discharge of the Congo River at the Kinshasa station (W in $m^3/s$) and $^{87}Sr/^{86}Sr$ values for the samples collected every 2 months at the Kinshasa station (Henchiri et al. 2016)

while dilute, DOC-rich tributaries draining the central depression (e.g., Sangha, Likouala, Alima) exhibited much lower values. The Lefini River, draining the Batékés plateaus, also showed very low Na-Sr signatures, consistent with its geologic setting.

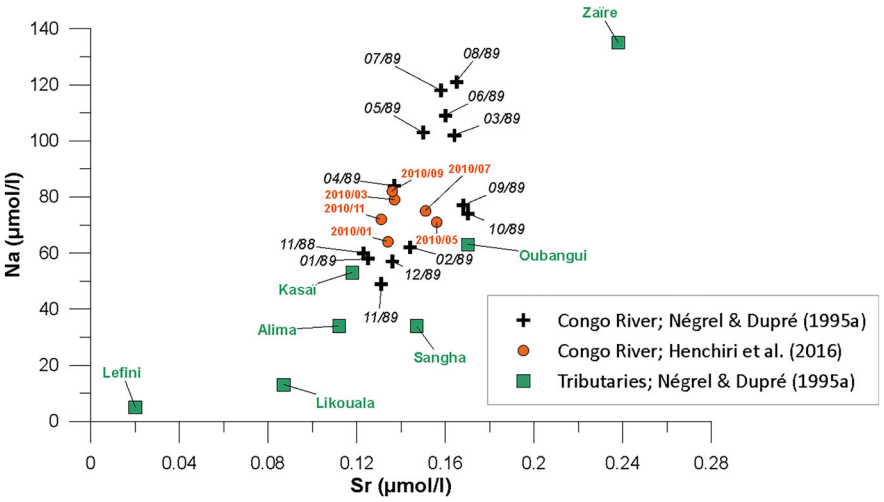



**Fig. 17** Plot of Na versus Sr contents for the samples of the Congo River, collected each month at the Brazzaville station (Négrel and Dupré 1995), every 2 months at the Kinshasa station (Henchiri et al. 2016) and for the tributaries (Oubangui, Zaïre, Kasaï, Sangha, Likouala, and Lefini; Négrel 1992)

The biogeochemical processes in the Congo River Basin are controlled by a complex interplay of lateral carbon inputs, organic matter decomposition, stream size, floodplain dynamics, and geological substrate. $CO_2$ and $CH_4$ emissions are sustained primarily by allochthonous carbon sources, especially from wetlands. Meanwhile, Sr isotopes and elemental ratios offer deep insights into hydrological and geochemical mixing, helping to trace the influence of both surface water and groundwater across varying spatial and temporal scales. These findings underscore the importance of integrating biogeochemical, hydrological, and isotopic approaches to understand carbon cycling and water movement in tropical river systems like the Congo.

## Supply and Demand of Water Resources

The Congo Basin's main water uses are urban/municipal supply, agriculture, hydropower, navigation, and biodiversity maintenance. The population of roughly 120 million (70% in rural areas) depends heavily on rainfed, slash-and-burn farming, a key driver of deforestation. Expanding irrigation could promote sedentary agriculture, curb forest loss, boost productivity, stabilize incomes, and mitigate rainfall variability impacts.

Hydropower potential is estimated at 100,000 MW, yet installed capacity is just 2700 MW. Electrification is low, with only 9% of the population having access. Major future projects—such as Grand Inga (40,000 MW) and Inga III (4320 MW)—could transform regional energy supply, reduce reliance on wood fuel, and cut deforestation pressure.

The basin also has around 25,000 km of navigable waterways, but navigation is hindered by infrastructure deficits. Strategic investments in ports, terminals, and dredging could lower transport costs, facilitate trade, and connect landlocked countries to global markets. Enhanced navigation would stimulate industry, attract investment, and foster political and economic integration. Additionally, improved access could support ecotourism, generating income and jobs while promoting conservation.

The Congo Basin's water resources hold transformative potential for regional development. Realizing this will require coordinated investment in water supply, irrigation, hydropower, and navigation infrastructure, alongside sustainable management to balance economic growth with environmental protection in the face of climate change.

## Dynamical Evolution of the Hydrology of the Congo Basin

Like all large river basins, large-scale geological processes have shaped the Congo Basin over geological epochs. However, the changes that this basin has been exposed to have resulted in a basin like no other currently on the planet. This intracontinental sag basin has resulted in a remarkable deposit of up to one billion years of sediments (Delvaux et al. 2021). It is important to understand these shaping influences as they explain much of the core hydrological systems of what we see today, while also highlighting the long-term non-stationary aspect of the basin's dynamic hydrology. The legacy of these geological changes is evident in the basin's current hydrological systems. The interplay between tectonic stability and climate-induced fluctuations has shaped the region's deep river channels (below Malebo Pool), its vast wetlands, and rich alluvial plains, making the Congo River remarkably stable in terms of discharge.

On very short timescales of the last 100 years or so, the system does appear to be relatively stable (Laraque et al. 2020). For example, a study of the planform of the main river channel and islands conducted by Trigg et al. (2022) using a comparison of recent satellite images and historical navigation maps shows that the main river is relatively stable and only appears to change slowly over the period assessed. However, there was an indication in this study that either a recent reduction in hydrology inputs or increase in sediment inputs were driving a slow accumulation of sediment in the main channel.

While on recent human timescales there appears to be relative stability in the hydrological systems of the Congo, this can be deceptive, as large systems can change, albeit relatively slowly and are actually always changing. Studies of hydrology variables at climate and river stations across the Congo Basin reveal that, set in this stable context, we observe both gradual changes such as increases in temperature (Samba et al. 2008) and discontinuities in runoff variables during particular historical periods in the last 100 years (Laraque et al. 2020). This indicates the main flood regime is not stationary (Bola et al. 2022a) and extremes such as floods have very real impacts on the local populations (Bola et al. 2022b), as many millions live near

and rely on the Congo for their livelihood and economic transport (Trigg et al. 2022). This can be worsened in the future as climate change impact show increasing trend in flood regime. The climatic and environmental shifts over the past tens of thousands of years have also contributed to the unique hydrology of the Congo Basin, influencing everything from river discharge to biodiversity. Understanding these deeper historical changes is essential for predicting how future climatic and anthropogenic changes may impact the basin.

Given the focus on "influencing equitable resource sharing and maintaining the Congo Basin's ecological role," it is important to understand the current drivers of hydrological change in the Congo Basin. The drivers constitute interconnected demands for water, energy, and food resources, and these competing demands drive changes across the basin's hydrology. The three major drivers are hydropower and large water infrastructure development, deforestation and land use change, and mining.

These trends highlight the urgency of integrated and sustainable resource management in the CRB. While much of the current deforestation remains artisanal, experiences from other basins show that unchecked development can lead to profound hydrological consequences. Understanding ecological thresholds and enforcing land use limits will be critical to safeguarding the basin's environmental services and the livelihoods that depend on them.

## Synthesis, Gaps, and Challenges

The time scale of this review spans from 1903 to the present. This is because we lack measurements prior to this year which marks the start of the hydrological monitoring in the Congo Basin. It is also unfortunate that indigenous knowledge about the hydrology in the Congo Basin is not documented prior to this period (Tshimanga 2009).

There is no doubt that there have been enormous efforts deployed during this time period to collect in situ data and use various empirical analyses and numerical models to establish an understanding of the basin's hydrologic variability and changes. The difficulty of acquiring spatial and temporal in situ data of sufficient quality prompted the use of earth observation datasets. However, quality in situ data are still required to validate data obtained from remote sensing. Many hydrology studies have been variously challenged by problems related to lack of appropriate data, as well as the lack of a thorough understanding of climate-hydrology processes. There has also been a lack of integration of this understanding in models and therefore, lack of integrated and critical model assessment. There is a lack of a quantitative understanding of the spatial heterogeneity and dynamics of different components of the hydrology of the Congo Basin, which inhibits the advancement of innovative approaches and their applications in water resources management, climate modeling, and ecosystem vulnerability studies. For example, it is currently unknown how changes to the wetland hydrology and energy balance might alter the local climate across the basin and beyond through teleconnections

(White et al. 2021). It is assumed that by stabilizing the regional hydrological cycle, wetland forests may reduce extreme variations in rainfall, which can otherwise lead to severe floods. A stronger scientific understanding of the land-atmosphere coupling over the vast wetland area of the Cuvette Centrale would give these wetlands a new value that goes beyond already known critical services such as local carbon storage and biodiversity. To advance in these fields, there is an urgent need to address the scarcity of in situ measurements of hydrological variables and to exploit the wealth of historical and newly available satellite observations.

Having looked at the past and present of the current basin hydrology dynamics, what does the future hold? Recent hydrological studies of multimodel regional climate downscaling suggest future changes in river flow ranging from −31.8% to +9.2% under RCP4.5 and −42.5% to +55.5% under RCP8.5 scenarios. In the upstream reaches, these changes are more pronounced. Discharge is also shown to decline in the basin's center and south while increasing in the southeast and northwest (Karam et al. 2023).

In the context of ongoing climate change, the CRB is geopolitically at the center of many proposed solutions due to it perceived abundance of water (Inogwabini 2020). However, across the basin, challenges such as overfishing and lack of transboundary management plans complicate this water resources management expectations. Thus, although the basin is commonly perceived as having a relatively low anthropogenic influence compared to other large river basins, this is unlikely to continue in the future as development pressures increase and humanity looks at climate change adaptation.

The future hydrology of the Congo Basin is expected to undergo significant changes due to climate change, with varying impacts across different regions of the basin. Increased temperatures and variable precipitation patterns will likely lead to changes in runoff, river flow, and the frequency of hydrological extremes such as droughts. The complexity and uncertainty in climate model projections highlight the need for comprehensive and adaptive water management strategies to mitigate the potential adverse effects on agriculture, hydropower, and water availability for human and ecological systems (Tshimanga and Hughes 2014).

While much progress has been made in the last few decades in beginning to understand the hydrological systems in the CRB and how the core of this system functions, nonetheless there is much we are still trying to explain. There are many hazards posed by changes in the future for the Congo Basin that may detrimentally affect its biodiversity and ecosystem services for humanity locally and at planetary scale. How these changes, which are inevitably coming, will affect the dynamics of the Congo Basin is still poorly understood. We urgently need to gain this understanding in order to manage as best as we can how changes manifest in the system. This will provide evidence-based decision-making to preserve and indeed, if possible, enhance the value of this unique and precious systems for local populations as well as globally. This can be exemplified by the need to improve the knowledge of surface-groundwater links. The regulating role of the aquifer is highlighted by the contrast between the low seasonal variations of the river flow rates in the Cuvette

Centrale despite the significant seasonal variability of rainfall in this part of the basin. This should be extended to other parts of the basin, in close relation with the study of wetlands.

The data scarcity problem needs to be addressed through the support of data rescue efforts, i.e., the digitization of colonial and post-colonial archives (mainly weather station and stream gauge data), as well as the expansion of the currently established monitoring network for surface waters and wetland groundwater levels as well as energy and carbon fluxes through eddy covariance towers. Together with satellite data, the new measurement data can be upscaled and combined with hydrological models to derive realistic replicates of the water cycle over the wetland in the Congo Basin that could be used in scenario modeling to present the impact of disturbance to regional and global stakeholders.

This review helps articulate a number of major challenges of hydrological research in the Congo Basin in terms of process understanding and critical information gaps, which require major scientific investment. Specifically, future work should address the following:

1. Local and external factors (atmospheric-ocean interactions and the monsoonal processes) that influence variability in rainfall
2. Influence of global warming on rainfall pattern and water storage and their seasonal distributions, and implications for rainfed agriculture-food security, hydropower, and ecosystems services
3. Forest hydrology: forest canopy interception and evapotranspiration dynamics
4. Local and regional moisture recycling and the impact of deforestation
5. The spatial distribution of permanently and seasonally inundated forests, interaction between rivers and wetland/peatland hydrology and their connectivity
6. Human disturbance in logging and oil palm concessions and local and remote impact on wetland/peatland hydrology and carbon stocks
7. Large-scale deforestation, mining and impacts of river flows, water quality, and biodiversity
8. Deforestation, evapotranspiration losses and impacts on runoff, groundwater recharge, and river base flows
9. Land cover change, land degradation, sediment yield, and changes in aquatic habitats
10. Floodplains and sediment dynamics
11. Hydro-climatic variability, trends, and environmental risks including extreme floods and droughts
12. Water pollution (plastic, industries, and mining)
13. River diversion, impoundment, and fragmentation of water resources/ecosystem services
14. Current and future water use patterns
15. Regional water stress, migrations, and conflicts

The results of such studies will not only be relevant to the Congo River Basin but will also yield important science insights that are widely applicable across other

tropical forest regions and which will transform our understanding of the role of the Congo Basin as a critical element in the global Earth System. While the challenges for hydrologic science are enormous, so are the potential rewards, and the Congo Basin is currently one of the most exciting frontiers in hydrological science.

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